# Shortcuts to Adiabaticity, Optimal Quantum Control, and Thermodynamics Conference

# Program and Book of Abstracts

## TSRC, Telluride, CO - July 14-18 2014

**Organizing Committee:**
**Adolfo del Campo**
**Karl Heinz Hoffmann**
**Christopher Jarzynski**
**Peter Salamon**

LA-UR-14-24509
TSRC hosts: Nana Naisbitt (970-708-0004) and Rory Sullivan (970-708-4542)
The Telluride Intermediate School at 725 W. Colorado Ave, Telluride CO 81435

# PROGRAM

**Conference venue** @ Room 224, The Telluride Intermediate School at 725 W. Colorado Ave, Telluride CO 81435.

**Breakfast** at TSRC will be served 30 minutes before each morning session.

**Sunday** July 13
TSRC Informal gathering at Arroyo Wine Bar and Gallery at 220 E. Colorado Ave 8:00PM for a “meet and greet”; Cash bar.

**Monday** July 14 **- (shortcuts focus)**

08:45 - 09:00 Opening words
09:00 - 09:40 “*Controlling quantum dynamics with assisted adiabatic processes*”, Stuart A. Rice, James Franck Institute, The University of Chicago
09:40 - 10:20 “*Shortcuts to adiabaticity: an overview*”, Adolfo del Campo Theoretical Division & Center for Nonlinear Studies, Los Alamos National Laboratory
10:20 - 10:40 “*Fast-forward protocol in lattice systems: Site-to-site population transfer of a Bose-Einstein condensate in an optical lattice*”, Shumpei Masuda, James Franck Institute, The University of Chicago

10:40 - 11:00 coffee break

11:00 - 11:40 “*Transitionless quantum driving in open quantum systems*”, G. Massimo Palma, NEST, Istituto Nanoscienze-CNR & Dipartimento di Fisica e Chimica, University of Palermo
11:40 - 12:00 “*Classical and Quantum Shortcuts to Adiabaticity for Scale-Invariant Driving”*, Sebastian Deffner, Department of Chemistry and Biochemistry and Institute for Physical Science and Technology, University of Maryland
12:00 - 12:20 “*Non-equilibrium scale invariance and shortcuts to adiabaticity in a one-dimensional Bose gas*”, Wolfgang Rohringer, Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien

12:20 - 12:40 “*Emergence of coherence and the dynamics of quantum phase transitions*”, Mathis Friesdorf, Freie Universität Berlin

12:40 - 01:40 lunch served at TSRC

03:00 - 03:30 “*Using classical mechanics to engineer quantum shortcuts to adiabaticity*”, Christopher Jarzynski, Department of Chemistry and Biochemistry and Institute for Physical Science and Technology, University of Maryland
03:40 - 04:00 “*Finite-time Availability in a Quantum System*”, Karl Heinz Hoffmann, Institute of Physics, Chemnitz University of Technology

04:00 - 04:20 coffee break

04:20 - 05:00 “*Breaking Barriers with Maxwell’s Demon*”, Mark G. Raizen Center for Nonlinear Dynamics and Dept. of Physics, The Univ. of Texas at Austin
05:00 - 05:20 “*Optimal Control of an Ensemble of a Hamiltonian System with Dynamical Algebra*”, Frank Boldt, Institute of Physics, Chemnitz University of Technology

6:00-8:00 TSRC Picnic at Ah Haa School for the Arts, 300 S. Townsend (family and guest welcome free of charge)
**Tuesday** July 15 **- (control & thermo)**
09:00 - 09:40 “*Controlling Quantum Dynamics Phenomena*”, Herschel Rabitz, Department of Chemistry, Princeton University
09:40 - 10:20 “*Optimal control of many-body quantum systems*”, Simone Montangero, Institut für Quanteninformationsverarbeitung, Universität Ulm
10:20 - 10:40 “*Shortcuts to Adiabatic Processes in a Thermodynamic Sense*”, Peter Salamon, Department of Mathematics and Statistics, San Diego State University

10:40 - 11:00 coffee break

11:00 - 11:40 “*The Dynamical Versions of the III-law of Thermodynamics*”, Ronnie Kosloff, Institute of Chemistry the Hebrew University, Jerusalem
11:40 - 12:20 “*Controlled Dynamics in Strongly Correlated Many Body Systems*”, Thomas Busch, Quantum Systems Unit, Okinawa Institute of Science and Technology & Department of Physics, National University of Ireland, UCC, Cork
12:20 - 12:40 “*Cooling many-body systems through optimal control of quantum evolution*”, Armin Rahmani, Theoretical Division, T-4 and CNLS, Los Alamos National Laboratory

12:40 - 01:40   lunch served at TSRC

06:00 - 07:15   TSRC Town Talk, Conference Center in Mountain Village

**Wednesday** July 16 **- (thermo)**

09:00 - 09:40   "*Nonequilibrium equalities in strongly irreversible processes*", Masahito Ueda, Department of Physics, University of Tokyo
09:40 - 10:20   "*Emergent thermodynamics in out-of-equilibrium quantum many-body systems*", Mauro Paternostro, Centre for Theoretical Atomic, Molecular and Optical Physics, School of Mathematics and Physics, Queens University, Belfast
10:20 - 10:40   "*Interference of Identical Particles and Its Influence on Quantum Work Distribution*", Haitao Quan, School of Physics, Peking University, Beijing

10:40 - 11:00   coffee break

11:00 - 11:40   "*Heat-machine control by quantum-state preparation: from quantum engines to refrigerators*", Gershon Kurizki, Weizmann Institute of Science
11:40 - 12:20   "*The Thermodynamic Geometry of the Ising Model*", Gavin Crooks, Physical Biosciences Division, Lawrence Berkeley National Laboratory
12:20 - 12:40   "*Confined Quantum Gas with Slowly and Rapidly Moving Pistons: Non-Equilibrium Equation of States towards Nano-Scale Heat Engine*", Katsuhiro Nakamura, Turin Polytechnic University in Tashkent, Uzbekistan & Department of Applied Physics, Osaka City University

12:40 - 01:40   lunch served at TSRC

**Thursday** July 17 **- (quantum annealing)**

09:00 - 09:40   "*Experiments with the DWave prototype*", Sergio Boixo, Google
09:40 - 10:20   "*Error Corrected Quantum Annealing with Hundreds of Qubits*", Daniel Lidar, Department of Electrical Engineering, Center for Quantum Information Science & Technology, Department of Physics and Astronomy, Department of Chemistry, University of Southern California, Los Angeles

10:20 - 10:40 “*Suppressing excitations in quantum spin chains*”, Marek M. Rams, Institute of Physics, Krakow University of Technology

10:40 - 11:00 coffee break

11:00 - 11:40 “*Quantum speedup by quantum annealing*”, Rolando Somma, Theory Division, Los Alamos National Laboratory, Los Alamos
11:40 - 12:20 “*Can Adiabatic Fast Passage be Used in Ion Trap Quantum Simulators?*”, James K. Freericks, Department of Physics, Georgetown University
12:20 - 12:40 “*Experimental Test of Quantum Jarzynski Equality with a Trapped Ion System*”, Kihwan Kim, Center for Quantum Information, Institute for Interdisciplinary Information Sciences,Tsinghua University, Beijing

12:40 - 01:40 lunch served at TSRC

## **Friday** July 18 - **(many-body)**

09:00 - 09:40 “*Thermalization from the perspective of the eigenstate thermalization hypothesis*”, Vanja Dunjko, Department of Physics, University of Massachusetts Boston
09:40 - 10:20 “*Quantum Simulation of Demon-like Algorithmic Quantum Cooling in linear Optics*”, Chuan-Feng Li, Key Lab of Quantum Information, University of Science and Technology of China, Hefei
10:20 - 10:40 “*Kibble-Zurek mechanism in Bose-Einstein condensates and generation of solitonic vortices*”, Gabriele Ferrari, INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento

10:40 - 11:00 coffee break

11:00 - 11:40 “*Chaos Induced Energy Hopping in Rydberg Atoms*”, Korana Burke, Department of Physics, University of California, Davis
11:40 - 12:00 “*Necessary and sufficient condition for quantum adiabatic evolution by unitary control fields*”, Zhenyu Wang, Institute of Theoretical Physics, Ulm University
12:00 - 12:20 closing words

# Experiments with the DWave prototype

Sergio Boixo
Google, 150 Main St, Venice Beach, CA 90291, USA

Quantum annealing is an optimization method designed to take advantage of quantum phenomena, such as quantum superposition, tunneling and quantum fluctuations. Diabatic transactions between energy levels, and thermal excitations and relaxation, can play an important role in quantum annealing (as opposed to adiabatic quantum computation). DWave has implemented a physical quantum annealing prototype with up to 512 qubits. The decoherence time scale in this device is much shorter than the annealing time. I will review recent work done in this prototype. On the one hand, we find evidence of entanglement within eight superconducting flux qubits. On the other hand, we find no evidence of a quantum speedup for the case of random Ising glasses when the entire data set is considered, and obtain inconclusive results when comparing subsets of problems on an instance-by-instance basis. I will present preliminary new results and theory comparing noisy quantum annealing, the DWave prototype, and several numerical models.

# Optimal Control of an Ensemble of a Hamiltonian System with Dynamical Algebra

Frank Boldt

Institute of Physics, Chemnitz University of Technology D-09107 Chemnitz, Germany

In my talk I will discuss Hamiltonian systems with dynamical algebra. These systems provide fascinating properties like canonical invariance. For such systems starting from a thermodynamic equilibrium state, all non-equilibrated states visited during time evolution can be described using generalized canonical ensembles. In this sense, equilibrium states as well as non-equilibrium states can be treated similarly.

Additionally, such special systems provide useful invariants like the Casimir invariant and its Casimir companion. These invariants simplify further discussion and allow to find so-called Shortcuts to Adiabaticity, which are special time-evolutions to connect adiabatically equilibrium states in finite time. Based on the introduced framework strategies to find optimal controls will be presented.

# Chaos Induced Energy Hopping in Rydberg Atoms

Korana Burke
Department of Physics, University of California, Davis, California 95616, USA

A highly excited quasi one-dimensional Rydberg atom exposed to periodic alternating external electric field pulses exhibits chaotic behavior. Even though this system is chaotic, we can understand its time evolution by studying the geometric structure of phase space called a homoclinic tangle. We utilize the knowledge about the geometric structure of phase space to design an experimental protocol for nonadiabatic energy change of an electron ensemble. The protocol consists of short pulse sequences that quickly and efficiently transfer electron ensemble from a starting energy state ($n$ 306) to a desired final energy state. The final state can have either much lower ($n < 230$) or much higher energy ($n > 500$) depending on the relative position of the starting ensemble with respect to the homoclinic tangle. We also present how the phase space geometry influences the efficiency of the transport between the energy states.

# Controlled Dynamics in Strongly Correlated Many Body Systems

Thomas Busch

Quantum Systems Unit, Okinawa Institute of Science and Technology, Okinawa, Japan
Department of Physics, National University of Ireland, UCC, Cork, Ireland

Developing strategies for controlling interacting quantum many body systems is of large interest in the area of quantum computing and quantum simulations. However, as the quantities of interest in these areas are usually quantum or classical correlation functions, mean field or other approaches relying on approximations are usually not sufficient.

In the presentation I will introduce exactly solvable many body systems and detail our efforts in designing algorithms that allow for the creation of macroscopical entangled states. In particular we are looking for so-called NOON states in strongly correlated systems and I will describe examples where these can be created in experimentally realistic systems using standard dynamics or possibly shortcut approaches.

# The Thermodynamic Geometry of the Ising Model

Gavin Crooks
Physical Biosciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

A fundamental problem in modern thermodynamics is how a molecular-scale machine performs useful work, while operating away from thermal equilibrium without excessive dissipation. For finite-time transformations within the linear-response regime, the dissipation is controlled by a Riemannian metric structure that bestows optimal protocols with many useful properties. I will talk about the thermodynamic geometry of the Ising model, how to locate and visualize geodesics, and some implications for storing bits in magnetic domains.

# Classical and Quantum Shortcuts to Adiabaticity for Scale-Invariant Driving

Sebastian Deffner

Department of Chemistry and Biochemistry and Institute for Physical Science and Technology, University of Maryland, College Park, Maryland 20742, USA

A shortcut to adiabaticity is a driving protocol that reproduces in a short time the same final state that would result from an adiabatic, infinitely slow process. A powerful technique to engineer such shortcuts relies on the use of auxiliary counterdiabatic fields. Determining the explicit form of the required fields has generally proven to be complicated. We present explicit counterdiabatic driving protocols for scale-invariant dynamical processes, which describe, for instance, expansion and transport. To this end, we use the formalism of generating functions and unify previous approaches independently developed in classical and quantum studies. The resulting framework is applied to the design of shortcuts to adiabaticity for a large class of classical and quantum, single-particle, nonlinear, and many-body systems.

# Thermalization from the perspective of the eigenstate thermalization hypothesis

Vanja Dunjko

Department of Physics, University of Massachusetts Boston, Boston MA 02125, USA

We present the current status in our understanding of thermalization in isolated systems, as viewed through the lens of the eigenstate thermalization hypothesis. After reviewing the field more broadly, we will pay special attention to the integrability-to-chaos transition and the geometrical structures that emerge in its study.

# Shortcuts to adiabaticity: an overview

Adolfo del Campo
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Center for Nonlinear Studies, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Quantum adiabatic processes -that keep constant the populations in the instantaneous eigenbasis of a time-dependent Hamiltonian- are very useful to prepare and manipulate states, but take typically a long time. This is often problematic because decoherence and noise may spoil the desired final state, or because some applications require many repetitions. "Shortcuts to adiabaticity" are alternative fast processes which reproduce the same final populations, or even the same final state, as the adiabatic process in a finite, shorter time. Since adiabatic processes are ubiquitous, the shortcuts span a broad range of applications in atomic, molecular and optical physics, such as fast transport of ions or neutral atoms, internal population control and state preparation (for nuclear magnetic resonance or quantum information), cold atom expansions and other manipulations, cooling cycles, wavepacket splitting, and many-body state engineering or correlations microscopy. Shortcuts are also relevant to clarify fundamental questions such as a precise quantification of the third principle of thermodynamics and quantum speed limits. We review different theoretical techniques proposed to engineer the shortcuts, the experimental results, and the prospects.

# Kibble-Zurek mechanism in Bose-Einstein condensates and generation of solitonic vortices

Gabriele Ferrari
INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, 38123 Povo, Italy

We report on the observation of solitonic vortices in an atomic Bose-Einstein condensate after free expansion. Clear signatures of the nature of such defects are the twisted planar density depletion around the vortex line, observed in absorption images, and the double dislocation in the interference pattern obtained through homodyne techniques. Both methods allow us to determine the sign of the quantized circulation. Experimental observations agree with numerical simulations. These solitonic vortices are the decay product of phase defects of the BEC order parameter spontaneously created via the Kibble-Zurek mechanism after a rapid temperture quench across the BEC transition in a cigar-shaped harmonic trap, and they are shown to have a very long lifetime.

# Can Adiabatic Fast Passage be Used in Ion Trap Quantum Simulators?

James K. Freericks

Department of Physics, Georgetown University, 37th and O st. NW, Washington DC, 20057, USA

One of the proposed uses of an ion trap quantum simulator is to adiabatically create a complex ground state of a nontrivial Hamiltonian. The simplest example to undertake this is in a transverse field Ising model with long-range spin-spin interactions. By starting with a large field and a state polarized along the field, one then reduces the field slowly to zero to end up in the nontrivial ground state of the field-free Hamiltonian. While this has been tried in a number of experiments, the evolution is always diabatic, so the system creates excitations. This phenomena has ben employed to create spectroscopy protocols for these systems, which provide interesting new information from the simulations, but have not achieved the original goal. I will end with a discussion of how fast passage ideas could be employed to allow these systems to create nontrivial quantum states with high purity within the experimental limitations for run times and for complexity of the fast passage protocol.

# Emergence of coherence and the dynamics of quantum phase transitions

Simon Braun, [1,2] Mathis Friesdorf, [3] Sean S. Hodgman, [1,2]
Michael Schreiber, [1,2] Jens P. Ronzheimer, [1,2] Arnau Riera, [3,4]
Marco del Rey, [5] Immanuel Bloch, [1,2] Jens Eisert, [3] and Ulrich Schneider [1,2]

1. Ludwig-Maximilians-Universität München, Munich, Germany
2. Max-Planck-Institut für Quantenoptik, Garching, Germany
3. Freie Universität Berlin, Berlin, Germany
4. Instituto de Física Fundamental, CSIC, Madrid, Spain
5. Max-Planck-Institut für Gravitationsphysik, Potsdam-Golm, Germany

Quantum phase transitions are an ideal playground to probe the low-energy behaviour of complex many-body systems and to explore the limits of the adiabatic theorem. When dynamically crossing such a transition, the closing of the gap at the critical point causes a breakdown of adiabaticity of the evolution and thus, defects are introduced into the system. This raises the following questions: How does a literal phase transition happen? To what extent can static ground state properties be probed by a dynamical experiment? When entering a critical phase associated with an infinite correlation length, at what rate and by what mechanism will coherence build up.

Ultracold atoms in optical lattices provide a clean, well isolated, and highly controllable system and allow for a thorough study of this question, in models that are, in any meaningful sense of the word, far from being integrable. In this talk, we will explore the Mott to superfluid transition by slowly decreasing the depth of the optical lattice, thus crossing the critical point. We verify our experimental results by extensive numerical simulations of the Bose-Hubbard model, thus performing an instance of a certified quantum simulation. We find a complex behaviour, uncovering intriguing new physics that cannot be captured by the Kibble-Zurek mechanism or any other known model. We connect our findings with insights into close-to-adiabatic quantum evolutions and carefully compare our continuous ramp setting with concepts of equilibration and thermalisation associated with sudden quenches. We also put the results into the context of notions of information propagation

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and Lieb-Robinson bounds.

## References

[1] S. Braun, M. Friesdorf, S.S. Hodgman, M. Schreiber, J.P. Ronzheimer, A. Riera, M. del Rey, I. Bloch, J. Eisert and U. Schneider, Arxiv:1403.7199

# Finite-time Availability in a Quantum System

Karl Heinz Hoffmann
Institute of Physics, Chemnitz University of Technology D-09107 Chemnitz, Germany

Classically, availability refers to the work available in any reversible process that brings about equilibrium between the system and an environment. Here we introduce an additional meaning of availability as the maximum work associated with the change of an external parameter in the Hamiltonian of a quantum system. In the context of the change in the frequency of a harmonic oscillator this extension seems natural since the associated availability in fact equals the traditional availability of the initial state of the quantum system relative to an environment at the temperature of the final state. This availability can be gained in a FEAT (fast effectively adiabatic transition) process and for times larger than or equal to the FEAT time, there exists an optimal control of the frequency which achieves the available work. For shorter times quantum friction effects are unavoidable and the available work is thereby lowered. This lost work is discussed in this talk.

# Using classical mechanics to engineer quantum shortcuts to adiabaticity

Christopher Jarzynski

Department of Chemistry and Biochemistry and Institute for Physical Science and
Technology, University of Maryland, College Park, Maryland 20742, USA

When designing a shortcut to adiabaticity, the aim is to construct a counter-diabatic Hamiltonian that suppresses transitions of a rapidly driven quantum system away from an adiabatic energy eigenstate. I will argue that a useful strategy for determining such counter-diabatic Hamiltonians involves exploiting the close correspondence between quantum and classical adiabatic invariants. This strategy can be applied both to scale-invariant and non-scale-invariant dynamical processes, and it can be used to obtain both local and non-local counter-diabatic Hamiltonians. I will illustrate these ideas with simple model systems including the tilted particle-in-a-box, and a double well potential.

# Experimental Test of Quantum Jarzynski Equality with a Trapped Ion System

Kihwan Kim
Center for Quantum Information, Institute for Interdisciplinary Information Sciences,
Tsinghua University, Beijing 100084, P. R. China

In this talk, we report an experimental test of the Quantum Jarzynski Equality with a single trapped 171Yb$^+$ ion. In thermodynamics, the work done on a system in thermal equilibrium is used to entirely change the free energy of the system only when it is applied in a quasi-static manner. In 1997, Jarzynski found a surprising equality that connects the free energy difference and the work done on the system even through non-equilibrium processes [1]. The Jarzynski equality has received a wide attention and application, which leads to experimental tests of the validity in many classical systems. While the quantum version of the Jarzynski equality was reported [2], the experimental verification of the quantum version has not yet been fully demonstrated due to experimental challenges required for the test [3]. In our experiment, we apply a laser induced force on a single 171Yb$^+$ ion trapped in harmonic potential. We perform projective measurements to obtain phonon distributions of an initial thermal state. Following that we apply laser induced force on the projected energy eigenstate, and find transition probabilities to final energy eigenstates after the work is done. By varying the speed of applying force from equilibrium to far-from equilibrium regime, we verified the quantum Jarzynski equality in an isolated system.

This work was supported in part by the National Basic Research Program of China Grant 2011CBA00300, 2011CBA00301, the National Natural Science Foundation of China Grant 61073174, 61033001, 61061130540, and 11374178. KK acknowledges the first recruitment program of global youth experts of China.

## References

[1] C. Jarzynski, Phys. Rev. Lett. **78**, 2690 (1997).

[2] S. Mukamel, Phys. Rev. Lett. **90**, 170604 (2003).

[3] G. Huber, F. Schmidt-Kaler, S. Deffner and E. Lutz, Phys. Rev. Lett. **101**, 070403 (2008).

# The Dynamical Versions of the III-law of Thermodynamics

Ronnie Kosloff
Institute of Chemistry the Hebrew University, Jerusalem 91904, Israel

Quantum thermodynamics addresses the emergence of thermodynamical laws from quantum me- chanics. The III-law of thermodynamics has been mostly ignored. There are seemingly two inde- pendent formulation of the third law. The first, known as the Nernst heat theorem, implies that the entropy flow from any substance at absolute zero temperature is zero: $\dot{S} = \mathcal{J}_c/T_c \to 0$ when $T_c \to 0$ and $\mathcal{J}_c$ is the heat current is the heat current. In order to insure the ful

fillment of the second law when $T_c \to 0$ it is necessary that the entropy production scales as $\dot{S} \sim T_c^{\alpha}$ with $\alpha > 0$. The third law imposes $\alpha > 0$ guaranteeing that at absolute zero $\dot{S} = 0$. As a result, $\mathcal{J}_c \sim T_c^{\alpha+1}$.

The second formulation of the III-law is a dynamical one, known as the unattainability principle: *No refrigerator can cool a system to absolute zero temperature at fi*

*nite time.* This formulation is more restrictive, imposing limitations on thespectral density and the dispersion dynamics of the heat bath. We quantify this formulation by evaluating the characteristic exponent of the cooling process

$$\frac{dT(t)}{dt} \sim -T^{\zeta}, \qquad T \to 0.$$

Namely for $\zeta < 1$ the system is cooled to zero temperature at fi

nite time. We relate the III-law to a generic quantum refrigerator model which is a nonlinear device merging three currents from three heat baths: a cold bath to be cooled, a hot bath as an entropy sink, and a driving bath which is the source of cooling power. A heat-driven refrigerator (absorption refrigerator) is compared to a power-driven refrigerator related to laser cooling. When optimized, both cases lead to the same exponent $\zeta$, showing a lack of dependence on the form of the working medium and the characteristics of the drivers. The characteristic exponent is therefore determined by the properties of the cold reservoir and its interaction with the system. Two generic heat bath models are considered: a cold bath composed of harmonic oscillators and a cold bath composed of ideal Bose/Fermi gas. The restrictions on the interaction Hamiltonian imposed by the third law will be addressed

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[1, 2, 3].

## References

[1] Amikam Levy and Ronnie Kosloff, Phys. Rev. Lett. **108**, 070604 (2012).

[2] Amikam Levy, Robert Alicki, and Ronnie Kosloff, Phys. Rev. E **85**, 061126 (2012).

[3] Amikam Levy, Robert Alicki, and Ronnie Kosloff, Phys. Rev. Lett. **109**, 248901 (2012).

# Heat-machine control by quantum-state preparation: from quantum engines to refrigerators

David Gelbwaser-Klimovsky and Gershon Kurizki
Weizmann Institute of Science, 76100 Rehovot, Israel

We explore the dependence of the performance bounds of heat engines and refrigerators on the *initial quantum state* and the subsequent evolution of their piston, modeled by a quantized harmonic oscillator. Our goal is to provide a fully quantized treatment of *self-contained (autonomous)* heat machines, as opposed to their prevailing semiclassical description that consists of a quantum system alternately coupled to a hot or a cold heat bath, and *parametrically* driven by a classical time-dependent piston or field. Here by contrast, there is no external time-dependent driving. Instead, the evolution is caused by the stationary simultaneous interaction of two heat baths (having distinct spectra and temperatures) with a single two-level system that is in turn coupled to the quantum piston. The fully quantized treatment we put forward allows us to investigate work extraction and refrigeration by the tools of quantum-optical amplifier and dissipation theory, particularly, by the analysis of amplified or dissipated phase-plane quasiprobability distributions. Our main insight is that quantum states may be thermodynamic resources and can provide a powerful handle, or control, on the efficiency of the heat machine. In particular, a piston initialized in a coherent state can cause the engine to produce work at an efficiency above the Carnot bound in the linear amplification regime. In the refrigeration regime, the coefficient of performance can transgress the Carnot bound if the piston is initialized in a Fock state. The piston may be realized by a vibrational mode, as in nanomechanical setups, or an electromagnetic field mode, as in cavity- based scenarios.

# Quantum Simulation of Demon-like Algorithmic Quantum Cooling in linear Optics

Chuan-Feng Li, Jin-Shi Xu, Xiao-Ye Xu, Yong-Jian Han, Guang-Can Guo
Key Lab of Quantum Information, University of Science and Technology of China, Hefei 230026, PR China

Simulation of low-temperature properties of many-body systems remains one of the major challenges in theoretical and experimental quantum information science. We demonstrate experimentally a Demon-like algorithmic quantum cooling method which is applicable to any physical system that can be simulated by a quantum computer. The experimental implementation is realized with a quantum optical network by introducing an auxiliary qubit, and the results are in full agreement with theoretical predictions. Then we apply this method to simulate the dynamics of Landau-Zener model supporting Kibble-Zurek mechanism . Our method may also be useful in simulations of low-temperature properties of physical and chemical systems that are intractable with classical methods.

## References

[1] Jin-Shi Xu, Man-Hong Yung, Xiao-Ye Xu, Sergio Boixo, Zheng-Wei Zhou, Chuan-Feng Li, Alan Aspuru-Guzik, and Guang-Can Guo, Nature Photonics **8**, 113 (2014).

[2] Xiao-Ye Xu, Yong-Jian Han, Kai Sun, Jin-Shi Xu, Jian-Shun Tang, Chuan-Feng Li and Guang-Can Guo, Physical Review Letters **112**, 035701 (2014).

# Error Corrected Quantum Annealing with Hundreds of Qubits

Kristen Pudenz[1,2,3], Tameem Albash[2,4], Daniel Lidar[1,2,4,5]
[1]Department of Electrical Engineering, [2]Center for Quantum Information Science & Technology, [3]Information Sciences Institute, [4]Department of Physics and Astronomy, [5]Department of Chemistry, University of Southern California, Los Angeles, California 90089, USA

It is unlikely that any quantum information processor will ever reach a useful scale without error correction. This applies also to adiabatic quantum computing (AQC), in spite of some degree of intrinsic robustness to control errors and thermal excitations. We have developed error correction techniques tailored to quantum annealing, a specialized form of AQC. Our strategy combines an energy penalty against bit-flip errors and a repetition code decoded via a majority vote protocol. I will discuss both theory and experimental results implementing this strategy for computations using close to 500 physical qubits on the D-Wave Two quantum annealing device located at USC. Scaling of code performance on both antiferromagnetic chains and random 2D Ising problems will be addressed, along with insights into device error mechanisms and choices of decoding strategy. The error correction substantially enhances the observed success probabilities.

## References

[1] Kristen Pudenz, Tameem Albash, Daniel Lidar, Error corrected quantum annealing with hundreds of qubits, Nature Commun. **5**, 3243 (2014).

# Fast-forward protocol in lattice systems: Site-to-site population transfer of a Bose-Einstein condensate in an optical lattice

Shumpei Masuda and Stuart A. Rice
James Franck Institute, The University of Chicago, Chicago, IL 60637

The fast-forward protocol [1] for accelerated coherent control of the evolution of quantum states defines a driving potential that is a functional of the system wave function; the application of that potential generates the same final state in a selected time TF that is shorter than the time that would be taken to reach the same state in the absence of the driving field. To date, the theory has been developed for acceleration of quantum adiabatic dynamics [2], systems with an electromagnetic field [3] and many-body systems [4], and it has been applied to the transport of particles and compression/expansion and splitting of a wave function. We have extended the fast-forward protocol to lattice systems [5], and shown that in a lattice system with fixed hopping rate there is a lower limit to the time $T_F$. We consider the site-to-site population transfer of a Bose-Einstein condensate in an optical lattice by controlling a harmonic potential. The harmonic potential is designed to approximate the exact driving potential. It is shown that the control with the fast-forward driving potential is stable to variation of the approximate field and that the approximate driving potential generates a high fidelity population transfer. An extension of the framework of fast-forward theory to many-body lattice systems is also presented.

## References

[1] S. Masuda and K. Nakamura, Phys. Rev. A **78**, 062108 (2008).

[2] S. Masuda and K. Nakamura, Proc. R. Soc. A **466**, 1135 (2010).

[3] S. Masuda and K. Nakamura, Phys. Rev. A **84**, 043434 (2011).

[4] S. Masuda, Phys. Rev. A **86**, 063624 (2012).

[5] S. Masuda and S. A. Rice, Phys. Rev. A **89**, 033621 (2014).

# Optimal control of many-body quantum systems

Simone Montangero
Institut für Quanteninformationsverarbeitung, Universität Ulm, D-89069 Ulm, Germany

We present an efficient algorithm to optimally control many-body quantum dynamics. We perform an information theoretical analysis of quantum optimal control processes that allows to set bounds to the resources needed to achieve controlled many-body quantum dynamics. Finally, we report some theoretical and experimental applications of quantum optimal controlled many-body dynamics, in particular we present a time-optimal quantum phase transition crossing of cold atoms in optical lattices.

# Confined Quantum Gas with Slowly and Rapidly Moving Pistons: Non-Equilibrium Equation of States towards Nano-Scale Heat Engine

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The idea of end-reversible engine (or finite-time Carnots heat engine) is highly phenomenological. It neither considered a quantum gas nor showed a non-equilibrium equation of states due to a moving piston. Concentrating on the thermally-isolated process, we shall obtain the non-equilibrium equation of states for a quantum gas in a nano-scale container (cylinder, cavity, billiard, etc) with a moving piston (wall). We consider two limiting cases of very slow and very rapid pistons, taking the Fermi velocity as a velocity standard. In the case of the container with time-dependent size, the pressure operator proves to be a sum of the adiabatic and non-adiabatic terms which are both time-reversal symmetric. Non-equilibrium state of a quantum gas is described by von Neumann equation for the density operator, which is solved perturbatively with use of adiabatic basis (for a very slow piston) and is exactly solvable by using a combination of scale and gauge transformations (for a very rapid piston). We elucidate the non-equilibrium effect of the moving piston on Bernoullis law and Poissons adiabatic equation which are two different expressions for the expectation of pressure operator. By-products of the present work include an asymptotic analytical expression for two peak structures in the spectrum of the transition probability, which is taken to justify the quantum fluctuation theorem for an ideal gas in a cavity with a very rapid piston.

# Transitionless quantum driving in open quantum systems

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We extend the concept of superadiabatic dynamics, or transitionless quantum driving, to quantum open systems whose evolution is governed by a master equation in the Lindblad form. We provide the general framework needed to determine the control strategy required to achieve superadiabaticity. We apply our formalism to two examples consisting of a two-level system coupled to environments with time-dependent bath operators.

# Emergent thermodynamics in out-of-equilibrium quantum many-body systems

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Thermodynamics is one of the pillars of physical, chemical and biological sciences. It is able to predict the occurrence and efficiency of complex chemical reactions and biological processes. In physics, the conduction of heat across a medium or the concept of the arrow of time are formulated thermodynamically. In information theory, the definitions of information and entropy are given in thermodynamical terms. Even more, the tightness of the link between information and thermodynamics can be deduced from the thermodynamic interpretation of the landmark embodied by Landauers erasure principle, Jaynes principle of maximum entropy, or the exorcism of Maxwells demon operated using information theoretical tools. Another example of the role of thermodynamics in the panorama of physical sciences is the analysis of the spectrum of blackbody radiation made by Planck, which triggered the quantum mechanical revolution. However, science and technology have evolved immensely from the early days of the quantum era, allowing us to witness quantum effects that could only be dreamed of decades ago. Our capabilities to control and guide processes at the microscopic scale has reached outstanding levels of dexterity. Yet, a series of tantalising questions arise: what happens to the principles of thermodynamics when we deal with the quick dynamics of small quantum systems brought dramatically out of equilibrium? Can we formulate in a thermodynamical way the working principles of quantum devices designed to perform transformations analogous to canonical thermo-machines? In this talk I will present a framework that is able to show the emergence of thermodynamics out of genuinely quantum processes enforced in quantum many- body systems, thus establishing a tight link between thermodynamics and quantum critical phenomena. I will discuss how work can be extracted from intricate (mesoscopic) quantum motors to ensure engines performances overcoming any classical counterpart and suggest tantalising connections between the irreversible quantum entropy produced across a process and the establishment of quantum correlations among the constituents of a quantum device.

# Interference of Identical Particles and Its Influence on Quantum Work Distribution

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Identical particles interfere with each other in nonequilibrium work processes. The effect of this interference on quantum work distribution has not been explored so far. We evaluate the transition probabilities between many-particle states in a quantum piston. By utilizing these transition probabilities we obtain the quantum work distribution for the nonadiabatic compression of identical particles. The difference of work distribution between Bosons and Fermions at low temperature is highlighted. We also reveal that, as expected, at high temperature the work distributions of Bosons and Fermions approach each other. Our study may be implemented in the newly developed Boson Sampling Machines in quantum information science.

# Controlling Quantum Dynamics Phenomena

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The basic principles of controlling quantum dynamics with applied fields will be discussed, especially considering the growing number of successful experiments. These findings will be expressed in terms of the quantum control landscape, which is the observable as a functional of the control. The topological and structural features of these landscapes greatly influence the ability to find effective controls. A summary will be given of the theoretical and experimental findings regarding landscape features and their implications. Illustrations ranging from simple to complex systems will be presented.

# Cooling many-body systems through optimal control of quantum evolution

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Nonadiabatic unitary evolution with tailored time-dependent Hamiltonians can prepare systems of cold atomic gases with various desired properties. For a system of two one-dimensional quasicondensates coupled with a time-varying tunneling amplitude, we show that the optimal protocol, for maximizing any figure of merit in a given time, is bang-bang, i.e., the coupling alternates between only two values through a sequence of sudden quenches. Minimizing the energy of one of the quasicondensates with such nonadiabatic protocols, and then decoupling it at the end of the process, can result in effective cooling beyond the current state of the art. Our cooling method can be potentially applied to arbitrary systems through an integration of the experiment with simulated annealing computations.

# Breaking Barriers with Maxwell's Demon

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We are developing new approaches to the control of atomic motion. The starting point is the supersonic beam, an ultra-bright source of atoms. We use pulsed magnetic fields to stop the beam, and now have realized an adiabatic slower. We further cool the atoms using a one-way wall, a direct realization of the historic thought experiment of Maxwell's Demon, proposed by James Clerk Maxwell in 1871. This toolbox of new methods is an alternative to Laser Cooling, with much better predicted performance in terms of generality, flux of ultra-cold atoms, and phase-space density.

# Suppressing excitations in quantum spin chains

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When the parameters of the Hamiltonian are driven across a second order phase transition at a finite rate then the system gets excited from its ground state. The density of excitations is qualitatively predicted by the universal Kibble-Zurek mechanism. Using the quantum Ising model as an example, I will discuss two schemes which lead to the suppression of those excitations. One is based on spatial inhomogeneity of the system [1], second on the idea of assisted transitionless driving [2].

## References

[1] J. Dziarmaga, M. M. Rams, New J. Phys. **12**, 055007 (2010); ibid. **12**, 103002 (2010).

[2] A. del Campo, M. M. Rams, W. H. Zurek, Wojciech H. Zurek, Phys. Rev. Lett. **109**, 115703 (2012).

# Controlling quantum dynamics with assisted adiabatic processes

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External control of the dynamical evolution of a quantum many-body system is sought after in tasks as diverse as selection of the product of a chemical reaction and quantum computing. In the last 25 years theoretical and experimental studies have established many variants of external control schemes that transfer population from a selected initial state or an initial wave packet of states of a system to a selected final state or a specified target wave packet of states; the specifics of these control schemes depend on the character of the spectrum of states of a system and the interaction between the system and an optical field, but all of them rely on coherence and interference effects embedded in the quantum dynamics. We consider a subset of control protocols that generate population transfer by an assisted adiabatic process that uses an auxiliary field to produce in a shorter time and/or with weaker driving fields the same target state that would have been generated by a strictly adiabatic transformation. In particular, we discuss the so-called counter-diabatic protocol as applied to enhancing the efficiency of vibrational energy transfer in a polyatomic molecule. The vehicles for these studies are population transfer between vibrational states of the thiophosgene ($SCCl_2$) molecule and the ground electronic state isomerization reaction HCN → CNH. Although we must use models of these systems in our calculations, the models are sufficiently complex to illustrate how the theoretical framework of an assisted adiabatic process depends on the character of the system studied, on the available control parameters, on the constraints imposed by the experimental setting, on the efficiency of population transfer to be achieved, and on the stability of the control process with respect to the variation of the external control fields.

# Non-equilibrium scale invariance and shortcuts to adiabaticity in a one-dimensional Bose gas

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We present experimental evidence for scale invariant behaviour of the excitation spectrum in phase-fluctuating quasi-1d Bose gases after a rapid change of the external trapping potential. Probing density correlations in free expansion, we find that the temperature of an initial thermal state scales with the spatial extension of the cloud as predicted by a model based on adiabatic rescaling of initial eigenmodes with conserved quasiparticle occupation numbers. Based on this result, we implement shortcuts to adiabaticity for the rapid expansion or compression of the gas by a stochastic optimal control approach. Temperature measurements of the phonon ensemble indicate that the shortcut procedure does not induce additional heating, consistent with the results of classical field simulations. Our findings demonstrate the feasibility of implementing shortcuts to adiabaticity at the level of elementary excitations for certain classes of quantum many-body systems.

# Shortcuts to Adiabatic Processes in a Thermodynamic Sense

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Shortcuts to adiabaticity processes preserve the occupation numbers in each quantum state. For systems showing canonical invariance, this will enable shortcuts to reversible adiabatic processes in a thermodynamic sense. Are there any other systems with this property? More generally, how close to a reversible adiabatic process from an initial thermal state to a final one can we carry out in a quantum system? A careful statement of the problem requires the notion of a ”prelude process” – a process that will be followed by contact to a heat bath. What can shortcuts to adiabaticity do for such processes? How and when can we make shortcuts to adiabaticity into reversible adiabatic processes in a thermodynamic sense?

# Quantum speedup by quantum annealing

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We study the glued-trees problem of Childs, et. al. [1] in the adiabatic model of quantum computing and provide an annealing schedule to solve an oracular problem exponentially faster than classically possible. The Hamiltonians involved in the quantum annealing do not suffer from the so-called sign problem. Unlike the typical scenario, our schedule is efficient even though the minimum energy gap of the Hamiltonians is exponentially small in the problem size. We discuss generalizations based on initial-state randomization to avoid some slowdowns in adiabatic quantum computing due to small gaps.

## References

[1] A. M. Childs, R. Cleve, E. Deotto, E. Farhi, S. Gutmann, and D. Spielman, Proc. 35th Annual ACM Symposium on Theory of Computing, 59-68 (2003).

# Nonequilibrium equalities in strongly irreversible processes

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We discuss nonequilibrium equalities which are valid even when initial probability vanishes in a certain region of phase space and when precise measurement is conducted. These situations have been elusive in previous works. The equalities are proved in a unifying way regardless of dynamics of the system and include the Jarzynski equality and its variants under feedback control. Inequalities derived from the equalities dictate stronger restriction on the averaged entropy production than the conventional second law in certain systems.

# Necessary and sufficient condition for quantum adiabatic evolution by unitary control fields

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We decompose the quantum adiabatic evolution as the products of gauge invariant unitary operators and obtain the exact nonadiabatic correction in the adiabatic approximation. A necessary and sufficient condition that leads to adiabatic evolution with geometric phases is provided. In the adiabatic evolution, while the eigenstates are slowly varying, the eigenenergies and degeneracy of the Hamiltonian can change rapidly. We show with examples that parametrized pulse sequences or fast modulation fields can lead to better adiabatic evolution.

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