Information Engines at the Frontiers of Nanoscale Thermodynamics

Organizing Committee:
James Crutchfield
Korana Burke
Tommy Byrd
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June 23 – July 01, 2016

Telluride Elementary School, 477 West Columbia Ave Telluride, CO

Contents

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 abstract have been sorted according to topics, and we will have sessions on *Information engines, thermodynamic control and optimal processes, quantum thermodynamics and quantum information, fluctuation theorems and stochastic processes*, and *Biophysics and information.*
- We will have no sessions on Sunday, but the meeting rooms will be available.
- Breakfast will be served at the Telluride Elementary School. However, there is **NO** breakfast on Sunday.
- Thursday, June 30, 2016 is reserved for the MURI review, and we have no regular session.
- The session chairs will strictly enforce 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.

	06/23/16	06/24/16	06/25/16	06/26/16	06/27/16	06/28/16	06/29/16	06/30/16	07/01/16
8:20	breakfast	breakfast	breakfast		breakfast	breakfast	breakfast	breakfast	breakfast
9:00	opening	**Patra**	**Davis**		**Sagawa**	**Wolpert**	**ten Wolde**	MURI	**Davidson**
9:40	**Crutchfield**	**Deffner**	**Ueda**		**Quan**	**Olli-Pentti**	**Iyer-Biswas**	MURI	**Parag**
10:20	coffee	coffee	coffee		coffee	coffee	coffee	coffee	coffee
11:00	**Boyd**	**Bartolotta**	**Acconcia**		**Demers**	**Roukes**	**Byrd**	MURI	**Mukherjee**
11:40	**Rahav**	**Jarzynski**	**Horowitz**		**Ruppeiner**	**Matheny**	**Mugler**	MURI	**Riechers**
12:20	lunch	lunch	lunch		lunch	lunch	lunch	lunch	closing
13:00	**Mandal**	**Crooks**	**Bonança**		**Li**	**DeWeese**	**Palacci**		lunch
13:40									
14:20									
15:00									
15:40									
16:20									
17:00									
17:30						town talk	TSRC bbq		
18:00	group dinner						TSRC bbq		
19:00					pizza dinner		TSRC bbq	group dinner	

2.2 Thursday, June 23, 2016: Information engines I

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

Check-In and breakfast at the Telluride Elementary 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: Demon Dynamics: Deterministic Chaos, the Szilard Map, and the Intelligence of Thermodynamic Systems

James P. Crutchfield
Complexity Sciences Center
Physics Department
University of California at Davis

We introduce a deterministic chaotic system – the Szilard Map – that encapsulates the measurement, control, and erasure protocol by which Maxwellian Demons extract work from a heat reservoir. Implementing the Demon's control function in a dynamical embodiment, our construction symmetrizes Demon and thermodynamic system, allowing one to explore their functionality and recover the fundamental trade-off between the thermodynamic costs of dissipation due to measurement and due to erasure. The map's degree of chaos – captured by the Kolmogorov-Sinai entropy – is the rate of energy extraction from the heat bath. Moreover, an engine's statistical complexity quantifies the minimum necessary system memory for it to function. In this way, dynamical instability in the control protocol plays an essential and constructive role in intelligent thermodynamic systems.

Joint work with Alexander B. Boyd.

10:20 am – 11:00 am: Coffee break

11:00 am – 11:40 am: Thermodynamics of Memory in Autonomous Maxwellian Demons

Alec Boyd
Complexity Sciences Center
Physics Department
University of California at Davis

Thermodynamic ratchets are a form of autonomous Maxwellian demon which are able to use structure in an input bit string to harvest useful work from a thermal bath. This is a paradigm for understanding how agents leverage structured thermal environments to do useful work. The ratchets behave as a memoryful channel/transducer, interacting with bits sequentially, and writing the result to an output string. Until now, most analysis of thermodynamic ratchets assumes memoryless IID statistics for the input string, which requires no memory to generate. By using computational mechanics we broaden our consideration to memoryful generators of the input string. We demonstrate that a ratchet need not have memory to most effectively leverage an IID (memoryless) environment, but it must have memory if there is structure in its environment that's generated by memory. A ratchet's memory must reflect the memory of the input generator to optimally harvest work.

11:40 am – 12:20 pm: Finding a new job for Maxwell's demon: Improving free energy calculations

Saar Rahav
Schulich faculty of Chemistry
Technion – Israel Institute of Technology

Our understanding of small out-of-equilibrium system have undergone a revolution in the last two decades, with the development of stochastic thermodynamics. It was found that small systems driven away from equilibrium satisfy the Jarzynski equality. This equality can be used to determine free energy differences from repetitions of a non-equilibrium process. However, such calculations are known to suffer from poor convergence. The deep connections between information and thermodynamics have also been extensively studied. Information engines, where measurement and feedback allow to extract additional work from a system, have been studied theoretically and realized in experiments. It is only natural to wonder whether measurement and feedback can also be useful in free energy estimation. We argue that measurement and feedback can greatly improve the convergence of such calculations, and furthermore show how the information gained from the measurement can be used for that purpose. We study numerically a pulling process of a DNA hairpin, modeled as a two-state system, as a test case for our approach.

Joint work with Shahaf Asban.

12:20 pm – 01:00 pm: Lunch

01:00 pm – 01:40 pm: Correlation-powered Information Engines and the Thermodynamics of Synchronization

Dibyendu Mandal
Department of Physics and Helen Wills Neuroscience Institute
University of California Berkeley

We have designed an information engine that is powered by correlations. Our engine can randomize an alternating sequence of 0's and 1's and utilize the associated increase in information entropy to transfer energy from a thermal reservoir to a work reservoir. A critical component of the engine is a synchronizing state that allows the engine to return to its desired dynamical phase when thrown into an unwanted, dissipative phase by corruptions in the sequence. This self-correcting mechanism is robust up to a critical level of corruption beyond which the system fails to act as an engine. We have found explicit analytical expressions for work and the critical level of corruption. We have summarized the performance of the engine through a functional phase diagram in its control parameter space.

6:00 pm Group Dinner: La Marmotte

Address: 150 W San Juan Ave

2.3 Friday, June 24, 2016: Thermodynamic control and optimal processes

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Elementary School

Session Chair: **TOMMY BYRD**

9:00 am – 9:40 am: Local shortcuts to adiabaticity in classical and quantum mechanics

Ayoti Patra
Department of Chemistry and Biochemistry
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. I will discuss strategies for preserving adiabatic invariants even under rapid driving. For a rapidly varying Hamiltonian $H(q, p, t)$, I will show how to construct an auxiliary potential $U(q, t)$ such that the adiabatic invariant is preserved exactly when the system evolves under $H(q, p, t) + U(q, t)$. In both the classical and the quantum versions of this problem, the auxiliary potential is constructed from an appropriately defined velocity flow-field. I will illustrate these ideas using numerical simulations, and I will explore whether the classical solution provides a useful approximate solution to the quantum problem.

9:40 am – 10:20 am: Shortcuts to adiabaticity: suppression of pair production in driven Dirac dynamics

Sebastian Deffner
Theoretical Division and Center for Nonlinear Studies
Los Alamos National Laboratory

Achieving effectively adiabatic dynamics in finite time is a ubiquitous goal in virtually all areas of modern physics. So-called shortcuts to adiabaticity refer to a set of methods and techniques that allow us to produce in a short time the same final state that would result from an adiabatic, infinitely slow process. In this paper we generalize one of these methods – the fast-forward technique – to driven Dirac dynamics. As our main result we find that shortcuts to adiabaticity for the $(1+1)$-dimensional Dirac equation are facilitated by a combination of both scalar and pseudoscalar potentials. Our findings are illustrated for two analytically solvable examples, namely charged particles driven in spatially homogeneous and linear vector fields.

10:20 am – 11:00 am: Coffee break

11:00 am – 10:40 am: Bayesian Updating in Thermodynamics

Tony Bartolotta
Nuclear Physics
California Institute of Technology

Measurements have been previously incorporated in thermodynamics, usually in the context of feedback control. These measurements provide information about the current state of the system allowing useful work to be extracted. Furthermore, they contain information about previous states of the system. Consequently, under a Bayesian framework, the distribution functions of the previous states must be updated. This updating changes the definitions of "initial" entropy and free energy. For a simple model where a single measurement is performed without feedback control, we derive several thermodynamic equalities and inequalities that incorporate the information-theoretic contributions of the Bayesian updating. We show that the Second Law of Thermodynamics is most naturally written in terms of cross entropies instead of Shannon entropies. Preliminary results for feedback controlled systems are also presented.

11:40 am – 12:20 pm: Nonequilibrium work relations for open quantum systems

Christopher Jarzynski
Department of Chemistry and Biochemistry & Institute for Physical Science and Technology
University of Maryland, College Park

Far-from-equilibrium work relations have been widely investigated, both theoretically and experimentally, for classical systems such as optically trapped colloidal particles and biopolymers undergoing mechanical stretching. However, the extensions of these results to quantum systems has proven to be conceptually difficult. This is particularly true for open quantum systems, which are in contact with thermal environments. I will discuss a special case of an open quantum system, in which it is assumed that the environment induces decoherence but no dissipation in the system of interest. I will show that the nonequilibrium work relation remains valid in this context, and I will present experimental results illustrating this result. The experiments were performed with trapped ions, and represent the first laboratory confirmation of the nonequilibrium work relation for an open quantum system.

12:20 pm – 01:00 pm: Lunch

01:00 pm – 01:40 pm: On the thermodynamics of strongly coupled systems

Gavin Crooks
Lawrence Berkeley National Lab

I'll talk about the non-equilibrium thermodynamics of a pair of driven systems that are strongly coupled to one another. If we look at the problem in the right way, we get deceptively simple expressions for the local entropy production, local fluctuation theorems, and local second laws. These expressions subsume feedback fluctuation theorems and various other special cases.

2.4 Saturday, June 25, 2016: Quantum thermodynamics and quantum information

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Elementary School

Session Chair: **SEBASTIAN DEFFNER**

9:00 am – 9:40 am: Nonequilbrium steady states of superfluids

Matthew Davis
School of Mathematics and Physics
University of Queensland

A number of recent experiments with ultracold gases have investigated superfluid transport between reservoirs. Using a classical field approach, we are studying the properties of superfluids in strongly nonequilibrium situations generated by controlling the thermodynamic properties of the reservoirs. We will present an introduction to the classical field methodology, and describe initial results of our simulations. A goal of our project is to design a many-body heat engine based on a quantum gas.

9:40 am – 10:20 am: Entanglement pre-thermalization in a Bose gas

Masahito Ueda
Department of Physics
The University of Tokyo

An isolated quantum system often shows relaxation to a quasi-stationary state before reaching thermal equilibrium. Such a prethermalized state was observed in recent experiments in a onedimensional Bose gas after it is coherently split into two. While the existence of local conserved quantities is usually considered to be the key ingredient of prethermalization, it has remained elusive whether nonlocal correlations between the subsystems can influence prethermalization of the entire system. We discuss the dynamics of coherently split one-dimensional Bose gases and show that the initial entanglement combined with energy degeneracy due to parity and translation invariance strongly affects the long-time behavior of the system. The mechanism of this "entanglement prethermalization" is quite general and not restricted to the one-dimensional Bose gas. In view of recent experimental realization of a system involving a small well-defined number of ultracold atoms, our predictions based on exact few-body calculations are amenable to experimental test.

10:20 am – 11:00 am: Coffee break

11:00 am – 11:40 am: Quantum speed limits and the maximal rate of quantum learning

Thiago Acconcia
Instituto de Fisica Gleb Wataghin
University of Campinas

Over the last decades, new technologies have been developed allowing us to manipulate small devices such as quantum-optical systems and quantum dots. Since the control of these devices demands quantum measurements, a quantification of the accessible information and its rate is imperative. In this talk, we present a study of the maximal rate of quantum learning, i.e., the rate with which the accessible quantum information can change under time-dependent perturbations. This rate is given by the ratio of the change of Holevo's information and the quantum speed limit time. As an illustration, we apply our findings to the quantum harmonic oscillator and evaluate the maximal rate of quantum learning by means of time-dependent perturbation theory.

Joint work with Sebastian Deffner.

11:40 am – 12:20 pm: Energy Cost of Controlling Mesoscopic Quantum Systems

Jordan M. Horowitz
Department of Physics
Massachusetts Institute of Technology

Small systems are continually bombarded by noise from their surroundings. Sometimes this noise can be helpful; thermal and chemical fluctuations are the fuel that power biological motors. However, for mesoscopic quantum devices noise is a nuisance that interferes with their proper functioning. For such systems, control mechanisms can be employed to suppress fluctuations. Since combatting noise necessarily involves lowering entropy, Landauer's principle suggests there is an energetic cost. In this talk, I will derive the minimal energy cost required to suppress noise in a mesoscopic quantum system with coherent feedback control in the presence of arbitrary Markovian noise processes. This result provides the fundamental cost of refrigeration and sets the minimum power consumption for a mesoscopic device to operate out of equilibrium. I will then illustrate this prediction by evaluating the energy efficiency of resolved-sideband cooling of a nano-mechanical resonator.

12:20 pm – 01:00 pm: Lunch

1:00 pm – 1:40 pm: Microcanonical Szilard engines beyond the quasistatic regime

Marcus Bonança
Instituto de Fisica Gleb Wataghin
University of Campinas

In this talk we discuss the possibility of extracting energy from a single thermal bath using microcanonical Szilard engines operating in finite time. This extends previous results on the subject which are restricted to the quasistatic regime. The feedback protocol is implemented based on linear response predictions of the excess work. It is claimed that the underlying mechanism leading to energy extraction is an effective spontaneous symmetry breaking that does not violate Liouville's theorem and preserves ergodicity throughout the cycle. We further discuss the quantum version of the engine.

2.5 Sunday, June 26, 2016: Free day

No program, no breakfast.

2.6 Monday, June 27, 2016: Fluctuation theorems and stochastic processes

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Elementary School

Session Chair: **KORANA BURKE**

9:00 am – 9:40 am: Fluctuation Theorem for Pure Quantum States

Takahiro Sagawa
Department of Applied Physics
The University of Tokyo

The origin of macroscopic irreversibility under microscopic reversible dynamics is a longstanding fundamental problem in nonequilibrium statistical mechanics. The fluctuation theorem and thermodynamics of information shed modern light on this problem, which lead to the second law of thermodynamics and its generalization with information. A crucial assumption in this research direction is that the initial state of the heat bath is, at least in the initial time, in the canonical distribution, which effectively breaks the time-reversal symmetry. On the other hand, it has been shown that even a pure quantum state, described by a single wave function, can relax to macroscopic thermal equilibrium by reversible unitary dynamics. However, the second law of thermodynamics and the fluctuation theorem in pure quantum states have been elusive, and the gap between the microscopic reversible and the macroscopic irreversible dynamics has not yet been bridged.

We here show that the second law of thermodynamics and the fluctuation theorem hold true for isolated genuine quantum systems [1], where pure quantum states obey unitary reversible dynamics. Our study is based on a rigorous proof by using the Lieb-Robinson bound, and numerical simulation of hard-core bosons. The entanglement entropy of a subsystem is shown connected to thermodynamic heat, highlighting the foundation of the information-thermodynamics link. Our results imply that thermal fluctuations emerge from purely quantum fluctuations in nonequilibrium dynamics, which is a novel scenario of the emergence of thermodynamics from quantum mechanics.

[1] E. Iyoda, K. Kaneko, and T. Sagawa, arXiv:1603.07857 (2016).

9:40 am – 10:20 am: Jarzynski Equality, Crooks Fluctuation Theorem and the Fluctuation Theorems of Heat for Arbitrary Initial States

Haitao Quan
Physics School
Peking University

By taking full advantage of the dynamical property imposed by the detailed balance condition, we derive a new refined unified fluctuation theorem for general stochastic thermodynamic systems. This fluctuation theorem involves the joint probability distribution functions of the final phase space point and a thermodynamic variable. Jarzynski equality, Crooks fluctuation theorem, and the fluctuation theorems of heat as well as the trajectory entropy production can be regarded as special cases of this refined unified fluctuation theorem, and all of them are generalized to arbitrary initial states. Our result is heuristic for further understanding of the relations and distinctions between all kinds of FTs, and might be valuable for investigating thermodynamic processes with information exchange.

[1] Zongping Gong and H. T. Quan, Phys. Rev. E, 92, 012131 (2015)

10:20 am – 11:00 am: Coffee break

11:00 am – 11:40 am: Stabilizing Nanoscale Thermodynamic Systems with Feedback Control

Jeff Demers
Department of Chemistry and Biochemistry
University of Maryland, College Park

In this talk, I'll discuss the energetic costs associated with stabilizing small systems in noisy thermal environments. We consider the simple and exactly solvable problem of linearly stabilizing a Brownian particle exposed to Gaussian white noise using feedback control, considering both perfect and noisy measurements. For the noisy measurement case, we employ the Kalman-Bucy filter from control theory to obtain the optimal state estimate given the noisy observations. Our analysis leads to a counter-intuitive result: in the limit of vanishing noise strength, the energetic cost associated with the noisy measurement case does not converge to the energetic cost associated with the perfect measurement case.

11:40 am – 12:20 pm: The Fokker-Planck equation has a natural time scale

George Ruppeiner
Division of Natural Sciences
New College of Florida

A number of models in stochastic thermodynamics are based on the Fokker-Planck equation. The solution to the Fokker-Planck equation yields the probabilistic time development of a mesoscopic system that is interacting with both random microscopic elements, and a macroscopic environment. The interaction with the macroscopic environment, mediated by control parameters, is a major element of finite-time thermodynamics, much discussed in Telluride over the years. In my talk, however, I will not discuss the optimal thermodynamic processes of finite-time thermodynamics, but focus instead on the microscopic noise terms in the Fokker-Planck equation. Although there are significant recent general theorems connecting the time development of mesoscopic systems, and how this is affected by microscopic noise, I propose that there is a basic element of stochastic processes that has been largely neglected by theory. The path integral solution to the Fokker-Planck equation, by Graham (1977) and others, clearly identifies a noise dependent Ricci curvature scalar R, whose inverse yields a transition time from an ordinary diffusive process to behavior of a different type. In my talk, I lay out Graham's formalism, and discuss the role of R. (I emphasize that this R is physically quite different from the thermodynamic curvature, which has also been discussed in Telluride.) I express the hope that the addition of new models and physical processes to stochastic thermodynamics have brought a time where this theme can lead to advances.

12:20 pm – 01:00 pm: Lunch

01:00 pm – 01:40 pm: Brownian motion at short time scales

Tongcang Li
Department of Physics and Astronomy
Purdue University

Brownian motion has played important roles in many different fields of science and engineering since its origin was first explained by Albert Einstein in 1905. Einstein's theory of Brownian motion, however, is only applicable at long time scales. At short time scales, Brownian motion of a suspended particle is not completely random, due to the inertia of the particle and the surrounding fluid. Moreover, the thermal force exerted on a particle suspended in a liquid is not a white noise, but is colored. Recently, we developed an ultrasensitive optical tweezer, and measured the instantaneous velocity of a Brownian particle in both gas and liquid. With an active feedback, we were able to cool the Brownian motion of a microsphere from room temperature to millikelvin temperatures. We are currently investigating generalized fluctuation theorems with an optically levitated nanosphere. This ultrasensitive optical tweezer provides a powerful tool for studying statistical mechanics of small systems.

7:00pm Group Pizza Dinner

2.7 Tuesday, June 28, 2016: Information engines II

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Elementary School

Session Chair: **TOMMY BYRD**

9:00 am – 9:40 am: Extending Landauer's Bound from Bit Erasure to Arbitrary Computation

David Wolpert
Santa Fe Institute

Recent advances in nonequilibrium statistical physics have led to great strides in the thermodynamics of computation, allowing the calculation of the minimal thermodynamic work required to implement a computation π when two conditions hold:

i) The output of π is independent of its input (e.g., as in bit erasure);

ii) We use a physical computer C to implement π that is tailored to the precise distribution over π's inputs, P_0.

First I extend these analyses to calculate the minimal work required even if the output of π depends on its input. I then show that stochastic uncertainty about P_0 increases the minimal work required to run the computer.

Next I show that if C will be re-used, then the minimal work to run it depends only on the logical map π, independent of the physical details of C. This establishes a formal identity between the thermodynamics of (re-usable) computers and theoretical computer science. I use this identity to prove that the minimal work required to compute a bit string σ on a universal Turing machine U is

$$\begin{gathered}\text{Kolmogorov complexity}_U(\sigma)\\ +\\ \log\,(\text{Bernoulli measure of the set of input strings that compute } \sigma)\\ +\\ \log(\text{halting probability of } U)\end{gathered}$$

This can be viewed as a thermodynamic "correction" to Kolmogorov complexity.

I end by using these results to relate the free energy flux incident on an organism / robot / biosphere to the maximal amount of computation that the organism / robot / biosphere can do per unit time.

09:40 am – 10:20 am: Dispersive thermometry with a Josephson junction

Saira Olli-Pentti
Low Temperature Laboratory
Department of Applied Physics
Aalto University School of Science

We study of a new mode of interaction between a Josephson junction and a multi-mode electromagnetic environment [1]. Namely, we have constructed a Josephson bolometer that detects weak electrical fluctuations and indicates the strength of these fluctuations via a frequency shift in a microwave resonator. With this ability, we demonstrate high-performance non-local thermometry by detecting the noise of a remote resistor. Importantly, even though this mode of operation resembles that of a noise thermometer, our device indicates the sensed temperature directly through a change in the phase of a microwave probe signal, instead of relying on power spectrum analysis with external electronics.

Using a standard HEMT preamplifier, we achieve a noise-equivalent temperature of $< 10\mu$K $\sqrt{(Hz)}$ at 50 mK with a power dissipation below 1 fW. The readout bandwidth, given by the resonance linewidth, is 7.5 MHz. This technique is amendable to the detection of the temperature or noise of various nanostructures with low back-action. In particular, we are targeting the readout of sensitive calorimeters.

Finally, we combine DC biasing of the junction with microwave probing for a detailed study of the nonlinear junction-environment interactions. Owing to careful control of the microwave environment, features appear only at voltages corresponding to well-defined resonances. We observe strong modulation of the internal quality factor of the resonator, indicating stimulated microwave emission by the junction. All features are accurately described by a theoretical model with few free parameters.

[1] arXiv:1604.05089

10:20 am – 11:00 am: Coffee break

11:00 am – 11:40 am: Prospects of Yoctocalorimetry and sub-kBT Information Processing

Michael Roukes
Robert M. Abbey Professor of Physics, Applied Physics, and Biological Engineering
California Institute of Technology

The intimate relation between thermodynamic quantities and information have been an intense topic of discussion since the time of Maxwell. Concurrent with theoretical developments in the field, industrial research in semiconductor processing has made possible instantiations of information processing with energy scales near Landauer's limit. The confluence of these two developments require an experimental investigation of the relationship between the informational and thermodynamic aspects at the single bit level. In my presentation, I will discuss the prospects for directly measuring the change of information in a single bit via calorimetry.

11:40 am – 12:20 pm: Nanoelectromechanical Bit Storage via Buckled Beams

Matt Matheny and Warren Fon
Condensed Matter Physics
California Institute of Technology

A simple model of bit storage used in tests of Landauer's limit is a double well potential. In order to isolate and access thermodynamic quantities of an informational bit via calorimetry, small size and integration into a semiconducting platform is optimal. We discuss a platform for developing a double well system using buckled nanoelectromechanical beams.

12:20 pm – 01:00 pm: Lunch

01:00 pm – 01:40 pm: Geometrical insights into optimal bit erasure and other nonequilibrium control problems

Mike DeWeese
Department of Physics
University of California Berkeley

A deeper understanding of nonequilibrium phenomena is needed to reveal the principles governing natural and synthetic molecular machines. Recent work has shown that when a thermodynamic system is driven from equilibrium then, in the linear response regime, the space of controllable parameters has a Riemannian geometry induced by a generalized friction tensor. We exploit this geometric insight to construct closed-form expressions for minimal-dissipation protocols for a variety of systems. We are particularly interested in understanding efficient finite-time bit erasure, as this could soon be the limiting factor for computer hardware design as computational demands approach limits imposed by physical law. After describing our basic framework, I will present results for specific optimization problems including optimal erasure of a classical bit for different physical representations, such as the orientation of a nanoscale macrospin subject to stochastic and external magnetic fields. We find some universal features for this broad class of erasure problems, whereas other aspects of our solutions depend on the details of the information representation.

06:00 pm – 07:00 pm: TSRC town talk – Clouds in a Bowl of Soup

Graham Feingold
Chemical Sciences Division
NOAA Earth System Research Laboratory

Cash bar at 5:30 pm.

2.8 Wednesday, June 29, 2016: Biophysics and information I

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Elementary School

Session Chair: **JIM CRUTCHFIELD**

9:00 am – 9:40 am: The thermodynamics of biochemical copying

Pieter Rien ten Wolde
Biochemical Networks group
FOM Institute AMOLF

Living cells continually make molecular copies: during the cell cycle DNA needs to be replicated, new proteins need to be synthesized, and even cell signaling critically relies on molecular copying: the mechanism of time integration entails copying the ligand-binding state of the receptor into stable chemical modification states of readout proteins. In this talk, I will discuss how such biochemical copy processes can be mapped onto canonical copy protocols as implemented in computational devices. I will first review Maxwell's demon and Szilard's engine, and explain why taking a measurement inevitable costs energy. I will then discuss the trade-off between the precision and energetic cost of taking a measurement, and show that cellular systems can come surprisingly close to the fundamental bound as set by the second law of thermodynamics.

9:40 am – 10:20 am: Emergent simplicity in complex biological dynamics

Srividya Iyer-Biswas
Department of Physics and Astronomy
Purdue University

In this talk I will discuss the scaling laws governing the stochastic growth dynamics of individual cells and populations, and connections thereof with energetic costs of cellular information processing.

10:20 am – 11:00 am: Coffee break

11:00 am – 11:40 am: Connecting dynamic and thermodynamic criticality in a communicating cell population

Tommy Byrd
Department of Physics and Astronomy
Purdue University

In recent years, evidence has suggested that biological systems operate near a critical point in their parameter space. However, the mechanisms of achieving and maintaining criticality, as well as the benefits of such a strategy, remain unclear. Here we investigate a minimal model of a critical biological system, consisting of a population of cells that produce molecules with positive feedback and exchange molecules with neighboring cells. Alone, a single cell exists in either a low- or a high-molecule number state upon passing through a dynamical critical point. Together, cells become correlated over a long range, reminiscent of a thermodynamic critical point. By mapping our stochastic model to a canonical model from thermodynamics, the Ising model, we aim to connect dynamic and thermodynamic criticality, and explore the benefits of criticality for collective information processing.

Joint work with Amir Erez and Andrew Mugler.

11:40 am – 12:20 pm: Collective information processing by communicating cells

Andrew Mugler
Department of Physics and Astronomy
Purdue University

All cells process information about their environment. At the same time, cells communicate. Can cell-cell communication enable enhanced, collective information processing? I will describe recent theoretical and experimental results in which this question is explored in several contexts, including concentration sensing and gradient sensing by cells that communicate over short or long distances. I will show how communication allows cells to perform qualitatively new behaviors that single cells cannot perform alone. Moreover, I will demonstrate that physical laws set fundamental bounds on the precision of sensing that can be tested in experiments. This work extends the study of cellular sensing and information processing to collective ensembles.

12:20 pm – 01:00 pm: Lunch

01:00 pm – 01:40 pm: Engineering with kinesin motors

Henri Palacci
Department of Biomedical Engineering
Columbia University

Motor proteins, such as kinesin, can serve as biological components in engineered nanosystems. A proof-of-principle application is a "smart dust" biosensor for the remote detection of biological and chemical agents, which is enabled by the integration of recognition, transport and detection into a submillimeter-sized microfabricated device. The development of this system has revealed a number of challenges in engineering at the nanoscale, particularly in the guiding, activation, and loading of kinesin-powered molecular shuttles. Overcoming these challenges requires the integration of a diverse set of technologies, illustrates the complexity of biophysical mechanisms, and enables the formulation of general principles for nanoscale engineering.Molecular motors also introduce an interesting new element into self-assembly processes by accelerating transport, reducing unwanted connections, and enabling the formation of non-equilibrium structures. The formation of nanowires and nanospools from microtubules transported by kinesin motors strikingly illustrates these aspects of motor-driven self-assembly. Our most recent work aimed to create a molecular system that is capable of dynamically assembling and disassembling its building blocks while retaining its functionality, and demonstrates the possibility of self- healing and adaptation. We show that this allows for more efficient use of the molecular building blocks, and demonstrate that this system is defect tolerant, self-healing, and adaptive.

Joint work with Stanislav Tsitkov, Amy Lam, Katira Parag, and Henry Hess

06:00 pm – 09:00 pm: TSRC barbecue

2.9 Thursday, June 30, 2016: MURI review

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Elementary School

9:00 am – 01:40 pm: MURI review

12:20 pm – 01:00 pm: Lunch

7:00 pm Group Dinner: Rustico Ristorante

Address: 114 E Colorado Ave

2.10 Friday, July 1, 2016: Biophysics and information II

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Elementary School

Session Chair: **SEBASTIAN DEFFNER**

9:00 am – 9:40 am: Information geometry identifies robust and sloppy parameter combinations in a neural integrator

Jacob Davidson
Department of Physics
University of California at Davis

Models in systems biology and neuroscience often have many parameters which are difficult or impossible to measure individually. Information geometry can be used to identify a lower-dimensional substructure embedded within a complex, multi-parameter model, and can explain why complicated models are still able to make well-defined predictions. It has been suggested that a "sloppy" structure is a general feature of biological systems, and that such a structure is a reason why coarse-grained theories are often so effective in capturing system behavior. We apply these methods to a recurrent neural network integrator model to identify important versus unimportant parameter combinations. This system, the oculomotor integrator, is a model circuit to represent short-term memory. We demonstrate that although multiple circuit configurations lead to near-identical performance, these configurations only differ in sloppy directions in parameter space. This result is compared in the context of other multi-scale models in physics and biology.

9:40 am – 10:20 am: Information Processing in Biological Systems: The Role of Biomolecular Motors

Katira Parag
Department of Mechanical Engineering
San Diego State University

With recent advances in the area of information thermodynamics, we now have an estimate on the lower bound for the energy requirements of information processing ? copying, modifying and erasing information in physical systems. We also have a more general expression for the second law of thermodynamics relating the change in the information content of a system and the work that can be extracted from the system. With an aim to understand how these principles apply to living biological systems and if there are universal rules that govern the flow and evolution of information within biological systems, we have built an in silico model of an information reader run by biomolecular motor proteins. While the power stroke of a biomolecular motor is driven by the hydrolysis of a nucleoside triphosphate (NTP) molecule, its directionality is determined by the polarity of the biopolymer it interacts with. Thus segments of biopolymers with alternating polarities arranged end to end can encode a binary information sequence. We test whether this information can be read efficiently with an array of collectively operation biomolecular motors. We also examine the role of information complexity on the energetic cost of information processing in such a biomimetic system. We aim to identify the factors that determine the rate, energetic cost, and accuracy of this information read out.

10:20 am – 11:00 am: Coffee break

11:00 am – 11:40 am: Thermodynamics and Information processing of Biological motors: A case study of F1-ATPase.

Shayantani Mukherjee
Department of Chemistry
University of Southern California

Biological motors are nano-scale machines of the cell that performs work utilizing chemical free energy harnessed from the noisy environment. The design principles of these motors have eluded a complete understanding of how information of the fluctuating environment is transferred and processed within the motor molecule, in order to change it into meaningful work that can be used by the living cell. Here, we will discuss the rotary motor F1-ATPase that powers unidirectional rotation of an embedded stalk by utilizing energy of ATP hydrolysis occurring in a chemical environment away from equilibrium. Structure based free-energy calculations of F1 rotation and chemical transformation reveal the way a biological protein molecule is capable of generating work and order from the underlying fluctuating environment. Parallels will be drawn with the "Maxwell's information demon" to elucidate the role of chemical state dependent gating, protein dynamics, and conformational flexibility in the overall thermodynamics and information processing of biological motors.

11:40 am – 12:20 pm: Strongly coupled systems, exact excess, and renormalized housekeeping

Paul Riechers
Department of Physics
University of California Davis

When a small but complex thermodynamic agent (such as a biological macromolecule) strongly couples with a structured stochastic environment, the joint interaction produces an emergent dynamic of non-Markovian transitions among the agent's nonequilibrium steady states induced by a particular environmental condition. We show that moments of the excess work and excess heat distributions can be calculated exactly, directly from the spectrum and projection operators of the transition rate operator of the joint dynamic. The average excess heat at one level of description becomes the additional housekeeping heat to maintain the next level of description. This framework naturally accommodates two-way feedback, highlighting the role of information transduction in the stochastic thermodynamics of biologically relevant continuous-time systems.

12:20 pm – 1:00 pm: Closing Remarks Followed by Lunch

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

3 Conference Venue and Maps

Conference will be held at:
Telluride Elementary School, 477 West Columbia Ave Telluride, CO

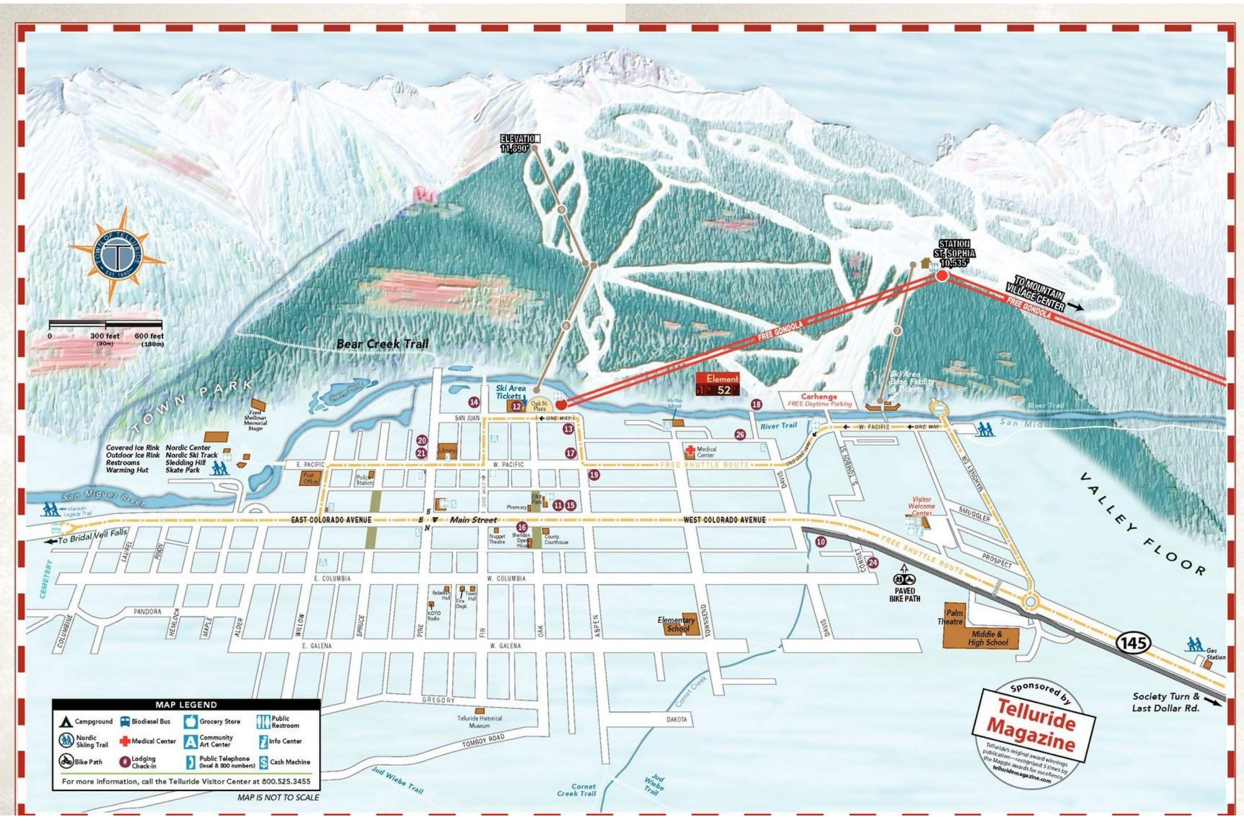

Figure 3.1: Map of the Town of Telluride

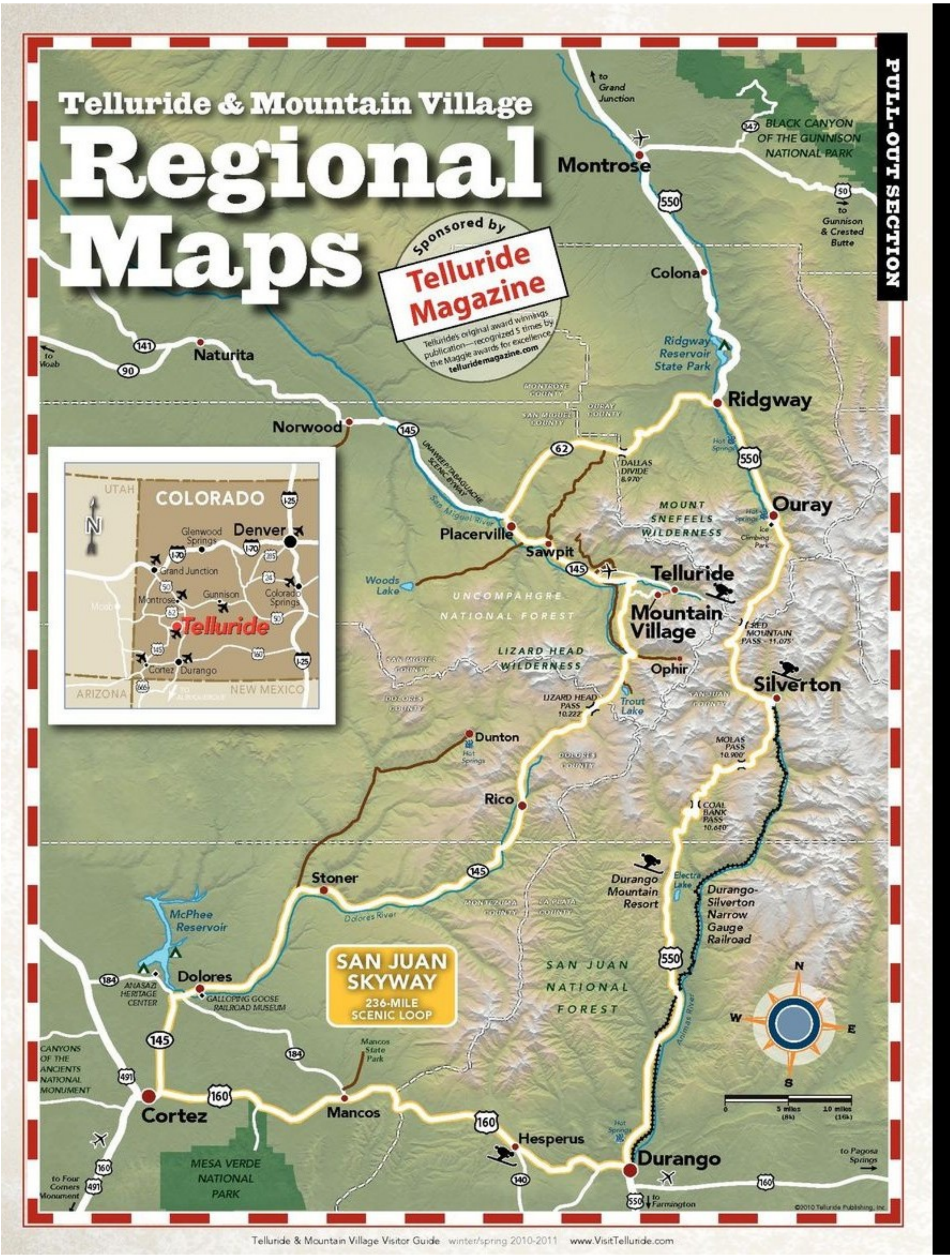

Figure 3.2: Regional Map

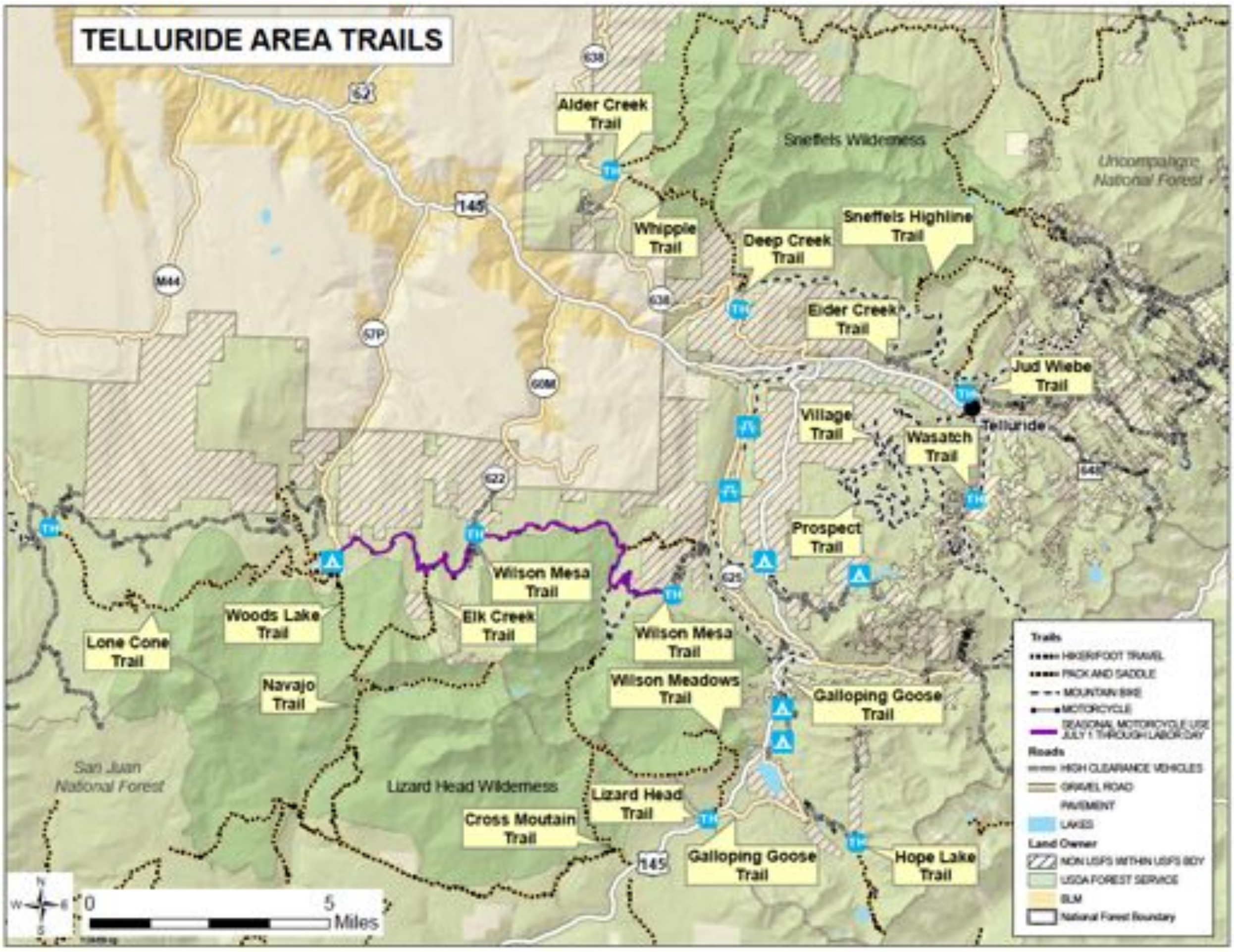

Figure 3.3: Telluride Area Trail Map