# Information Engines at the Frontiers of Nanoscale Thermodynamics

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August 03 – August 11, 2017

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.
- 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 08/03 | Friday 08/04 | Saturday 08/05 | Sunday 08/06 | Monday 08/07 | Tuesday 08/08 | Wednesday 08/09 | Thursday 08/10 | Friday 08/11 |
|---|---|---|---|---|---|---|---|---|---|
| 8:20 | breakfast | breakfast | breakfast | | breakfast | breakfast | breakfast | breakfast | breakfast |
| 9:00 | opening | **Franson** | **Salamon** | | **DeWeese** | **Zwolak** | **Ueda** | **Boyd** | **van den Broeck** |
| 9:40 | **Crutchfield** | **Sagawa** | **Aghamohammadi** | | **Krishnaprasad** | **Ares** | **Safranek** | **Briggs** | **Mandal** |
| 10:20 | coffee | coffee | coffee | | coffee and picture | coffee | coffee | coffee | coffee |
| 11:00 | **Kolchinsky** | **Rahav** | **Hinczewski** | | **Patra** | **Matheny** | **Bartolotta** | **Wolpert** | **Jarzynski** |
| 11:40 | **Wimsatt** | **Katti** | **Demers** | | **Burke** | **Saira** | **Deffner** | **Byrd** | **Mahoney** |
| 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 | town talk | TSRC bbq | group | |
| 18:20 | | Rustico | | | pizza | | TSRC bbq | dinner | |
| 19:00 | | Ristorante | | | | | TSRC bbq | TBA | |

## 2.2 Thursday, August 03, 2017: Thermodynamics of information I

### 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
Tommy A. Byrd
Sebastian Deffner

### 9:40 am – 10:20 am: Hierarchical Thermodynamical Systems

**James P. Crutchfield**
University of California, Davis

Maintained by environmental fluxes, biological systems are thermodynamic processes that operate far from equilibrium without detailed-balanced dynamics. Yet, they often exhibit well defined nonequilibrium steady states (NESSs). More importantly, critical thermodynamic functionality arises directly from transitions among their NESSs, driven by environmental switching. Here, we identify the constraints on excess heat and dissipated work necessary to control a system that is kept far from equilibrium by background, uncontrolled "housekeeping" forces. We determine how much work must be expended when controlling systems maintained far from equilibrium, show that Maxwellian Demons can leverage mesoscopic-state information to take advantage of the excess energetics in NESS transitions, and determine the work dissipated when driving between functionally relevant configurations of active energy-consuming complex systems. These highlight universal thermodynamic laws that apply to the accessible degrees of freedom within the effective dynamic at any emergent level of hierarchical organization. By way of illustration, we analyze a voltage-gated sodium ion channel whose molecular conformational dynamics play a critical functional role in propagating action potentials in mammalian neuronal membranes.

(1) P. M. Riechers and J. P. Crutchfield, J. Stat. Phys. (2017) doi:10.1007/s10955-017-1822-y.

(2) A. B. Boyd, D. Mandal, P. M. Riechers, and J. P. Crutchfield, Phys. Rev. Lett. 118 (2017) 220602.

(3) A. B. Boyd, D. Mandal, and J. P. Crutchfield, New J. Phys. 18 (2016) 023149.

(4) A. B. Boyd and J. P. Crutchfield, Phys. Rev. Lett. 116 (2016) 190601.

*Joint work with Paul Riechers, Alec Boyd, Dibyendu Mandal, and Sarah Marzen*

### 10:20 am – 11:00 am: Coffee break

### 11:00 am – 11:40 am: Semantic information, observation and self-maintaining non-equilibrium systems

**Artemy Kolchinsky**
Santa Fe Institute

Recent research on the physics of Maxwellian demons, measurement, and feedback control has established fundamental bounds relating extractable free energy and correlations between subsystems. Here, correlations between subsystems are quantified in terms of the syntactic measures of information given by Shannon's information theory. However as Shannon himself famously emphasized, such measures of syntactic information do not reflect how much information is "relevant" for a given system - it does not tell us how much 'semantic' information one stochastic subsystem has for another.

We argue that some of the same tools of nonequilibrium statistical physics used to analyze systems in terms of syntactic information provide a definition of semantic information. To begin, we note that complex real-world systems – e.g., biological organisms, man-made machines, weather patterns, etc. – are nonequilibrium systems. For such systems to persist into the future they must remain out of thermodynamic equilibrium, which may require them to exploit information in their environment. We therefore define the semantic information that a given system has about its environment as that part of the syntactic information it has about its environment which is causally necessary to maintain itself in a nonequilibrium state.

We formalize and analyze two versions of this definition of semantic information. The first kind is semantic information which is encoded in an initial distribution. The second kind, which we call 'observation', is semantic information which is dynamically acquired by a system by actively performing measurements.

### 11:40 am – 12:20 pm: Thermodynamics of Elementary Information Processing

**Gregory Wimsatt**
University of California, Davis

We simulate single-bit information processing tasks with a controllable double-well system via Langevin dynamics in both the overdamped and underdamped limits. We demonstrate that appropriate control protocols lead to faithful and efficient bit erasure, achieving Landauer?s bound on dissipated heat. We also describe efficient randomness generation (bit-creation), which is the reverse of erasure. We then demonstrate trade-offs between measures of effectiveness of the informational processing: average energy costs, fidelity, thermodynamic efficiency, stability, and total protocol time. The notion of metastable distributions and their manipulations clarify the results and motivate future directions.

### 12:20 pm – 01:00 pm: Lunch

## 2.3 Friday, August 04, 2017: Information engines and Maxwell demons

### 8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Intermediate School

Session Chair: **TOMMY BYRD**

### 9:00 am – 9:40 am: Velocity-dependent forces and Maxwell's demon

**James D. Franson**
University of Maryland Baltimore County

The dipole force on an atom moving in a focused laser beam is velocity-dependent due to the Doppler shift. This can be used to implement a Maxwell's demon. What is interesting about this example is the fact that photon scattering and other forms of dissipation can be negligibly small, while quantum information theory and the second law of thermodynamics require that there be a minimum energy cost associated with the implementation of a Maxwell's demon. This "paradox" will be resolved by showing that Schrödinger's equation does not predict an effect of this kind as one might expect. On the other hand, velocity-dependent dipole forces have been observed in several experiments. The implications of this situation will be discussed.

### 9:40 am – 10:20 am: Thermodynamics of autonomous measurement and feedback

**Takahiro Sagawa**
University of Tokyo

In this decade, thermodynamics of information has attracted much attention both theoretically and experimentally (1). In this talk, I will discuss a general theory of Maxwell?s demons with autonomous measurement and feedback. Especially, I will focus on a generalized fluctuation theorem (2) and the Onsager reciprocity (3) with continuous information flow (or the learning rate). I will also discuss the role of transfer entropy in thermodynamics (4) and our recent result on thermodynamics of sufficient statistics (5).

(1) J. M. R. Parrondo, J. M. Horowitz, T. Sagawa, Nature Physics 11, 131-139 (2015).

(2) N. Shiraishi, T. Sagawa, Phys. Rev. E E 91, 012130 (2015).

(3) S. Yamamoto, S. Ito, N. Shiraishi, T. Sagawa, Phys. Rev. E 94, 052121 (2016).

(4) S. Ito, T. Sagawa, Phys. Rev. Lett. 111, 180603 (2013).

(5) T. Matsumoto, T. Sagawa, in preparation.

### 10:20 am – 11:00 am: Coffee break

### 11:00 am – 10:40 am: Against the flow: a colloidal Maxwell demon

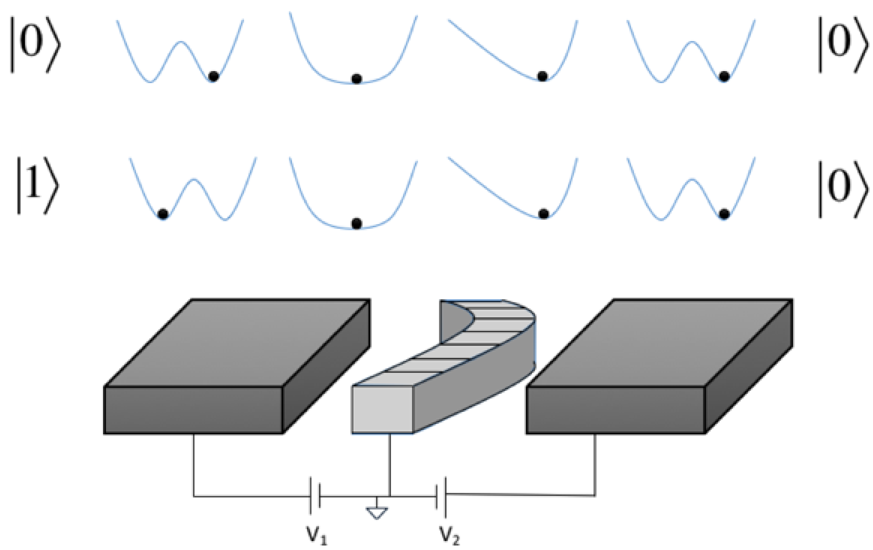
**Saar Rahav**
Technion, Israel

The connection between information and thermodynamics have been fascinating scientists ever since Maxwell envisioned his celebrated demon. Technological progress now allows to realize what was conceived as a thought experiment. Indeed, recent years have seen several experimental realizations of information engines.

In this talk, I will describe a realization of Maxwell?s demon in which a colloidal particle is ?pushed? against a fluid flow. Beyond its appealing simplicity, our experimental setup also exhibits an almost full conversion of information to useful work. Very little work is applied directly on the particle. In addition, the setup allows to measure the particle?s position frequently, leading to nontrivial correlations between the outcomes of consecutive measurements. The effect of these correlations on the useful information acquired is investigated with the help of computer simulations.

### 11:40 am – 12:20 pm: A Buckled Nanoelectromechanical System Near the Thermodynamic Limit

**Raj Katti**
California Institute of Technology




In 1961, Landauer suggested that the heat dissipation accompanying the erasure of $N$ bits averages to $\Delta Q = k_B T \ln(2)$ per bit. A scalable solid-state system has not been developed which is able to operate at such low dissipation. Such a system could open the doors for studying the ultimate limits of loss in sensing and computation. We present the design for and initial characterization of a nanoelectromechanical system capable of realizing a tunable bistable potential well. Calculations demonstrate that device dimensions and control parameters fall within a target range realizable by standard nanofabrication processes.

*Joint work with Matthew Matheny, Jarvis Li, Azadeh Ansari, and Michael Roukes*

**12:20 pm – 01:00 pm: Lunch**

**5:45 pm: Group Dinner at Rustico Ristorante**

Address : 114 E Colorado Ave

## 2.4 Saturday, August 05, 2017: Entropy production and thermodynamic costs

### 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: Dissipation in a sequence of relaxations: the Ladder Theorem

**Peter Salamon**
San Diego State University, San Diego

The talk will begin with a review of finite-time thermodynamic results related to control for minimum entropy production. We then consider one relaxation: the complete equilibration of a system to a bath. We show that replacing one relaxation with two relaxations starting and ending at the same states but reaching an intermediate equilibrium along the way always produces less entropy than the single relaxation. We present a proof of this Ladder Theorem, which asserts that the entropy production in a relaxation process is decreased when the relaxation proceeds via intermediate steps. We illustrate the theorem with the familiar example of a piston lifting a pile of sand. We close by exploring some applications to physical and biological processes

*Joint work with Ty Roach and Forest Rohwer*

### 9:40 am – 10:20 am: Thermodynamics of Random Number Generation

**Cina Aghamohammadi**
University of California, Davis

I am going to talk about the thermodynamic costs of the three main approaches to generating random numbers via the recently introduced Information Processing Second Law. Given access to a specified source of randomness, a random number generator (RNG) produces samples from a desired target probability distribution. This differs from pseudorandom number generators (PRNGs) that use wholly deterministic algorithms and from true random number generators (TRNGs) in which the randomness source is a physical system. For each class, we analyze the thermodynamics of generators based on algorithms implemented as finite-state machines, as these allow for direct bounds on the required physical resources. This establishes bounds on heat dissipation and work consumption during the operation of three main classes of RNG algorithms?including those of von Neumann, Knuth, and Yao and Roche and Hoshi?and for PRNG methods. We introduce a general TRNG and determine its thermodynamic costs exactly for arbitrary target distributions. The results highlight the significant differences between the three main approaches to random number generation: One is work producing, one is work consuming, and the other is potentially dissipation neutral. Notably, TRNGs can both generate random numbers and convert thermal energy to stored work. These thermodynamic costs on information creation complement Landauer's limit on the irreducible costs of information destruction.

### 10:20 am – 11:00 am: Coffee break

### 11:00 am – 11:40 am: Thermodynamic costs and the evolution of noise regulation by microRNAs

**Michael Hinczewski**
Case Western Reserve University

Nonequilibrium processes within living systems exact a high price: the constant maintenance of fuel molecules and raw materials at sufficient concentrations to provide thermodynamic driving potentials for biological function. Optimizing that function with respect to thermodynamic costs is a factor constraining evolution, particularly at the very earliest stages of life where the metabolic chemistry responsible for maintaining those potentials was necessarily primitive and relatively inefficient. Yet thermodynamic costs are not the only factor that matters, and biology is strewn with counter-intuitively complex chemical mechanisms whose evolutionary predecessors must have consumed significant energy resources without any clear fitness benefit. So how do such mechanisms evolve in the first place, and how strong is the guiding hand of thermodynamic optimization? My talk explores these issues through one specific example: gene regulation in higher organisms (i.e. humans and other eukaryotes) by microRNAs. These small RNA molecules (only 22 nucleotides long) are versatile tools for controlling the expression of genes into proteins, interfering with the messenger RNAs that are an intermediate step in the expression process. They provide a way of fine-tuning noise in protein population levels, because a microRNA-targeted gene that compensates for the interference by transcribing more messenger RNAs can keep the average number of proteins produced the same, while reducing the variance. Such noise control, together with other regulatory functions facilitated by microRNAs, is believed to have played important roles in the evolution of complex multi-cellular life. Yet it is a considerable expenditure of resources, similar to setting up a factory production line for a valuable good, funding gangs of thieves to constantly raid the factory, and compensating for losses by increasing the production rate. Moreover it is nontrivial to get the purported benefit of this scheme: we show that optimal noise control requires a certain range of biochemical parameters, and outside that range you expend even more resources to gain the same degree of noise reduction, or in some cases actually increase noise levels in the system. So how would such a regulation scheme arise, and has evolution actually optimized it? Using a combination of statistical physics, information theory, and population genetics, we arrive at some tentative answers to these questions. Our results give insights into one peculiar feature of this system: why the job requires such short RNA molecules (the significance of the "micro" in microRNA).

### 11:40 am – 12:20 pm: A second law-like inequality for general feedback control systems

**Jeff Demers**
Smithsonian Conservation Biology Institute

Feedback control (as opposed to non-feedback or "open loop" control) allows one to enact apparent violations of the second law of thermodynamics when manipulating physical systems. The benefits of these apparent violations are quantified by information theoretic modifications to the minimal cost of control implied by the second law, where the cost of control is typically defined as work done or entropy produced. In this talk, I'll show that for any general cost of control, the benefits of employing feedback control to manipulate general dynamical systems are also quantified by a second law-like inequality with an information theoretic term. This inequality allows one to view problems in control theory, where an agent is typically interested minimizing costs such as fuel consumption or the time to intercept a target, under the lens of thermodynamics. Our results point to possible deeper connections between cost functionals, information transfer, and a generalized notion of free energy.

**12:20 pm – 01:00 pm: Lunch**

## 2.5 Sunday, August 06, 2017: Free day

No program, no breakfast or lunch.

## 2.6 Monday, August 07, 2017: Stochastic thermodynamics

### 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: Optimal Protocols for Erasure in a Classical Nanomagnetic Spin System

**Mike DeWeese**
University of Californina, Berkeley

The fluctuating environment experienced by mesoscale and nanoscale particles poses a challenge to future computational technology design. In particular, the issue of bit erasure efficiency, which is typically negligible in modern information processing devices, will be central to nanoscale computer engineering in the coming decades. Using a geometric framework, we approximate optimal erasure cycles of a single classical bit represented by the orientation of a macrospin consisting of a ferromagnetic domain of roughly 10,000 spins subject to stochastic and external magnetic fields. We compute optimal protocols modeled as geodesics in parameter space endowed with a Riemannian metric derived from the inverse diffusion tensor for a realistic model of macrospin magnetic free energy — the Landau-Lifshitz-Gilbert (LLG) equation. We find that the optimal paths in this model are straight lines in parameter space, so that the optimal erasure protocol consists of simultaneously ramping up the transverse and longitudinal components of the externally applied magnetic field at a constant rate and then instantaneously returning to zero field strength at the end of the cycle. For a broad temperature range, we derive a simple, closed-form expression of the work required to perform erasure in this model and we demonstrate that our optimal protocol is 20 to 40 times more efficient in terms of the excess work required beyond the Landauer bound compared with the naive protocol proposed in recent experimental work.

*Joint work with Patrick Zulkowski*

### 9:40 am – 10:20 am: Subriemannian Geometry and Finite-time Thermodynamics

**P. S. Krishnaprasad**
University of Maryland, College Park

Subriemannian geometry has its roots in optimal control problems. The Caratheodory-Chow-Rashevskii theorem on accessibility also places the subject in contact with an axiomatic approach to macroscopic thermodynamics. Explicit integrability of optimal control problems in this context is of interest. As in the case for integrability questions in mechanics, here too symmetries, conservation laws, reduction (and enlargement) have a key role. In this talk we discuss model problems of optimal control in non-equilibrium statistical mechanics. Of special interest is the problem of determining thermodynamic cycles that draw useful work from fluctuations. We discuss certain numerical techniques to compute optimal cycles.

*Joint work with PhD student Yunlong Huang, and Dr. Eric Justh of NRL.*

### 10:20 am – 11:00 am: Coffee break

### 11:00 am – 11:40 am: Shortcuts to adiabaticity using flow-fields

**Ayoti Patra**
University of Maryland, College Park

Adiabatic invariants - quantities that are preserved under the slow driving of a system's external parameters are important in classical mechanics, quantum mechanics and thermodynamics. Shortcuts to adiabaticity are strategies for preserving adiabatic invariants under rapid driving, typically by means of an auxiliary field to suppress excitations that are generated during rapid driving. I will review a general approach that we have developed for obtaining classical and quantum shortcuts in terms of flow fields that describe the desired adiabatic evolution. I will establish strong connections between the classical and quantum auxiliary fields. I will also extend the method to classical stochastic systems, and establish that the flow-fields thereby method is a unifying framework for obtaining shortcuts.

### 11:40 am – 12:20 pm: Ionization of Hydrogen Atom in Crossed Electric and Magnetic Fields

**Korana Burke**
University of Californina, Davis

In this talk I will show you how to look at ionization from dynamical systems point of view. Ionization of hydrogen atom in crossed electric and magnetic fields has been of scientific interest for many years. Not only is this a beautiful example of a chaotic system, but it is also widely considered a stepping stone to understanding the escape in the classic gravitational three body problem. The electrons classical motion resembles the motion of the Moon in the Sun-Earth-Moon three body system. One of the major challenges in studying chaotic ionization of hydrogen in crossed electric and magnetic fields is the ability to define a Poincare surface of section that captures all the allowed electron trajectories, but at the same time does not suffer from tangencies. Furthermore, this system has four dimensional phase space, further complicating the use of standard dynamical system tools. In this talk, I will lead you through construction of local Poincare return map that defines a local surface of section which governs the ionization process.

### 12:20 pm – 01:00 pm: Lunch

### 5:30 pm: Group Pizza Dinner

Location: Tent behind the Telluride Intermediate School

## 2.7 Tuesday, August 08, 2017: Quantum and nanotechnologies

### 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: An energy-resolved atomic scanning probe

**Michael Zwolak**
NIST, Gaithersburg

The scanning tunneling microscope is arguably the most versatile instrument for probing the local density of states of material surfaces, molecules, and devices. Despite its versatility, it has a limited range of accessible energies, whereas other spectroscopic techniques typically have a limited spatial resolution. Tunable atomic systems, though, can mimic, e.g., materials and electronics and probe them in ways not easily achievable by traditional techniques, especially for transport phenomena. Here, we fuse atomic and tunneling techniques to demonstrate a method that provides both spatial and energy resolution, as well as expands the accessible energy range to that prevalent in many-body systems. In this hybrid approach, the current supplies a simple, yet quantitative operational definition of a local density of states for both interacting and non-interacting systems as the rate at which particles can be siphoned from the system of interest by a narrow energy band of non-interacting states. Ultra-cold atomic lattices are a natural platform for implementing this concept to visualize the energy and spatial dependence of the atom density in interacting, inhomogeneous lattices, including ones with nontrivial topologies.

### 9:40 am – 10:20 am: Circuit optomechanics with carbon nanotubes

**Natalia Ares**
University of Oxford, UK

Exploiting resonant enhancement of light-matter interaction, cavity optomechanics opens new possibilities for the study of quantum devices (1). In the first part of this talk, I will focus on sensitive measurements of mechanical motion. A radio-frequency circuit allowed us to probe the vibrations of a suspended carbon nanotube (2). By using a gate voltage to tune the carbon nanotube into resonance with the radio-frequency signal, the mechanical signal is transduced efficiently to an electrical signal. I will evaluate the suitability of this readout scheme for monitoring mechanical motion near the phonon ground state at the level of uncertainty necessitated by the Heisenberg uncertainty principle. In the second part of the talk, I will discuss the feasibility of an experiment on the role of information in thermodynamics based on an optomechanical setup. Combining electrical and mechanical degrees of freedom, this experiment might enable a key capability: direct measurements of work exchange in the quantum regime (3).

(1) M. Aspelmeyer, T. J. Kippenberg and F. Marquardt, Rev. Mod. Phys. 86, 1391 (2014)

(2) N. Ares et al., Phys. Rev. Lett. 117, 170801 (2016)

(3) C. Elouard, M. Richard and A. Auffves, New J. Phys. 17, 55018 (2015)

### 10:20 am – 11:00 am: Coffee break

### 11:00 am – 11:40 am: Towards Energetic Measurements of Mesoscopic Heat Baths Coupled to Strongly Nonlinear Nanoelectromechanical Systems

**Matthew Matheny**
California Institute of Technology

Nanomechanical resonators typically exhibit nonlinearity only when driven to large amplitudes. This implies that, unless at high temperatures, nanoelectromechanical systems in contact with a thermal bath will act as simple harmonic oscillators. On the other hand, due to practical considerations, measurements of energy changes in a bath $\sim k_B T$ require extremely low temperatures. I will discuss these issues in detail and outline our platform for combining strongly nonlinear nanoelectromechanical systems with ultrasensitive calorimetry at extremely low temperatures.

*Joint work with Olli-Pentti Saira, Raj Katti, and Michael Roukes*

### 11:40 am – 12:20 pm: Measuring the energetics of nanoscale engines at low temperatures

**Olli-Pentti Saira**
California Institute of Technology

Recent years have seen a broad range of theoretical developments related to intrinsic fluctuations in nanoscale engines. Such engines can perform either (electro-)mechanical work or computational tasks. Importantly for applications, minimizing the activation energy of an engine generally improves its efficiency. At the same time, accounting of the energetics of the system becomes non-trivial, which is perhaps best exemplified by apparent violations of laws of thermodynamics that can manifest in the nanoscale.

It is therefore important to consider experimental platforms where the various theoretical concepts have physical manifestations. One quickly discovers that the fluctuations inherent to the engine operation are often comparable or even smaller than the noise of the measurement apparatus used to probe the engine. To date, most experimental works on stochastic thermodynamics have directly tracked the temporal dynamics of the relevant degrees of freedom. Energetic quantities are then inferred from the instantaneous coordinates using an assumed or calibrated potential, i.e., $x(t) \leftarrow k * x(t)^2/2 + m * x'(t)^2/2$ for a harmonic mechanical system. In this talk, I will describe opportunities for implementing direct energetic measurements instead. The experimental focus will be on inferring the heat $(Q)$ produced by the engine from the slight temperature increase of its local bath. This way, no knowledge of the internal microscopic dynamics of the engine are needed. The main experimental challenge is then to realize a local bath with sufficiently low heat capacity and thermal conductance combined with sensitive thermometry. It seems feasible that these requirements can be met in a low-temperature experiment making use of superconducting and micro/nanomachined parts.

*Joint work with Matthew Matheny, Raj Katti and Michael Roukes*

### 12:20 pm – 01:00 pm: Lunch

### 06:00 pm – 07:00 pm: TSRC town talk – Tracking Carbon Dioxide Capture and Mineral Sequestration by NMR–Molecular 'Fingerprints' of CO2 and Carbonates

**Sophia Hayes**
Washington University in St. Louis

Cash bar at 5:30 pm.

## 2.8 Wednesday, August 09, 2017: Quantum thermodynamics and quantum information

### 8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Intermediate School

Session Chair: **TOMMY BYRD**

### 9:00 am – 9:40 am: Quantum many-body dynamics and critical phenomena under continuous observation

**Masahito Ueda**
University of Tokyo

Quantum gas microscopy has revolutionalized our approach to quantum many-body systems where atoms trapped in an optical lattice can be observed in real time at the single-particle level. At such extreme precision, the measurement backaction due to Heisenberg?s uncertainty relation can no longer be ignored. One should naturally be led to the question of whether or not many-body dynamics will be modified and, if so, in what way. We will address this issue by focusing on few-body dynamics and quantum critical phenomena. In the former, the measurement distinguishablity of multiple particles leads to a complete suppression of relative positional decoherence and quantum correlations persist under continuous observation in a manner analogous to decoherence-free subspace (PRA95, 022124 (2017)). In the latter, the measurement backaction is shown to shift the quantum critical point and yield a unique critical phase beyond the scope of the standard universality class (PRA94, 053615 (2017); Nat. Commun. 8, 15791 (2017)). Our results can be investigated by current experimental techniques in ultracold atoms.

### 9:40 am – 10:20 am: Quantum coarse-grained entropy and thermodynamics

**Dominik Safranek**
University of California, Santa Cruz

We extend classical coarse-grained entropy, commonly used in many branches of physics, to the quantum realm. Classical coarse graining partitions phase space, which is difficult to implement in quantum mechanics. However by performing two non-commuting kinds of measurement, first to gather coarse-grained positional information, and then energy, our prescription leads to results in accord with the thermodynamic entropy for equilibrium systems and appears to extend well to non-equilibrium situations. This should have many applications, particularly to experiments on isolated quantum systems.

### 10:20 am – 11:00 am: Coffee break

### 11:00 am – 11:40 am: Work fluctuations in time-dependent quantum field theories

**Anthony Bartolotta**
California Institute of Technology

The two-time energy measurement formalism of the quantum Jarzynski equality has been used to great effect in studying the work fluctuations of non-relativistic systems with discrete spectra. In attempting to extend the two-time measurement formalism to a fully relativistic quantum field theory, one immediately comes in conflict with several foundational assumptions of quantum field theory. It will be shown that these difficulties can be overcome for a restricted class of quantum field theories. Focusing on a time-dependent version of scalar phi-four, we derive analytic expressions for the work distribution functions at leading order and show that these expressions have straightforward physical interpretations. The quantum Jarzynski equality can be shown to hold analytically and several protocols are investigated numerically.

### 11:40 am – 12:20 pm: Quantum speed limits: from Heisenberg's uncertainty principle to optimal quantum control

**Sebastian Deffner**
University of Maryland Baltimore County

One of the most widely known building blocks of modern physics is Heisenberg's indeterminacy principle. Among the different statements of this fundamental property of the full quantum mechanical nature of physical reality, the uncertainty relation for energy and time has a special place. Its interpretation and its consequences have inspired continued research efforts for almost a century. In its modern formulation, the uncertainty relation is understood as setting a fundamental bound on how fast any quantum system can evolve. In this talk we will discuss important milestones, such as the Mandelstam-Tamm and the Margolus-Levitin bounds on the quantum speed limit, and summarize recent applications in a variety of current research fields – including quantum information theory, quantum computing, and quantum thermodynamics.

### 12:20 pm – 01:00 pm: Lunch

### 06:00 pm – 09:00 pm: TSRC barbecue

Location: Tent behind Telluride Intermediate School

## 2.9 Thursday, August 10, 2017: Thermodynamics of information 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: Thermodynamics of Modularity: Irretrievable Dissipation of Localized Information Processing

**Alec Boyd**
University of California, Davis

Information processing often happens through the composition of many modular information processing units, like universal logic gates. Modularity allows us to perform complex global computations through a series of simpler localized computations. However, there are thermodynamic costs to modularity. Global correlations among the information bearing degrees of freedom, which are a thermodynamic fuel, can easily dissipate when computations happen locally. We quantify the minimum irretrievable dissipation of localized computations in terms of a conditional mutual information, and show that it has immediate consequences for physical information transducers, known as information ratchets. We can achieve perfect efficiency, as with global information processing, with localized computations by designing the internal states of the ratchets such that they capture the global correlations in the information reservoir. For ratchets that extract work from a structured pattern, this means the internal states are predictive of their input, and for ratchets that generate a structured pattern, this means that the internal states are retrodictive of their output.

### 9:40 am – 10:20 am: What can information do? Information and non-equilibrium thermodynamics

**Andrew Briggs**
University of Oxford, UK

Information and the arrow of time are linked through the second law of thermodynamics. The Flanders and Swan statement of the second law is "You can?t pass heat from the cooler to the hotter; you can try it if you wanna but you far better notta." A more conventional statement is that any irreversible process results in an increase in entropy. The close relationship between information and entropy was observed by Claude Shannon, who found that the equations describing the transmission of information in a noisy channel bore an uncanny similarity to equations of statistical thermodynamics. The conventional inequalities associated with the second law are currently being replaced by equalities, notably the Jarzynski equality. This has particular application on the nanoscale, where it becomes practical to test the Jarzynski equality in experimental structures. This may be closely related to experimental tests of the Szilard engine in thermodynamics, where information provides fuel at the rate of kBT ln(2) per bit of information consumed, and the Landauer limit in computing, where energy is dissipated at the rate of kBT ln(2) per bit of information reset or erased. Most of the progress in these areas has been in the classical domain, and the quantum domain is ripe to be explored. This topic is promising for the potential to relate information processing to energy dissipation, with relevance to energy consumption in computers and in brains.

**10:20 am – 11:00 am: Coffee break**

**11:00 am – 11:40 am: The minimal hidden computer needed to implement a visible computation**

**David Wolpert**
Santa Fe Institute

We consider the problem of constructing a physical process to implement some desired (single-valued) function $f$ over a set of visible states $X$. The physical process is represented as a time-inhomogeneous continuous-time Markov chain (CTMC), for example modeling the dynamics of a driven system connected to a heat bath. A prototypical example is a physical implementation of a logical gate in a circuit.

In general, there exists functions f which are not implementable by any possible CTMC. However, we demonstrate that for any f, an implementation is always possible if the system has access to some additional "hidden" states not in $X$. We then consider a natural decomposition of any such CTMC-based implementation into a countable set of discrete steps, demarcated from one another by the raising or lowering of barriers restricting probability flow between states. We demonstrate a tradeoff between the minimal number of hidden states and the minimal number of steps needed to implement any given f, analogous to space / time tradeoffs in computational circuit complexity theory.

This novel space / time trade-off is an inescapable and fundamental feature of continuous-time Markov processes, including the majority of the systems considered in stochastic thermodynamics. As an example, a digital computer is commonly implemented by circuits comprising many gates. Our results mean that each of those gates, viewed as a separate function f, itself can be decomposed into a sequence of discrete steps involving a set of hidden states, and there is a space/time trade-off between the number of steps and number of hidden states.

*Joint work with Artemy Kolchinsky and Jeremy Owen*

**11:40 am – 12:20 pm: Critical Exponents of a Biochemical Feedback Model**

**Tommy Byrd**
Purdue University

Biochemical feedback leads to dynamical transitions between cellular states, reminiscent of phase transitions in statistical physics. Yet it is unknown whether cells exhibit the scaling properties associated with phase transitions, and if they do, to which universality class they belong. Here we show using a generic birth-death model that biochemical feedback near a bifurcation point exhibits the scaling exponents of the Ising universality class in the mean-field limit. The theory allows us to calculate an effective order parameter, temperature, external field, and heat capacity from T-cell fluorescence data without fitting. Experiments agree with the scaling predictions, suggesting that this type of nonequilibrium criticality plays an important role in cell biology.

**12:20 pm – 01:00 pm: Lunch**

**Group Dinner: Details TBA**

## 2.10 Friday, August 11, 2011: Thermodynamic control and optimal processes

### 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: Stochastic efficiency of machines

**Christian van den Broeck**
Hasselt University, Belgium

We review the implications of the fluctuation theorem on the stochastic efficiency of small scale thermodynamic and information processing machines.

(1) G. Verley, M. Esposito, T. Willaert and C. Van den Broeck, "The unlikely Carnot efficiency", Nature Communications, DOI: 10.1038/ncomms 5721 (2014).

(2) G. Verley, T. Willaert, C. Van den Broeck, and M. Esposito "Universal theory of efficiency fluctuations", Phys. Rev. E 90, 052145 (2014).

(3) C. Van den Broeck and M. Esposito, "Ensemble and Trajectory Thermodynamics: a Brief Introduction", Physica A 418, 6-16 (2015).

(4) K. Proesmans and C. Van den Broeck, "Stochastic Efficiency: Five Case Studies", New J. Phys. 17, 065004 (2015).

(5) K. Proesmans, C. Driesen, B. Cleuren and C. Van den Broeck, "Efficiency of Single-Particle Engines", Phys. Rev. E 92, 032105 (2015).

(6) K. Proesmann, Y. Dreher, M. Gavrilov, J. Bechhoefer and C. Van den Broeck, "Brownian duet: a novel tale of thermodynamic efficiency", Phys. Rev. 6, 041010 (2016).

### 9:40 am – 10:20 am: Entropy production and fluctuation theorems for active matter

**Dibyendu Mandal**
University of California, Berkeley

Active biological systems reside far from equilibrium, dissipating heat even in their steady state, thus requiring an extension of conventional equilibrium thermodynamics and statistical mechanics. In this Letter, we have extended the emerging framework of stochastic thermodynamics to active matter. In particular, for the active Ornstein-Uhlenbeck model, we have provided consistent definitions of thermodynamic quantities such as work, energy, heat, entropy, and entropy production at the level of single, stochastic trajectories and derived related fluctuation relations. We have developed a generalization of the Clausius inequality, which is valid even in the presence of the non-Hamiltonian dynamics underlying active matter systems. We have illustrated our results with explicit numerical studies.

(1) D. Mandal, K. Klymko, and M. R. DeWeese, Entropy production and fluctuation theorems for active matter, arXiv:1704.02313 (2017)

### 10:20 am – 11:00 am: Coffee break

### 11:00 am – 11:40 am: Guessing the direction of Time's Arrow

**Christopher Jarzynski**
University of Maryland, College Park

As famously articulated by Sir Arthur Eddington, the second law of thermodynamics implies a directionality to the flow of time: the arrow of time points in the direction of increasing entropy. This deep fact of Nature is something that we intuitively grasp in our everyday lives, which is why we typically find it easy to distinguish between a movie played forward in time, and one played backward. With nanoscale systems the situation becomes more subtle due to the prominence of statistical fluctuations. At sufficiently small length and time scales, a system may behave in a manner that appears contrary to the direction of time's arrow, apparently "consuming" entropy rather than producing it. Our ability to distinguish the direction of the arrow of time can be formulated as a problem in statistical inference, in which we must guess whether we are seeing a movie run forward or backward. Surprisingly, this ability can be quantified and shown to obey a universal law. I will show how this law emerges from elementary considerations related to far-from-equilibrium fluctuation theorems, and I will present experimental results that have verified its validity, using a driven quantum dot.

### 11:40 am – 12:20 pm: Prediction vs Generation in Simple Markov Chains

**John Mahoney**
University of California, Davis

We present the minimal generators for all binary Markov chains and calculate their generative complexity. While this is in general a non-convex optimization and thus relies on numerics, we find an analytic solution for this particular set of processes. Importantly, processes in this class have a smaller generative complexity than statistical complexity—the minimal memory required by a *predictor* of the process. We then examine other information theoretic properties of these minimal generators, including their crypticity, oracular information, and gauge information, and compare the minimal generators to minimal predictors. Finally, we discuss the thermodynamic implications of this distinction.

### 12:20 pm – 1:00 pm: Closing Remarks

James P. Crutchfield
Korana Burke
Tommy A. Byrd
Sebastian Deffner

# 3 Conference Venue and Maps

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

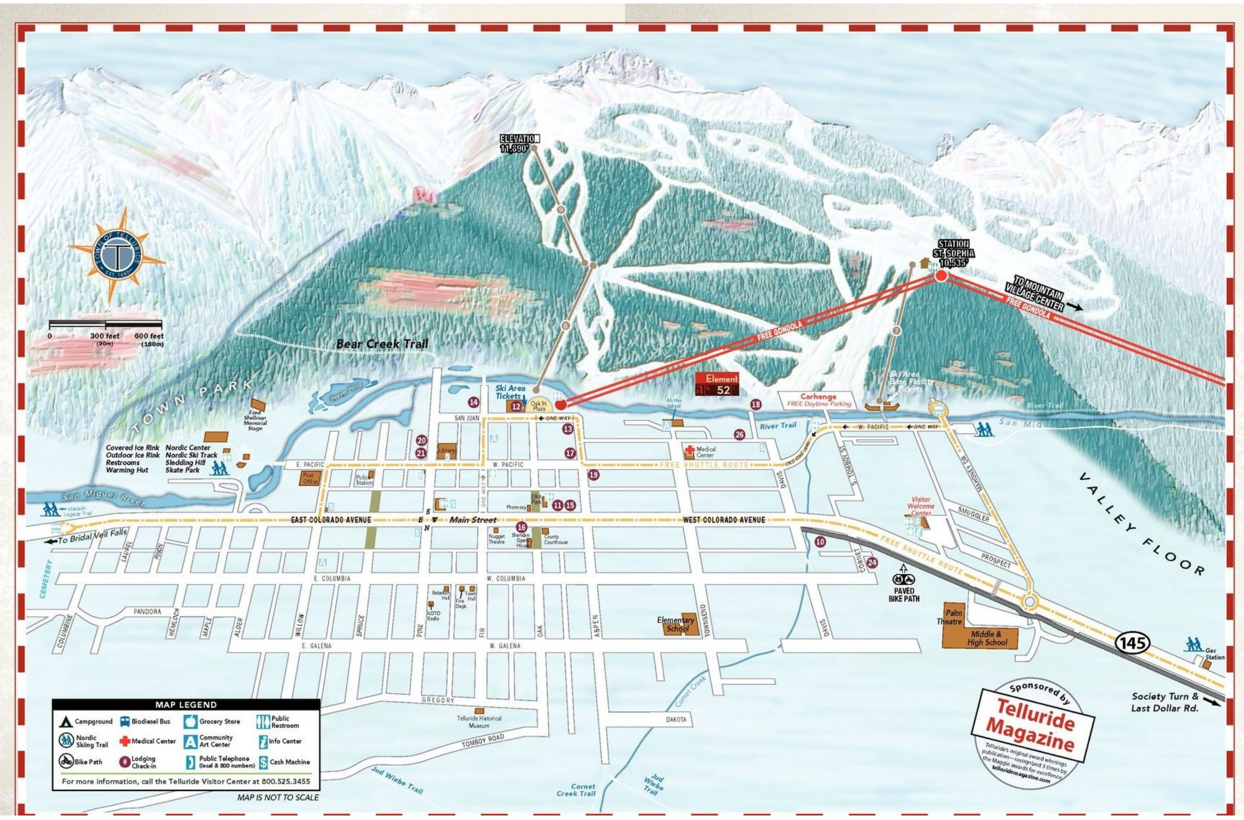



Figure 3.1: Map of the Town of Telluride

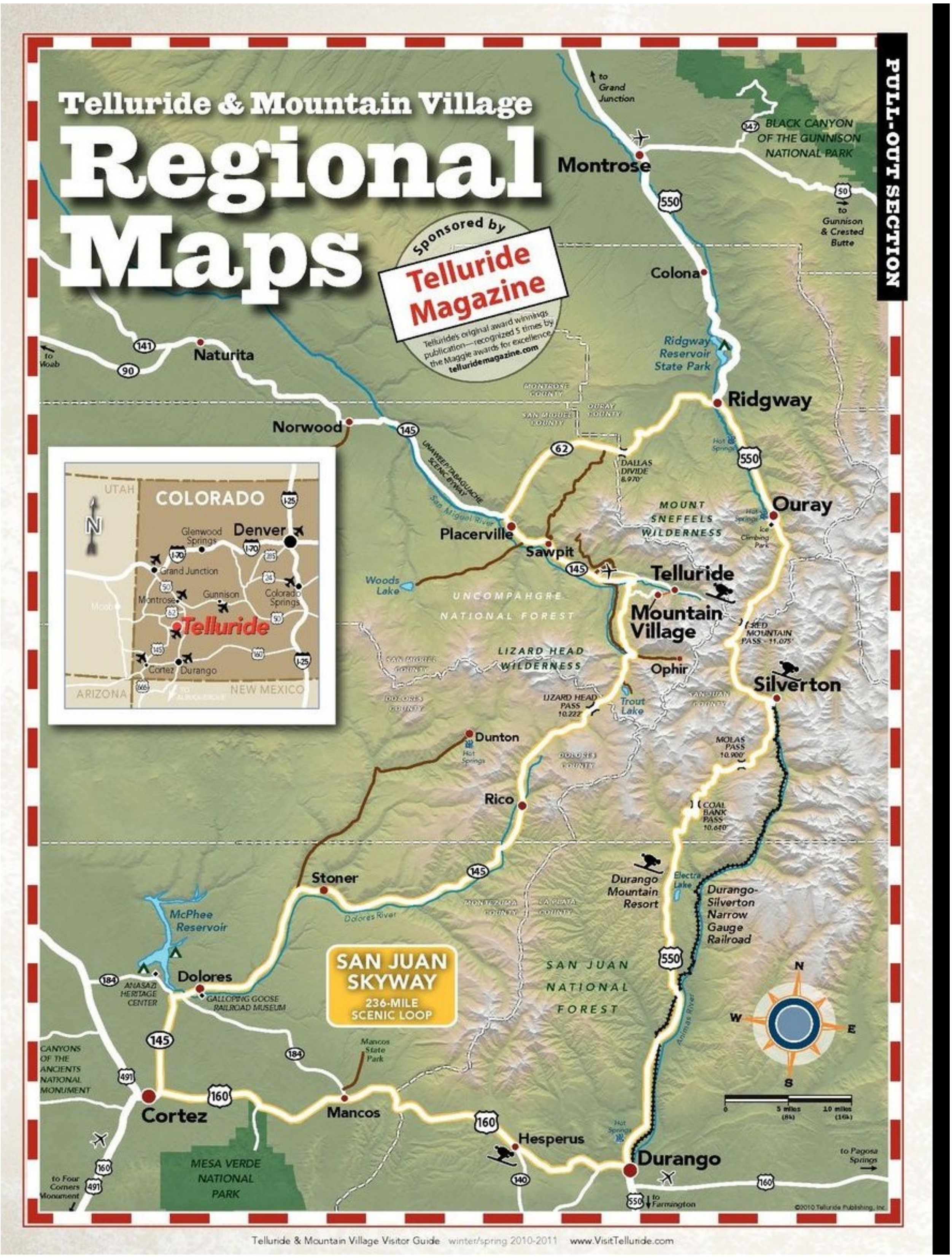



Figure 3.2: Regional Map

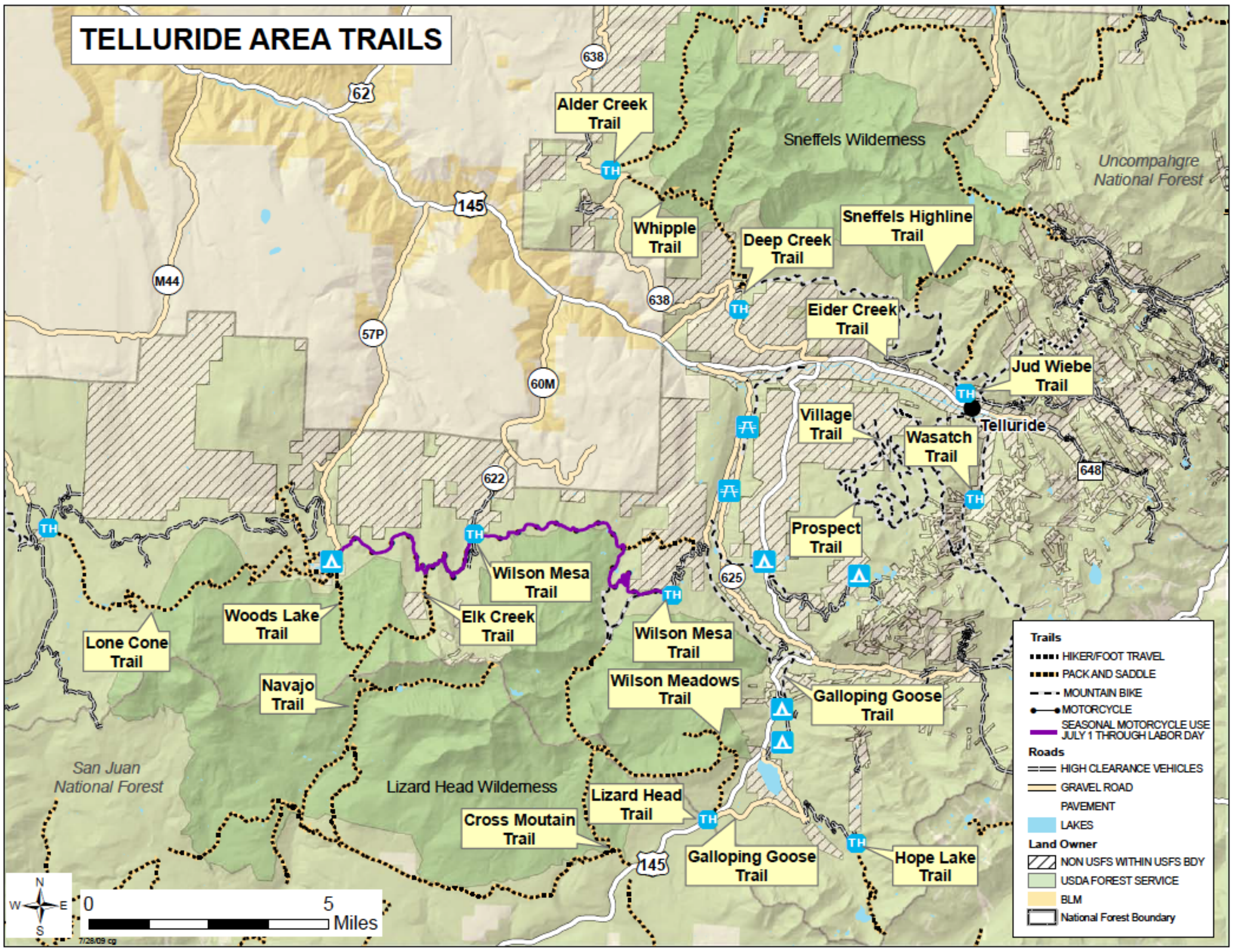



Figure 3.3: Telluride Area Trail Map