Information Engines at the Frontiers of Nanoscale Thermodynamics

Organizing Committee:
James Crutchfield
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July 19 – July 27, 2018

Telluride Intermediate School, 725 W Colorado Ave Telluride, CO 81435

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1 Scope

Synthetic nanoscale machines, like their macromolecular biological counterparts, perform tasks that involve the simultaneous manipulation of energy, information, and matter. In this they are information engines systems with two inextricably intertwined characters. The first aspect, call it physical, is the one in which the system is seen embedded in a material substrate that is driven by, manipulates, stores, and dissipates energy. The second aspect, call it informational, is the one in which the system is seen in terms of its spatial and temporal organization generates, stores, loses, and transforms information. Information engines operate by synergistically balancing both aspects to support a given functionality, such as extracting work from a heat reservoir. Recent years witnessed remarkable progress in the theoretical understanding and experimental exploration of how physical systems compute, process, and transfer information. We are on the verge of a synthesis that will allow us to account for a new thermodynamics of information. As we continue to develop a deeper understanding of the world around us, the fundamental question arises, How does nature compute? Numerous researchers, both theorists and experimentalists, are working towards understanding how information is transferred through and transformed at the nanoscale – with applications ranging from biological systems to quantum devices. The aim of this workshop is to exchange ideas from research in Nonequilibrium Thermodynamics, Classical and Quantum Information, Statistical Mechanics, Biophysics, and Nonlinear Dynamics. These questions are relevant in a wide variety of fields including Nanoscale Statistical Mechanics, Finite-Time Thermodynamics, Quantum Thermodynamics, Quantum Computation, Quantum Communication, Quantum Optimal Control Theory, and Biological Physics.

2 Program

2.1 Overview

Useful information:

- The workshop is organized around stimulating discussion and sharing ideas. The schedule is relaxed. Talks are only in the mornings, leaving the afternoons free for work, discussions, and recreation. There are also a number of evening events, from group dinners to the BBQ and a community talk that bring us back together.
- Some useful area maps are provided at the end of this Program.
- The abstract have been sorted according to topics, and we will have sessions on *thermodynamics of information, information engines and Maxwell demons, quantum thermodynamics and quantum information, stochastic thermodynamics, quantum and nanotechnologies, entropy production and thermodynamic cost*, and *thermodynamic control and optimal processes.*
- We will have no sessions on Sunday, but the meeting rooms will be available.
- Breakfast and lunch will be served at the Telluride Intermediate School. However, there is **NO** breakfast or lunch on Sunday.
- Groupd dinners and TSRC BBQ are held at the tent next to the Telluride Intermediate School
- Information Scholars are going to announced during the last talk on Thursday 7/26
- The session chairs will observe the Frauenfelder rules:

  > Hans Frauenfelder is the inventor of the "Frauenfelder Rules", which provide a guideline about the most successful way to run a seminar at a research workshop, according to which a presentation should take up no more than 66% of the allotted time, the rest being used for questions and in-depth discussion.

  So, please make sure that your presentation is at most 30 mins, which leaves at least 10 mins for discussion.

	Thursday 07/19	Friday 07/20	Saturday 07/21	Sunday 07/22	Monday 07/23	Tuesday 07/24	Wednesday 07/25	Thursday 07/26	Friday 07/27
8:20	breakfast	breakfast	breakfast		breakfast	breakfast	breakfast	breakfast	breakfast
9:00	opening	**Pak**	**Boyd**		**Marzen**	**Jarzynski**	**Hodson**	**Šafránek**	**Krishnaprasad**
9:40	**Crutchfield**	**Aghamohammadi**	**Riechers**		**M. Zwolak**	**Ochoa**	**Saira**	**Girolami**	**Huang**
10:20	coffee	coffee	coffee		coffee and picture	coffee	coffee	coffee	coffee
11:00	**Deffner**	**Goldt**	**Wimsatt**		**Hinczweski**	**Huxtable**	**Brito**	**Matheny**	**Horowitz**
11:40	**Bhuniyan**	**Rupe**	**Rahav**		**Elenewski**	**Anzà**	**J. Zwolak**	**Burke**	**Salamon**
12:20	lunch	lunch	lunch		lunch	lunch	lunch	lunch	closing
13:00									
13:40									
14:20									
15:00									
15:40									
16:20									
17:00									
17:40	group dinner				group dinner		TSRC bbq		
18:20						town talk	TSRC bbq		
19:00							TSRC bbq		

2.2 Thursday, July 19, 2018: Thermodynamics of computation

8:20 am – 9:00 am: Badge Pick-Up & Breakfast at TSRC

Check-In and breakfast at the Telluride Intermediate School

Session Chair: **KORANA BURKE**

9:00 am – 9:40 am: Opening talk

James P. Crutchfield
Korana Burke
Sebastian Deffner

9:40 am – 10:20 am: Mutually Incompatible Realities and the Thermodynamic Cost of Extracting Meaning From Complex Environments

James P. Crutchfield
University of California, Davis

Presumably, an intelligent agent survives in and adapts to a complex environment by employing an internal model that captures as well as possible regularities encountered in its interactions. This is captured by the thermodynamic Principle of Requisite Complexity. Better models increase survival. Curiously, for a single environment there can be a multiplicity of optimal models that competing agents (i) can use to maximum benefit but that (ii) do not agree on the environments structure. Analyzing the agents environment-interaction semantics one concludes that their world-views are mutually incompatible – the same environmental events mean different things to each. Moreover, incompatible realities have physical consequences. The Information Processing Second Law of Thermodynamics applied to agent-environment interactions determines the minimal, necessary costs (energy dissipation) an agent must invest to make sense of its environment. A corollary shows that the total semantic content that can be extracted (i) by a predictive agent is the environments statistical complexity C_μ and (ii) by a generative agent is the average memory C_g required to simulate the environment, where $C_g \leq C_\mu$. We draw out the thermodynamics of agents that operate under such semantically incompatible views of an environment. While optimality here assumes agents have correct environmental models, the semantic and thermodynamic analyses easily extend to agents employing approximate or out-right incorrect models. In this setting, both meaningful and meaningless interactions arise and their informational and thermodynamic costs can be quantified. A final result demonstrates that just as there are fluctuations in an agents thermodynamic functioning, there are fluctuations in meaning and so in an agents moment-by-moment reality. The result is a thermodynamics of how agents holding mutually incompatible realities can coexist in a single world.

10:20 am – 11:00 am: Coffee break

11:00 am – 11:40 am: Quantum fluctuation theorems go Quantum Computers

Sebastian Deffner
UMBC

Near term quantum hardware promises unprecedented computational advantage. Crucial in its development is the characterization and minimization of computational errors. We will review recent developments in informational quantum fluctuation theorems and propose the use of them to characterize the performance of quantum annealers. We will see that this versatile tool provides simple means to determine whether the quantum dynamics are unital, unitary, and adiabatic, or whether the system is prone to thermal noise. Our proposal was experimentally tested on two generations of the DWave machine, which illustrates the sensitivity of the fluctuation theorem to the smallest aberrations from ideal annealing [1].

[1] Gardas and Deffner, arXiv:1801.06925

11:40 am – 12:20 pm: Shortcuts to adiabaticity for single qubit control in quantum annealers

Mujibur Bhuniyan
UMBC

Our goal is to suppress computational errors in quantum annealers arising from parasitic excitations induced by finite-time driving. A rather recent tool-kit from quantum control provides a way to suppress such computational errors. Dubbed "shortcuts to adiabaticity" these methods provide means to implement fast processes with the same, error-free outcome that would result from infinitely slow driving.

The most prominent example of quantum annealers is the DWave machine. Its chip can be well-described as a quantum Ising model in the transverse field. Previous work has studied how to implement shortcuts to adiabaticity for global changes of the magnetic field. For realistic applications, however, such as in the DWave machine one is rather interested in only local changes of the field, i.e., in control of single qubits rather than flipping all qubits at the same time. Therefore, our work focuses on deriving shortcuts for such local perturbations. The quantum Ising model can be mapped onto "stacked" avoided crossing, which are commonly known as the Landau-Zener model. This model is the best studied example for the dynamics of qubits, and thus it provides a natural entry point into the analysis. Already our first results revealed interesting issues arising from local perturbation: for global changes the energy diagram is fully determined by avoided crossings; for local control, however, the energy diagram is comprised of avoided crossing and diabatic crossings of the energy levels. Using the Transitionless Quantum Driving shows that the selection rule prohibits some transitions and stops the counterdriving field from diverging at those crossings.

A better understanding of local control will lead to the development of a more efficient and easier way to achieve better "Shortcuts To Adiabaticity" that will be realistic and fast enough to be useful.

Joint work with Sebastian Deffner.

12:20 pm – 01:00 pm: Lunch

5:30 pm: Group Dinner

Location: Tent behind the Telluride Intermediate School

2.3 Friday, July 20, 2018: Thermodynamics of information I

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Intermediate School

Session Chair: **SEBASTIAN DEFFNER**

9:00 am – 9:40 am: Converting nearly all available information into work by a Brownian information engine

Hyuk Kyu Pak
Institute for Basic Science (IBS)

We report on a lossless information engine that converts nearly all available information from an error-free feedback protocol into mechanical work. Combining high-precision detection at resolution of 1nm with ultrafast feedback control, the engine is tuned to extract the maximum work from information on the position of a Brownian particle. We show that the work produced by the engine achieves a bound set by a generalized second law of thermodynamics, demonstrating for the first time the sharpness of this bound. We validate a generalized Jarzynski equality for error-free feedback-controlled information engines [1].

Joint work with Govind Paneru, Dong Yun Lee, and Tsvi Tlusty

[1] G. Paneru, D. Y. Lee, T. Tlusty, H. K. Pak, Phys. Rev. Lett. **120**, 020601 (2018)

9:40 am – 10:20 am: Large Deviations in Thermodynamic Computation

Cina Aghamohammadi
University of California, Davis

We propose a framework for the study of large deviations in thermodynamic computation with a long memory. The thermodynamic computation is done by a machine in contact with thermal reservoir known as information engine which manipulates information on the input tape to information on the output tape by some given stochastic law. Information on the input tape can be highly correlated with a really long memory and as a result, Non-Markovian which makes the problem non-trivial. Here we study large deviations of computation accuracy and also cost of computation.

10:20 am – 11:00 am: Coffee break

11:00 am – 10:40 am: Stochastic Thermodynamics of Learning

Sebastian Goldt
Université Paris-Saclay

Unraveling the physical limits of information processing is an important goal of non-equilibrium statistical physics. It is motivated by the search for fundamental limits of computation, such as Landauer's bound on the minimal work required to erase one bit of information. Further inspiration comes from biology, where we would like to understand what makes single cells or the human brain so (energy-)efficient at processing information.

In my seminar, we will analyse the thermodynamic efficiency of learning. After briefly reviewing the interplay of information processing and dissipation from the perspective of stochastic thermodynamics, we will show that the dissipation of any physical system, e.g. a neural network, bounds the information that it can infer from data or learn from a teacher. We discuss a number of examples along the way and outline directions for future research.

11:40 am – 12:20 pm: Local Causal States and Discrete Coherent Structures

Adam Rupe
University of California, Davis

Coherent structures form spontaneously in nonlinear spatiotemporal systems and are found at all spatial scales in natural phenomena from laboratory hydrodynamic flows and chemical reactions to ocean, atmosphere, and planetary climate dynamics. Phenomenologically, they appear as key components that organize the macroscopic behaviors in such systems. Despite a century of effort, they have eluded rigorous analysis and empirical prediction, with progress being made only recently. As a step in this, we present a formal theory of coherent structures in fully-discrete dynamical field theories. It builds on the notion of structure introduced by computational mechanics, generalizing it to a local spatiotemporal setting. The analysis main tool employs the local causal states, which are used to uncover a systems hidden spatiotemporal symmetries and which identify coherent structures as spatially-localized deviations from those symmetries. The approach is behavior-driven in the sense that it does not rely on directly analyzing spatiotemporal equations of motion, rather it considers only the spatiotemporal fields a system generates. As such, it offers an unsupervised approach to discover and describe coherent structures. We illustrate the approach by analyzing coherent structures generated by elementary cellular automata, comparing the results with an earlier, dynamic-invariant-set approach that decomposes fields into domains, particles, and particle interactions.

Joint work with James P. Crutchfield.

12:20 pm – 01:00 pm: Lunch

2.4 Saturday, July 21, 2018: Thermodynamics of information II

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Intermediate School

Session Chair: **JAMES P. CRUTCHFIELD**

9:00 am – 9:40 am: Shortcuts to Erasure: Fast, Efficient, and Accurate Thermodynamic Computing

Alec Boyd

Landauer's Principle states that thermodynamic information processing has a necessary energy cost which must exceed the product of the temperature and the change in Shannon entropy of the information bearing degrees of freedom. However, this lower bound is only achievable for quasistatic computations, which are controlled very slowly such that the system stays near equilibrium for the entire control protocol. If we wish to process information in finite time, and thus speed up a computational protocol that is designed to operate close to equilibrium, then the system is pushed out of equilibrium, leading to unreliable logical outcomes. Yet, in overdamped Langevin dynamics, recent results show how to add an additional term to the Hamiltonian, called the counterdiatabatic potential energy, which guides the system along the desired computational path. These counterdiabatic protocols provide shortcuts between equilibrium states, allowing us to precisely design finite time computations. Compensating for the practical advantage of operating in finite time, counterdiabatic shortcuts require excess work beyond Landauer's bound. We show that this excess work, which is irretrievably dissipated into the environment, is proportional to the speed of the computation as well as the square of the information storing system's length scale. We then find shortcuts to erase a bit in a metastable symmetric double-well, numerically calculating the associated counterdiabatic potential and the excess work. We see that the dissipated excess work increases with the fidelity of the erasure, but that it is possible do perfect erasure in finite time with finite work. We also see that the effectiveness of information storage in the metastable double-well affects the energetic cost of erasure. We show that the information lifetime of the bistable system is proportional to the excess work required, meaning that more robust information storage devices require more energy to manipulate. Thus, there is a richer set of tradeoffs, beyond Landauer's relationship between information and energy, in the more realistic case of finite time information processing. If designing a fast computational protocol, this work describes a more nuanced relationship between the work cost, the rate of computation, the size of the information bearing degrees of freedom, the fidelity of erasure, and robustness of information storage.

9:40 am – 10:20 am: Dissipation required to compute reliably with time-symmetric protocols

Paul Riechers

In the low-error limit of reliable digital computation, we find a fundamental reliability–energetic-efficiency tradeoff (or, equivalently, an error–dissipation tradeoff) if we restrict ourselves to using time-symmetric protocols for implementing computations. Specifically, if we insist on a low probability of error $\epsilon \ll 1$, then the expected dissipation is:

$$\left\langle W_{\text{diss}}^{(t\text{-sym})} | \gtrsim \right\rangle k_{\text{B}}T \left\langle \left[\mathcal{C}(\mathcal{C}(\mathcal{M}_0)) \neq \mathcal{M}_0 \right] \right\rangle_{\mathcal{M}_0} \ln(\epsilon^{-1}) \ ,$$

where $\mathcal{C}$ is the computation to be implemented, $k_{\text{B}}T$ is the thermal energy, $[\cdot]$ is the Iverson bracket, and $\mathcal{M}_0$ is the random variable for the memory input to the computation. That is: the scaling of this dissipation is $\sim \ln(1/\epsilon)$, with a coefficient that depends on the reciprocity of memory transitions in the deterministic computation to be implemented. For the typical Landauer erasure, this implies $\left\langle W_{\text{diss}}^{(t\text{-sym})} | \gtrsim \right\rangle \frac{k_{\text{B}}T}{2} \ln\left(\epsilon^{-1}\right)$. We also derive a similar relation for the universal NAND gate. The reciprocity coefficient implies that strictly-reciprocal logic gates, such as the identity and NOT gates, where $\mathcal{C}(\mathcal{C}(m))$ always returns m, are exempt from this dissipation, and can use time-symmetric protocols efficiently. For all other computations, time-asymmetric control must be used to avoid this dissipation. Finally, we show that our result applies not only to engineered computation, but also implies a generic error–dissipation tradeoff in steady-state transformation of genetic information as carried out by biological systems.

10:20 am – 11:00 am: Coffee break

11:00 am – 11:40 am: Fractional Fluctuation Theorems: Work Decomposition in Metastable Information Processing

Greg Wimsatt
University of California, Davis

Information processing is physical. It requires particular and precise control of the underlying thermodynamic system. While system parameters in a control protocol begin and end in the same configuration, their intermediate paths determine the evolution of the system's informational states. Since the equilibrium free energy does not change over a protocol, Jarzynski's integral fluctuation theorem determines that the ensemble-averaged exponential net work is unity for a system that begins in equilibrium. Moreover, if the protocol executes bit erasure, Landauer's bound stipulates that the average work must be greater than $k_B T \ln 2$.

That said, the full work distribution generated during thermodynamic computing is surprisingly complex. Even if simple, efficient, and accurate, the effective information processing may exhibit thermodynamically-distinct temporal substages. For example, the bit erasure protocol of Jun et. al. (2014 PRL 113.190601) consists of four substages, each linearly changing a single protocol parameter. Combining substage decomposition with partitioning the microscopic state-space into thermodynamically-metastable regions, a symbolic dynamics emerges that naturally decomposes the work distribution into canonical components, with each obeying its own fractional fluctuation theorem. Practically, through describing macroscopic observables, such as net work, these components can be used to diagnose the predominance of specific microscopic informational failure and success modes. In this way, the fractional fluctuation theorems can be used to guide optimal protocol design.

11:40 am – 12:20 pm: Fluctuation theorems for stochastic resetting systems

Saar Rahav
Technion

Resetting is an event in which an external agent returns a system to a pre-ordained state. The dynamics of systems with resetting has been extensively studied due to the usefulness of resetting in search problems. Our understanding of the thermodynamics of processes with resetting is less developed. Interestingly, inclusion of resetting means that the system?s dynamics is inherently out-of-equilibrium. The development of stochastic thermodynamics has considerably increased our knowledge regarding out-of-equilibrium systems and processes. In a recent paper Fuchs et. al. used stochastic thermodynamics to derive a version of the second law for dynamics with resetting [Europhys. Lett. 113, 60009 (2016)]. We examine the fluctuations of resetting systems. We identify two integral fluctuation theorems that are satisfied by stochastic resetting systems, and discuss their physical interpretation.

Joint work with Arnab Pal.

12:20 pm – 01:00 pm: Lunch

2.5 Sunday, July 22, 2018: Free day

No program, no breakfast or lunch.

2.6 Monday, July 23, 2018: Biophysics

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Intermediate School

Session Chair: **SEBASTIAN DEFFNER**

9:00 am – 9:40 am: Optimized bacteria are environmental prediction engines

Sarah Marzen
MIT

It's clear that humans are sophisticated information engines, with exquisitely low power consumption requirements. In this talk, I argue that optimized bacteria– much simpler organisms– are also environmental prediction engines, and that they can store relevant predictive information using epigenetic memory. However, optimized bacteria are not environmental prediction engines if there is enough noise in their sensors. We suggest new biological experiments to test whether or not evolved bacteria are, in fact, environmental prediction engines.

Joint work with James P. Crutchfield.

9:40 am – 10:20 am: Nurturing Nature for Nanotechnology

Michael Zwolak
NIST

It has long been a dream to design molecular devices and machines. We are not, though, very good at it, but Nature is. From the complex machinery of the ribosome to the integration of information, sensing, and actuation in cells, biological systems conduct the most exquisite nanofabrication and molecular operation that we know of. Our best methods so far for creating nanoscale objects mimic and exploit biological systems – top-down lithographic techniques notwithstanding. DNA nanotechnology, in particular, makes information – the sequence of bases – into structures by taking advantage of the specificity of Watson-Crick pairing. An appropriate chosen sequence of DNA, or sequences of many pieces of DNA, will self-assemble into different shapes and patterns, and can even generate structures that move and respond to different stimuli. This assembly process, though, is not fool proof; it does not always give us what we want. To do as biology does (whether chemical, e.g., ribosomal, or structural), we better develop the tools to measure, model, and understand biomolecular assembly. I will present theoretical principles of biomolecular nanostructure design, as well as experimental results to test these principles in the context of DNA origami. In other words, I will discuss how we can better nurture Nature to give us novel structures and devices, from sensors to machines to drug delivery systems.

10:20 am – 11:00 am: Coffee break

11:00 am – 11:40 am: Steering evolution: shortcuts to adiabaticity in population genetics

Michael Hinczewski
Case Western Reserve University

One of the great challenges in modern medicine is the rapid evolution of drug resistant genetic variants, whether in the case of bacterial infections and antibiotics, or metastatic cancer and chemotherapy. There is growing interest in therapeutic strategies that bias the evolutionary trajectories of cellular populations through rationally designed control protocols: for example varying drug dosage levels, drug types, and/or order of application. If chosen correctly, such protocols can guide the population into genetic states that are known to be maximally susceptible to a particular final treatment. Often such strategies assume enough time passes for relaxation to evolutionary equilibrium (for example after each switch of drug type in a sequential treatment), limiting their practicality. Recently developed methods that ensure the system evolves through a chosen sequence of equilibrium distributions, so-called shortcuts to adiabaticity, are thus potentially useful in this context. My talk explores how such shortcuts can be formulated for two classic models of population genetics: a discrete Markovian description that is valid under certain simplifying assumptions, and a more realistic continuum theory that takes the form of a Fokker-Planck equation with coordinate-dependent diffusivity.

11:40 am – 12:20 pm: Topological Connectivity and Energy Transport in Biomolecules

Justin Elenewski
NIST

Biomolecular devices harness the structural diversity of living systems to deliver functionalities that are often inaccessible in conventional nanomachines. The theoretical description of these devices becomes highly nuanced at the single–molecule level, where granular characteristics, high–dimensional energy landscapes, and a lack of symmetries collude to make atomistic simulations imperative. While generally successful, this approach is insufficient in a strongly nonequilibrium regime — particularly for heat transport — where conventional sampling and dimensional reduction techniques fail to capture essential aspects of energy landscape architecture. In this talk, we introduce a well–controlled approach to simplify these landscapes, circumventing the aforementioned difficulties while faithfully reflecting the dynamics of energy propagation. Furthermore, we use a model protein to demonstrate that heat transport in biomolecules is highly sensitive to topological characteristics of the conformational ensemble. These properties define a crossover between energy localization and free transport, suggesting general design principles for biomimetic and soft–matter based nanosystems.

Joint work with Kirill Velizhanin and Michael Zwolak.

12:20 pm – 01:00 pm: Lunch

5:30 pm: Group Dinner

Location: Tent behind the Telluride Intermediate School

2.7 Tuesday, July 24, 2018: Foundations of thermodynamics I

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Intermediate School

Session Chair: **KORANA BURKE**

9:00 am – 9:40 am: Tightest universal bound on second law violations

Christopher Jarzynski
University of Maryland, College Park

So-called “violations” of the second law are a fascinating feature of the thermodynamics of nanoscale systems. When a macroscopic system undergoes an isothermal process, the second law of thermodynamics is given by the inequality $W \geq \Delta F$, which states that the work performed on the system must be no less than the free energy difference between initial and final states. For nanoscale systems, one can observe occasional violations of this inequality. A natural measure of the magnitude of the violation is given by the dimensionless quantity $x = (\Delta F - W)/kT$. I will derive a simple expression that provides a bound on the probability of observing such violations, as a function of x, and I will argue that this expression provides the tightest possible universal bound. I will also discuss a simple model system for which this bound can be saturated, and will argue that this model is experimentally realizable using quantum dots.

Along the way, I will describe a model process for which nearly every realization results in a “violation” of the second law, i.e. $W < \Delta F$ almost always, but on average the second law remains valid: $\langle W \rangle > \Delta F$, where the angular brackets denote an average over infinitely many realizations.

9:40 am – 10:20 am: Dynamic and thermodynamic representations of nanoscale systems in the strong coupling regime

Maicol A. Ochoa
NIST

Energy conversion in nanoscale devices has motivated the search for new thermodynamic principles and concepts that hold valid far from the thermodynamic limit. While significant progress has been made in the field, the identification of consistent thermodynamic and dynamic descriptions in the strong coupling regime has been challenging. This challenge takes a particular form when quantum fluctuations and other quantum properties of the nanoscale system are considered. In this talk, I will describe several strategies that we have developed to study model systems in this regime. In the first part, I will derive sound definitions of nonequilibrium heat and work rates starting from exact dynamical descriptions of model systems. This strategy has some limitations that I will discuss. Consequently, in the second part, I will take a different approach by formulating exact equilibrium thermodynamic representations of model systems to include in a later step finite-time dynamics and nonequilibrium rates. The results of these investigations provide a systematic and consistent approach to the dynamics and thermodynamics of slowly modulated nanoscale systems.

[1] Phys. Rev. B **97**, 085434 (2018)

[2] Phys. Rev. B **94**, 035420 (2016)

[3] Phys. Rev. B **92**, 235440 (2015)

[4] Phys. Rev. B **91**, 115417 (2015)

[5] Phys. Rev. Lett. **114**, 080602 (2015)

10:20 am – 11:00 am: Coffee break

11:00 am – 11:40 am: Optimization of a quantum heat engine

Gregory Huxtable
UMBC

We determined the theoretical efficiency of a nano heat engine (ion contained in a linear Paul trap) following a quantum Otto cycle and operating at maximum power output. To find the maximum-power efficiency of the single-ion heat engine, we employed endoreversible thermodynamics, which has the advantage that all quantum effects are fully encoded in the equation of state for the single ion. A nano heat engine with a single ion as its working medium was first created in 2016. This proof-of-principles experiment opened the door to realistic investigations of small thermodynamic devices, which generically operate far from thermal equilibrium. Similar to how the classical heat engine has been central to the development of classical thermodynamics, the quantum heat engine will be a key experimental tool to quantum thermodynamics. We are generally interested in the efficiency of engines when operating at maximum power output (non-equilibrium), as opposed to when they remain in equilibrium, since we cannot operate engines infinitely slow. It was also found that a classical Otto cycle operating at maximum power output with an ideal gas as its working medium, has an efficiency of $1 - \sqrt{T_C/T_H}$, which is the same as the Carnot cycle operating at maximum power output (Curzon and Ahlborn, 1974. AJP). Thus, the efficiency discovered by Curzon and Ahlborn may be more general than previously thought.

Joint work with Sebastian Deffner.

11:40 am – 12:20 pm: Observable's Statistical Mechanics

Fabio Anzà
University of Oxford

A crucial point in statistical mechanics is the definition of thermal equilibrium, which is given as the state that maximises the von Neumann entropy, under the validity of some constraints. Arguing that such definition can never be experimentally probed, we propose a new notion of thermal equilibrium, focused on observables rather than on the full state of the system. The thermal properties that such principle heralds are investigated. In particular:

(1) Its relation with ordinary statistical mechanics is studied and understood

(2) An intimate connection with the Eigenstate Thermalisation Hypothesis is brought to light

(3) Consequences for unravelling the dynamical properties of a Many-Body Localised system are presented.

12:20 pm – 01:00 pm: Lunch

06:30 pm – 07:15 pm: TSRC town talk – Geo-Engineering a Climate Change Solution

Telluride Conference Center in Mountain Village

Frank N Keutsch, PhD
Professor of Chemistry and Chemical Biology, Harvard University

Cash Bar starts at 6:00pm

2.8 Wednesday, July 25, 2018: Quantum thermodynamics

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Intermediate School

Session Chair: **KORANA BURKE**

9:00 am – 9:40 am: Quantum and classical time crystals in spin chains

Wade Hodson
University of Maryland, College Park

Discrete time crystals are a recently discovered nonequilibrium phase of matter, characterized by a robust subharmonic response in a periodically driven quantum system. In previous theoretical and computational analyses, the emergence of this phase has been linked to properties including many-body localization, the presence of disorder, and the relaxation phenomenon known as prethermalization. In this talk, I will present an overview of the theory behind time crystals, discuss a spin chain model where nearest-neighbor interactions and disorder have been shown to stabilize the time crystal phase, and share some simulation results which point to the existence of time crystal-like dynamics in driven classical systems.

9:40 am – 10:20 am: Towards bolometric measurement of the heat of erasure in a quantum bit

Olli-Pentti Saira
Caltech

The concept of the heat of erasure elegantly captures the equivalence of informational and thermodynamic entropy that governs all physical computing devices. After decades of study, it remains relevant due to its wide range of applicability, and profound technological implications for the minimum energy consumption of processors. In my talk, I will describe in detail a new experimental approach for measuring the heat of erasure utilizing superconducting flux qubits and ultrasensitive bolometers.

In our experiment, all damping that enables the execution of irreversible logical operations is localized at a resistor residing on a bolometer platform. This allows us to explore a new regime where the repeated execution of a logical cycle has a weak yet accurately measurable effect on the environment of the bit. Previous works have dealt with environments that are either massive – and hence unaffected by entropy transfer at the scale of individual bits – or deeply quantum and host at most a few quantized excitations at any given time.

The main benefit of the bolometer approach is that it is impervious to the operation of the logical cell. In practice, this means that there are no additional constraints on the magnitude or rate of change of the external controls that steer the computation. This enables fast logical cycles, and promises compatibility with more complex multi-bit logical operations in the future.

I will show detailed simulations and preliminary experimental data.

10:20 am – 11:00 am: Coffee break

11:00 am – 11:40 am: Work on a quantum dipole by a single-photon pulse

Frederico Brito
University of São Paulo, São Carlos

The work performed by a classical electromagnetic field on a quantum dipole is well known in quantum optics, where the absorbed power linearly depends on the time derivative of the average dipole moment. However, the problem concerning the work performed by a single-photon state on a quantum dipole still lacks an answer. As a matter of fact, the average quantum dipole moment exactly vanishes in such a scenario. In this talk, we address this problem. For that, quantum work is defined as the unitary contribution to the energy variation of the quantum dipole. It is shown that this definition furnishes a correspondence with the energy spent by the photon pulse to dynamically Stark shift the dipole. On the other hand, the non-unitary contribution to the dipole energy is defined here as a generalized quantum heat. It is shown that this generalized quantum heat is the energy corresponding to out-of-equilibrium photon absorption and emission. By providing physical means for being accessed, such connections for quantum work and generalized heat represent a step forward for such definitions.

11:40 am – 12:20 pm: QFlow lite: Applying Machine Learning to Quantum-Dot Experiments

Justyna Zwolak
Joint Center for Quantum Information and Computer

There are a myriad of quantum computing approaches, each having its own set of challenges to understand and effectively control their operation. For semiconductor-based methods (e.g., coupled quantum dots), control is provided by electrostatic confinement, band-gap engineering, and input voltages on nearby electrical gates. Currently, heuristics are used to set the input voltages in order to reach a stable few electron configuration. It is desirable, however, to have an automated protocol to achieve a target electronic state, especially as the size of the system is scaled up.

In recent years, machine learning has emerged as a "go to" technique for image recognition and other tasks. It can give reliable results when trained on robust and comprehensive data. We show how convolutional neural networks (CNNs) can be trained to recognize the electronic state within quantum dot arrays. We find $\sim 95\%$ agreement between the CNN characterization and the Thomas-Fermi model predictions for nanowires. Using optimization techniques, such trained networks can be then implemented to automatically tune the device to desired dot configuration without the human intervention. I will discuss how different data (i.e., current through the quantum dots versus charge sensor readout) affects the performance of the CNN, as well as our recent findings for tuning the quantum dot device to a specific charge configuration. This machine learning approach gives opportunities for the control of quantum dot devices - both in- and out-of-equilibrium - as they scaled to larger and larger arrays necessary for computing and fundamental applications.

12:20 pm – 01:00 pm: Lunch

06:00 pm – 09:00 pm: TSRC barbecue

Location: Tent behind Telluride Intermediate School

2.9 Thursday, July 26, 2018: Foundations of thermodynamics II

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Intermediate School

Session Chair: **JAMES P. CRUTHFIELD**

9:00 am – 9:40 am: Classical Observational entropy

Dominik Šafránek
University of California, Santa Cruz

Observational entropy is a type of coarse-grained entropy that generalizes the ideas of Boltzmann entropy to quantum systems, and applies to any density matrix. This entropy rises in a closed quantum system, to the correct thermodynamic value, and it effectively describes process of regions becoming equilibrated with each other (arXiv:1803.00665 [quant-ph]). In this talk we will take a step back to classical physics, and show how the classical version of this entropy generalizes Boltzmann entropy so it can be used to describe dynamics of classical systems with non-deterministic initial conditions, which is where the standard definition of Boltzmann entropy fails.

9:40 am – 10:20 am: How difficult is it to prepare a quantum state?

Davide Girolami
LANL

I propose an information-theoretic framework to quantify genuine multipartite quantum coherences and correlations, answering questions such as: what is the amount of seven-partite correlations in a given state of ten particles? Axiomatically, the measures are good descriptors of the complexity of correlation structures in multipartite systems, satisfying a set of desirable properties. Operationally, they quantify how difficult it is to prepare a quantum state from incoherent and uncorrelated inputs.

10:20 am – 11:00 am: Coffee break

11:00 am – 11:40 am: Information Measures in a Ring of Synchronized Oscillators

Matt Matheny
Caltech

Synchronization, the mutual locking of weakly coupled oscillators, is ubiquitous in the natural world. Here I describe an experiment with 8 coupled magnitude-phase oscillators in a ring network. Here we find that spatiotemporal symmetries are strongly broken, with transitions between states that are highly dissipative. The behavior of these exotic dynamical states is not known to be described by a single order parameter. However, since we are able to measure every oscillator in real time, we calculate several proposed information-theoretic measures in this noisy, multistable, 16-dimensional system. We discuss the utility of such measures to understand dynamics within our system.

11:40 am – 12:20 pm: Information Engines in Review

Korana Burke
UC Davis

This is a third installation of the Information Engines workshop and the second year of Information Scholars. We will first start by announcing the 2018 Information Scholars. Following the ceremony, I will offer a brief review of the results and conversations presented at the workshop over the past three years. The hope is to turn this talk into a conversation about where we see our field going in the next three years.

12:20 pm – 01:00 pm: Lunch

2.10 Friday, July 27, 2018: Thermodynamic control

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Intermediate School

Session Chair: **SEBASTIAN DEFFNER**

9:00 am – 9:40 am: Games, Controllability, and Geometry

P. S. Krishnaprasad
University of Maryland, College Park

Certain differential equation models with roots in population biology, mathematical genetics, and game theory can be studied from the perspective of manipulating the time course of phenomena. Thus, control problems on the probability simplex are of interest. In this context we show that there exists interesting algebraic and geometric structure on the probability simplex. This is useful in tackling a variety of questions of control-theoretic relevance, including accessibility, variational principles, and optimal paths. We illustrate some of these ideas in low-dimensional games.

Joint work with Vidya Raju.

9:40 am – 10:20 am: Optimal Control of KPZ Equation Using Deep Reinforcement Learning

Yunlong Huang
University of Maryland, College Park

The Kardar-Parisi-Zhang (KPZ) equation is a nonlinear stochastic partial differential equation which describes the temporal change of the height $h(x,t)$ of an interface at location x and time t. In this talk, we discuss the control of KPZ equation in one spatial dimension. One key problem of KPZ equation is to investigate the roughness of the interface. In a finite time duration, we would like to control the roughness by varying temperatures at different places. We first investigate the reachability of the control system to show that varying the temperatures at different locations will have effect on the variation of the height of the interface. We then formulate the roughness minimization problem to be a high-dimensional stochastic optimal control problem. In order to cope with the well-known "curse of dimensionality" arising in the Hamilton-Jacobi-Bellman equation associated to an optimal control problem, we pursue an approach based on deep reinforcement learning. The application of this approach to KPZ equation demonstrates promising numerical efficacy.

Joint work with P. S. Krishnaprasad.

10:20 am – 11:00 am: Coffee break

11:00 am – 11:40 am: Phase transition in protocols minimizing work fluctuations

Jordan M. Horowitz
MIT

Essential to any well-functioning thermodynamic engine is the rapid and reliable extraction of work at high thermodynamic efficiency. Accomplishing this goal requires not only quantifying the trade-offs between power and efficiency, but also doing so while constraining power fluctuations. Whereas the thermodynamic uncertainty relation offers universal constrains on power fluctuations for autonomous steady state heat engines, no such statement can be made about cyclically-operating nonautonomous engines. As a first step in this direction, I will characterize in this talk those optimal finite-time thermodynamic protocols that optimize the compromise between work and work fluctuations for two canonical models of driven mesoscopic systems a harmonically-trapped Brownian particle and a quantum dot. Remarkably, we find that as we shift the weight of our optimization objective from average work to work standard deviation, there is an analog of a first-order phase transition in protocol space: two distinct protocols exchange global optimality with mixed protocols akin to phase coexistence.

11:40 am – 12:20 pm: Informed Exergy Pathways

Peter Salamon
San Diego State University

I advance the thesis that biological processes are not driven by entropy production but, rather, by informed exergy flow, i.e. exergy flow through pathways that have been constrained by the passage of information from a previous time. Living systems direct flows of exergy from sources, such as the sun or chemical bonds, through informed pathways to achieve homeostatic and environmental control, and ultimately to reproduce. Living systems can extract work from an exergy source only if the exergy flows through specific pathways which are informed by the passage of information, for example, the information stored in the DNA molecules that are passed from parents to progeny. The ability of biological systems to compete for exergy flows and efficiently direct such flows through informed pathways to extract work is the basis for what defines how well a living entity will survive and reproduce. This differential ability to direct flows of exergy through informed pathways is ultimately what determines fitness and long-term evolutionary trajectories.

Consider the expression for the entropy production associated with a process given its probability of proceeding forwards, P_f, and backwards, P_r, as

$$k_B \ln(P_f/P_b),$$

where k_B is Boltzmanns constant. Much of this entropy production can be eliminated by informing the process, typically by changing the odds ratio above. The talk will explore the many mechanisms for changing this ratio.

Joint work with Ty Roach and Forest Rohwer.

12:20 pm – 1:00 pm: Closing Remarks

James P. Crutchfield
Korana Burke
Sebastian Deffner

3 Conference Venue and Maps

Conference will be held at:
Telluride Intermediate School, 725 W Colorado Ave Telluride, CO 81435

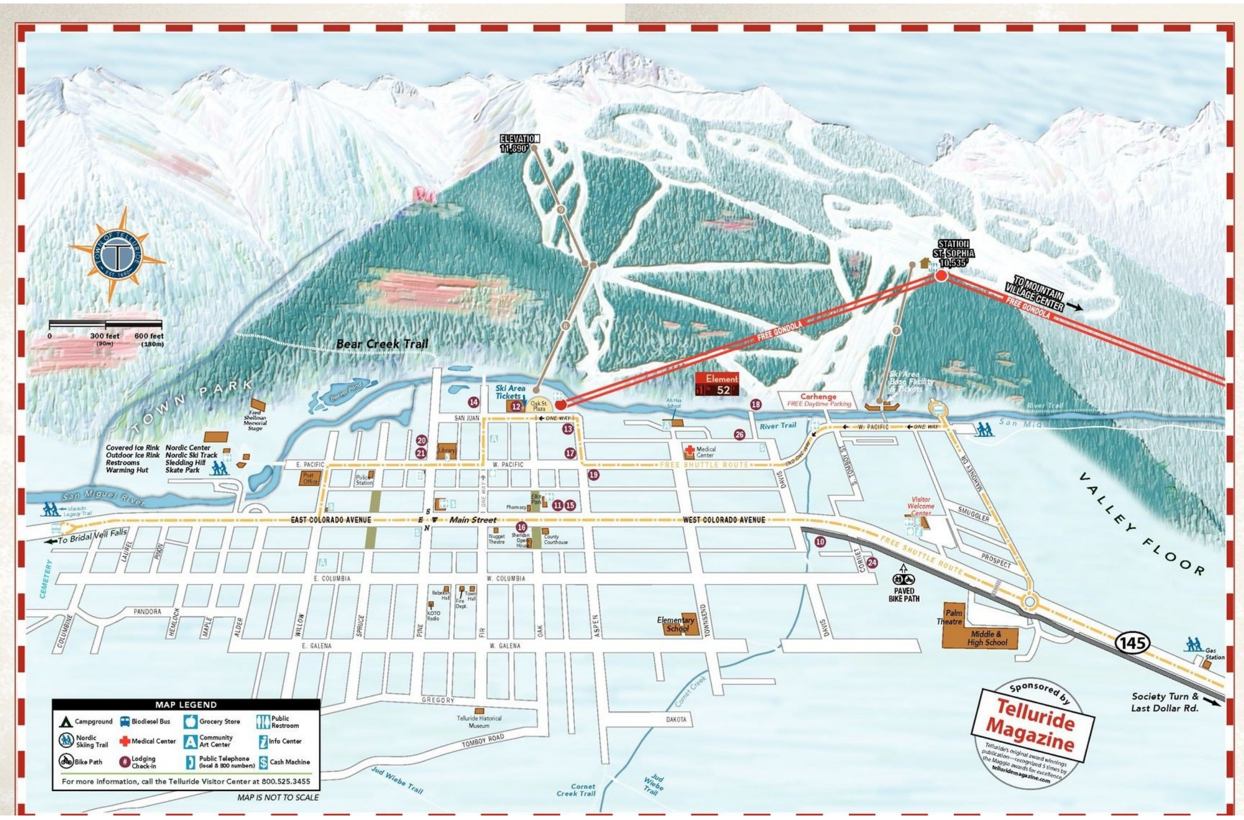

Figure 3.1: Map of the Town of Telluride

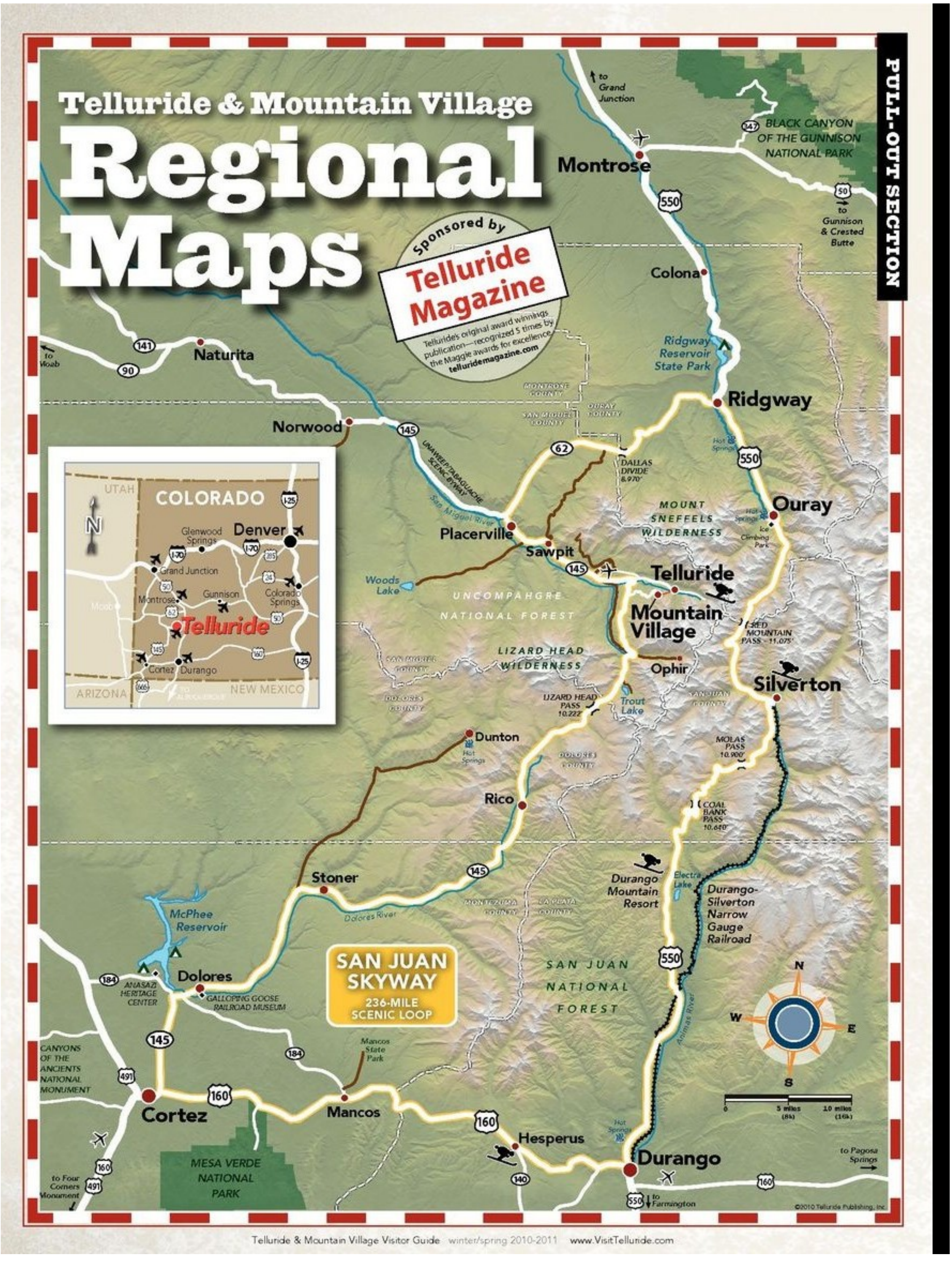

Figure 3.2: Regional Map

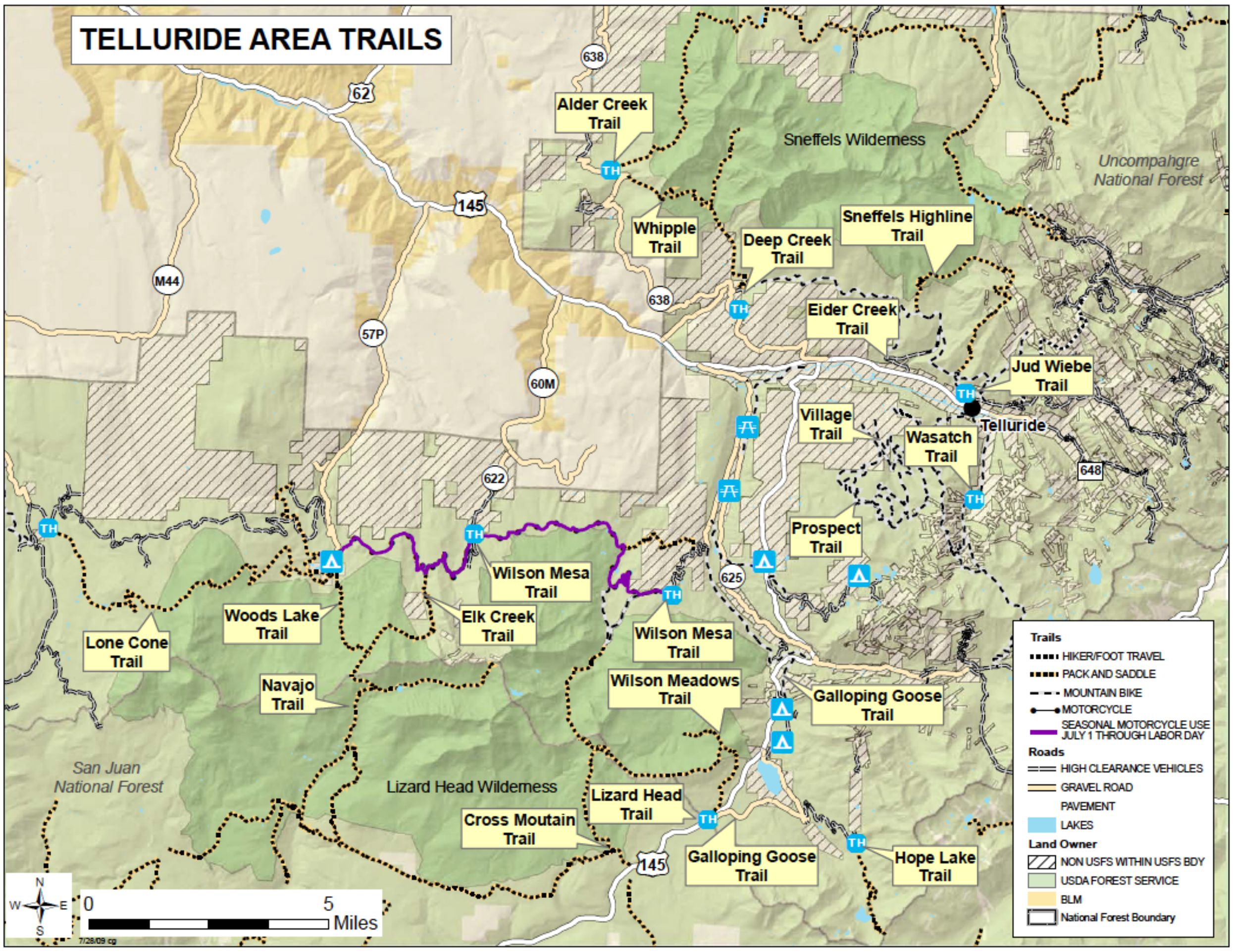

Figure 3.3: Telluride Area Trail Map