Information Engines at the Frontiers of Nanoscale Thermodynamics

Organizing Committee:
Fabio Anza
Korana Burke
James Crutchfield
Sebastian Deffner
Christopher Jarzynski

July 19 – July 28, 2023

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

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 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 and Stochastic 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

Practical information:

- The workshop is organized to stimulate discussion and sharing ideas. Intentionally, the schedule is relaxed, with talks only in the mornings. This leaves 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—events that bring us back together.
- Several useful area maps are provided at the end of this Program.
- The abstracts have been (roughly) sorted according to topics. There are sessions on *Information engines and Maxwell demons, Optimal Prediction, Quantum thermodynamics and quantum information, Nonequilibrium thermodynamics and statistical mechanics, and Control and Optimal Processes in Thermodynamics.*
- There are no sessions on Sunday, but the meeting rooms will be available.
- Breakfast will be served at the Telluride Intermediate School. However, there is **NO** breakfast on Sunday.
- The session chairs will observe the Frauenfelder rules:

  > Hans Frauenfelder introduced these to provide a guideline about successful ways 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 40 minutes, which leaves at least 20 minutes for discussion.

2.2 COVID-19 Guidelines

We are committed to making this workshop safe and enjoyable for all participants. We wish to be a vaccinated community. Please do your best to help us realize this.

We request that all participants get tested when they arrive and retest three days later.

If anyone tests positive and so misses the workshop, we will have ways for you to participate remotely.

This all said, we are not requiring participants to wear masks during our workshop, although you are welcome to do so! We do ask that you wear masks—preferably KN95 or N95—while on airplanes and in airports. This will reduce the risk of spreading COVID.

	Wednesday 07/19	Thursday 07/20	Friday 07/21	Saturday 07/22	Sunday 07/23	Monday 07/24	Tuesday 07/25	Wednesday 07/26	Thursday 07/27 (remote)	Friday 07/28
8:20	breakfast	breakfast	breakfast	breakfast		breakfast	breakfast	breakfast	breakfast	breakfast
9:00	Meet/Greet	Opening	**Anza**	**Poulton**		**Rahav**	**Wimsatt**	**Salamon**	**Boyd**	**Discussion**
10:00	Meet/Greet	**Crutchfield**	**Riechers**	**Jurgens**		**Anza**	**Pratt**	**Kolchinsky**	**Ray**	**Discussion**
11:00	coffee	coffee	coffee	coffee		coffee	coffee	coffee	coffee	coffee
11:20	Meet/Greet	**Semaan**	**Townsend**	**Upadhyaya**		**Green**	**Habermehl**	**Crutchfield**	**Miangolarra**	**Discussion**
									DeWeese	
12:20	lunch	lunch	lunch	lunch		lunch	lunch	lunch	lunch	lunch
									Deffner	
13:00										
14:00										
15:00										
16:00										
17:00										
17:30	TSRC bbq							TSRC bbq		
18:30	TSRC bbq						Town talk	TSRC bbq		
19:30	TSRC bbq							TSRC bbq		

Revised 23 July 2023

2.3 Wednesday July 19, 2022: Meet & Greet

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

Check-In and breakfast at the Telluride Intermediate School

9:00 am – 11:00 am: Introductions

Fabio Anza
James P. Crutchfield
Korana Burke

11:00 am – 11:20 am: Coffee break

11:20 am – 12:20 am: Round table and free discussions

Fabio Anza
James P. Crutchfield
Korana Burke

12:20 pm – 1:00 pm: Lunch

2.4 Thursday, July 20, 2023: Maxwellian demons

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

Check-In and breakfast at the Telluride Intermediate School

Session Chair: **FABIO ANZA**

9:00 am – 10:00 am: Opening

Fabio Anza
James P. Crutchfield
Korana Burke
Sebastian Deffner

10:00 am – 11:00 am: Information In & Between Complex Processes

James P. Crutchfield
University of California Davis

What foundations ground our understanding of biological sensory information processing? A constructive answer comes from appealing to dynamical systems and information theory. I will review the history of predictive equivalence in optimally predicting and minimally modeling complex processes. This includes analytical methods and statistical inference for estimating a process' randomness and structure and the natural semantics that arise. The complexity of neural spike trains and extreme weather events illustrate the breadth of applications. Adding energetics brings in thermodynamic transformations of complex processes and so maps between them—the domain of sensory information processing of stimulus and response. Predictive equivalence is relevant again and leads to optimal, minimal transducers—a foundational representation for biological sensory processing.

11:00 am – 11:20 am: Coffee break

11:20 am – 12:20 pm: First and Second Law of Information Processing

Mikhael Semaan
University of Utah

Autonomous Maxwellian ratchets are Maxwellian demons which can explicitly leverage correlations among information-bearing degrees of freedom to exchange thermodynamic resources; for example, to extract heat from a single bath and convert it to work, at the cost of modifying the values in a data tape. Previous studies have bounded this behavior in a variety of circumstances, deriving "information processing second laws" for the ratchet's functionality.

The steady-state surprisal of stochastic thermodynamics provides another concrete link between a ratchet's information-bearing and thermodynamic structure. By considering its average change (and rate thereof) under a given process, we uncover an information processing first law that extends—to strict equalities—various information processing second laws. We then show how stochastic thermodynamics' integral fluctuation theorems take the first law equality to second law inequalities, recovering previous results. Explicitly accounting for nonequilibrium steady states, however—effectively, affording us a greater variety of integral fluctuation theorems—reveals that these second laws can be further tightened, implying different functional thermodynamics compared to the equilibrium steady-state case.

In this talk, we will derive the information processing first and second laws and apply them to an example ratchet designed to tunably violate detailed balance in its effective dynamics. This explicates the quantitative and qualitative effects of nonequilibrium steady states on ratchet thermodynamic functionality. Finally, we will close with open questions which suggest exciting avenues for future inquiry.

12:20 pm – 1:00 pm: Lunch

2.5 Friday, July 21, 2022: Quantum information and thermodynamics

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Intermediate School

Session Chair: **KORANA BURKE**

9:00 am – 10:00 am: How local classicality emerges from global quantumness

Fabio Anza
University of Trieste & University of California, Davis

Classical mechanics emerges from quantum mechanics in the macroscopic and decoherent regime of an open quantum system interacting with a large environment. Aside specific models, the generic details of how this happens are not fully understood. Exploiting the information-theoretic definition of classicality of a quantum system provided by Quantum Darwinism, I will show that there is one and only one structure of a pure state of system+environment which is compatible with a quantum system exhibiting classicality: branching states. This work was done in collaboration with A. Touil, S. Deffner and J. Crutchfield.

A. Touil, F. Anza, S. Deffner, J.P. Crutchfield, Branching States as The Emergent Structure of a Quantum Universe, ArXiv:2208.05497

10:00 am – 11:00 am: Thermodynamically ideal quantum-state inputs to any device

Paul Riechers
Nanyang Technological University, Singapore

We investigate and ascertain the ideal inputs to any finite-time thermodynamic process. We demonstrate that the expectation values of entropy flow, heat, and work can all be determined via Hermitian observables of the initial state. These Hermitian operators encapsulate the breadth of behavior and the ideal inputs for common thermodynamic objectives. We show how to construct these Hermitian operators from measurements of thermodynamic output from a finite number of effectively arbitrary inputs. Behavior of a small number of test inputs thus determines the full range of thermodynamic behavior from all inputs. For any process, entropy flow, heat, and work can all be extremized by pure input states—eigenstates of the respective operators. In contrast, the input states that minimize entropy production or maximize the change in free energy are non-pure mixed states obtained from the operators as the solution of a convex optimization problem. Our examples illustrate the diversity of 'ideal' inputs: Distinct initial states minimize entropy production, extremize the change in free energy, and maximize work extraction.

11:00 am – 11:20 am: Coffee break

11:20 am – 12:20 pm: Rabi enhanced tunneling from solid-state spin qubits: a Lindblad equation for Rabi driven spins in tunneling contact with a reservoir

Emily Townsend
National Institute of Standards and Technology

Lindblad equations describe the dissipative dynamics of a quantum system interacting with a (typically larger and often memoryless) second system such as a thermal bath. When the system Hamiltonian is not time dependent a complete set of its eigenstates can be used as a basis for expanding the system-bath interaction Hamiltonian, and there is a standard method for obtaining a Lindblad equation by tracing over the bath. However, for a spin in a solid-state qubit, driving Rabi oscillations with an oscillating magnetic field yields a time-dependent system Hamiltonian, which mixes spin-up and spin-down states of the spin. If an electron experiencing this Rabi driving also has a weak tunneling contact to a nearby lead, there should be a Lindblad equation describing this driven-dissipative behavior. We have used the unitary time evolution operator that solves the Rabi problem, $U(t, t_0)$, to transform into the interaction picture with respect to the system Hamiltonian, which, along with typical assumptions about the bath and a secular approximation on products of pairs of different-time matrix elements (on elements of $U(t_1, t_0)U(t_0, t_2)$), gives a 4-dimensional matrix form of the Lindblad equation. Numerical solutions in the low temperature limit show that when driven on resonance, the average charge occupancy is reduced by a third compared to far off-resonance driving or undriven behavior. This implies that the resonant frequency can be measured by sweeping the driving frequency and monitoring the charge occupancy of the device.

2.6 Saturday, July 22, 2022: Optimal Prediction

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Intermediate School

Session Chair: **JAMES P. CRUTCHFIELD**

9:00 am – 10:00 am: Optimal prediction of a noisy signal

Jenny Poulton
AMOLF

Autonomous or self-perpetuating systems typically exist in dynamic environments. A general requirement for self-perpetuating systems to thrive in such environments is the ability to respond to changing conditions. Ideally, a system would make an instantaneous change to respond to an environmental change. In reality, mounting a response takes time. Given this, an optimal response requires systems to predict an environmental change. For many signals, the trajectory of the signal in the past will be predictive of its future behavior. Measuring this trajectory allows a system to predict future values of the signal.

Signal noise is an unavoidable feature of any signal detection process. It corrupts the signal at the point of detection, meaning that the detected signal is different from the actual signal. Systems use time averaging to mitigate signaling noise, but this brings its own challenges. Given the presence of signal noise, how accurately can a system estimate the current value of a signal? Additionally, how well can a system predict the future value of a signal?

For a system to predict the future, it must extract characteristics of a noisy signal trajectory that are informative of the future. In this talk we will discuss these characteristics, consider what makes a sensor optimal for predicting the future, and ask whether extant biological signal processing motifs use similar strategies.

10:00 am – 11:00 am: Finite and Infinite Models: Optimal Prediction of Hidden Markov Processes

Alexandra Jurgens
INRIA Bordeaux

Even simply defined, finite-state generators produce stochastic processes that require tracking an uncountable infinity of probabilistic features for optimal prediction. For processes generated by hidden Markov chains, the consequences are dramatic. Their optimal predictive models, known as epsilon machines, are generically infinite state. Until recently, one could determine neither their intrinsic randomness nor structural complexity. However, new methods have been developed to accurately calculate the Shannon entropy rate (randomness) and to constructively determine their minimal set of predictive features. We also address the complementary challenge of determining how structured hidden Markov processes are by calculating their statistical complexity dimension—the information dimension of the minimal set of predictive features. This introduces a scaling law for the minimal memory resources required to optimally predict a broad class of truly complex processes.

11:00 am – 11:20 am: Coffee break

11:20 am – 12:20 pm: Non-Abelian transport distinguishes three usually equivalent notions of entropy production

Twesh Upadhyaya
University of Maryland, College Park

We extend entropy production to a deeply quantum regime involving noncommuting conserved quantities. Consider a unitary transporting conserved quantities ("charges") between two systems initialized in thermal states. Three common formulae model the entropy produced. They respectively cast entropy as an extensive thermodynamic variable, as an information-theoretic uncertainty measure, and as a quantifier of irreversibility. Often, the charges are assumed to commute with each other (e.g., energy and particle number). Yet quantum charges can fail to commute. Noncommutation invites generalizations, which we posit and justify, of the three formulae. Charges noncommutation, we find, breaks the formulae's equivalence. Furthermore, different formulae quantify different physical effects of charges' noncommutation on entropy production. For instance, entropy production can signal contextuality-true nonclassicality-by becoming nonreal. This work opens up stochastic thermodynamics to noncommuting-and so particularly quantum-charges.

12:20 pm – 1:00 pm: Lunch

2.7 Sunday, July 23, 2022: Free day

No program, no breakfast or lunch.

2.8 Monday, July 24, 2022: Optimal Processes in Thermodynamics

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Intermediate School

Session Chair: **KORANA BURKE**

9:00 am – 10:00 am: Singular optimal solutions of periodically driven molecular machines

Saar Rahav
Technion - Israel Institute of Technology

The investigation of optimal processes has a long history in the field of thermodynamics. It is well known that finite-time processes that minimize dissipation often exhibit discontinuities. We use a combination of numerical and analytical approaches to study the driving cycle that maximizes the output in a simple model of a stochastic pump: a system driven out of equilibrium by a cyclic variation of external parameters. We find that this optimal solution is singular since it alternates between two configurations at a diverging rate. The appearance of such a singular optimal solution in a thermodynamic process is surprising. Nevertheless, we argue that such solutions are expected to be quite common in models whose dynamics exhibit exponential relaxation, as long as the driving period is allowed to be arbitrarily short. Our results may have implications for the design of artificial molecular motors that are driven by a cyclic variation of parameters.

10:00 am – 11:00 am: The Eigenstate Thermalization Hypothesis: A Review

Fabio Anza
University of Trieste & University of California, Davis

A simple review of the quantum Eigenstate Thermalization Hypothesis that attempts to describe the process of thermodynamic relaxation in quantum systems.

11:00 am – 11:20 am: Coffee break

11:20 am – 12:20 pm: Statistical-mechanical speed limits on dissipation

Jason Green
University of Massachusetts Boston

Physical systems powering motion or creating structure in a fixed amount of time dissipate energy and produce entropy. An outstanding challenge is to understand how this tension between dissipation and speed emerges from classical, chaotic dynamics. I will discuss our recent progress in coupling nonlinear dynamics and statistical physics with a classical density matrix theory [1] and statistical mechanical speed limits [2,3]. These bounds connect the geometries of phase space and information [4] to constrain the relationship between dissipation and time for systems away from equilibrium.

[1] Density matrix formulation of dynamical systems, S. Das, J. R. Green, Phys. Rev. E 2022 106(5)

[2] Speed limits on deterministic chaos and dissipation, S. Das, J. R. Green, Phys. Rev. Res. 2023 5(1)
[3] Maximum speed of dissipation, S. Das, J. R. Green, ArXiv:2305.12047
[4] Classical Fisher information for differentiable dynamical systems, M. Sahbani, S. Das, J. R. Green, ArXiv:2307.00026

12:20 pm – 1:00 pm: Lunch

2.9 Tuesday, July 25, 2022: Nonequilibrium thermodynamics and statistical mechanics I

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Intermediate School

Session Chair: **JAMES CRUTCHFIELD**

9:00 am – 10:00 am: Trajectory Class Fluctuation Theorem for Events of Zero and Nonzero Probability

Gregory Wimsatt
University of California, Davis

The Trajectory Class Fluctuation Theorem (TCFT) has provided equalities between thermodynamic quantities and a wide variety of informational coarse grainings on nonequilibrium processes. But the TCFT has been limited to coarse grainings corresponding to nonzero-probability events. We have strengthened it via an emphasis on measure theory to apply to events of even zero probability. The TCFT now spans the most detailed to the coarsest levels of description. As examples of this breadth, we recover from the TCFT Jarzynski's Equality, Crooks' Detailed Fluctuation Theorem, and Crooks' Work Fluctuation Theorem.

10:00 am – 11:00 am: Nanoscale Dynamical Computing: Superconducting Circuits for Thermodynamically-Efficient Classical Information Processing

Christian Pratt
University of California, Davis

Alternative nondiscrete computing paradigms open the door to exploiting recent innovations in computational hardware. Dynamical computing is one such paradigm that synthesizes momentum computing—an extremely energy-efficient design framework—with nanoscale thermodynamic computing. We demonstrate how this synthesis can be implemented with Josephson junction technology. Investigating the dynamics and thermodynamics of superconducting quantum interference devices (SQUIDs), though, requires (i) constructing physically-realizable superconducting circuits, (ii) thoroughly understanding circuit energetics, and (iii) designing sufficiently complex circuits that support a suite of useful operations. Historically, first-principle circuit design led to prohibitive algebraic complications that precluded achieving these goals. We show how to circumvent these complications by (i) extending time-dependent flux quantization methods, (ii) implementing solution-finding optimizations that facilitate physically interpreting circuit degrees of freedom, and (iii) respecting physically-grounded constraints. Practically, this leads to more efficient circuit prototyping and analysis and access to more general and scalable circuit architectures. The analytical efficiency is demonstrated by directly reproducing the thermodynamic potential induced by the variable β rf (vβ-rf) SQUID. We then show how to inductively couple two vβ-rf SQUIDs to construct a device capable of performing 2-bit computations.

11:00 am – 11:20 am: Coffee break

11:20 am – 12:20 am: Physical Computation: Realizing analog computation with nonlinear NEMS oscillators

Scott Habermehl
California Institute of Technology

Networks of coupled nonlinear oscillators exhibit complex spatiotemporal dynamics which are fundamental to the operation of numerous natural and engineered systems, ranging from the human brain to the North American power grid. However, current laboratory experiments for studying these systems lack the necessary rigor for a deep exploration of the parameter space and, thus, have only examined a tiny slice. Our group is currently building an experimental network of 8 nonlinear oscillators with highly controllable nodes (oscillators) and edges (couplings). In this talk, I will briefly review the underlying technology, nano-electro-mechanical systems (NEMS), and its nanoscale physics. Then, I will discuss our efforts to combine oscillators networks, the tools of dynamical systems theory, and machine learning to understand how complex nonlinear systems are able to process information. In particular, we use Lyapunov exponents to analyze the computational performance of reservoir computers based on oscillator networks. Finally, I will conclude by discussing some of the challenges involved in building real-world networks and utilizing them for reservoir computing.

12:20 pm – 1:00 pm: Lunch

6:00 pm – 7:00 pm: TSRC Town talk *Imaging the True Colors of Cancer* Cash bar at 5:30 pm.

2.10 Wednesday, July 26, 2022: Nonequilibrium thermodynamics and statistical mechanics II

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Intermediate School

Session Chair: **FABIO ANZA**

9:00 am – 10:00 am: Steppingstones for thermodynamic relaxation

Peter Salamon
University of California, San Diego

We analyze a problem that arises when considering sequential relaxations of a thermodynamic system. The problem builds on the observation that adding a new relaxation step by braking a previous step into two, always decreases the dissipation, provided only that the inserted state be in-between the start and end points of the step being divided. What this observation forces is a definition of what it means to be in-between, i.e. to be a steppingstone. We say that a state R is in-between two states P and Q provided the two-step relaxation P $\rightarrow$ R followed by R $\rightarrow$ Q produces less entropy than the one step relaxation P $\rightarrow$ Q. For small relaxations, where the entropy production equals the distance squared over two, all points inside the $(n-1)$-sphere with PQ as a diameter are steppingstone states, i.e. relaxing to one of them, even partially, will reduce the entropy production of the relaxation from P to Q. This is illustrated in Figure 1, whose inset also shows the pie-in-the-sky version which seeks the various possible steppingstone routes through metabolic pathways.

10:00 am – 11:00 am: Information geometry for nonequilibrium processes

Artemy Kolchinski
University of Tokyo

The geometry of thermodynamic states has played an important role in classical thermodynamics, for instance for studying equilibrium fluctuations and optimal near-equilibrium protocols. However, this geometry is only thermodynamically meaningful in systems that relax toward equilibrium. For this reason, it is not applicable to genuine nonequilibrium processes, which are driven by non-conservative forces and relax toward nonequilibrium steady states, limit cycles, or chaos. In this work, we propose a thermodynamic geometry appropriate for genuine nonequilibrium processes, whether described by a linear master equation or a nonlinear rate equation. Specifically, we study the information geometry of the dynamic fluxes (nonnegative quantities which represent transport of matter), rather than the geometry of thermodynamic states. Our formulation leads to new thermodynamic uncertainty relations and speed limits, new techniques for thermodynamic inference, and new decompositions of EP. As a particular application, we discuss a new universal decomposition of EP into "excess" and "housekeeping" components, which represent the contributions from conservative and nonconservative forces respectively.

11:00 am – 11:20 am: Coffee break

11:20 am – 12:20 am: Information In & Between Complex Processes Redux

James P. Crutchfield
University of California Davis

What foundations ground our understanding of biological sensory information processing? A constructive answer comes from appealing to dynamical systems and information theory. I will review the history of predictive equivalence in optimally predicting and minimally modeling complex processes. This includes analytical methods and statistical inference for estimating a process' randomness and structure and the natural semantics that arise. The complexity of neural spike trains and extreme weather events illustrate the breadth of applications. Adding energetics brings in thermodynamic transformations of complex processes and so maps between them—the domain of sensory information processing of stimulus and response. Predictive equivalence is relevant again and leads to optimal, minimal transducers—a foundational representation for biological sensory processing.

12:20 pm – 1:00 pm: Lunch

5:30 pm – 7:30 pm: TSRC BBQ

2.11 Thursday, July 26, 2022: Remote Talks

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Intermediate School

Session Chair: **FABIO ANZA**

9:00 am – 9:40 am: Qunifilarity: Classically Predictable Quantum Processes

Alec Boyd
Trinity College

A string of quantum bits, read from past to future, forms a type of quantum process. We show that if such a process has zero discord from past to future, then there exists a qunifilar generator of the process, which is a quantum generalization of a unifilar epsilon-machine. The entropy rate and excess entropy of the process can be exactly calculated from the qunifilar generator. Moreover, the generator can be used to design a thermodynamically efficient information engine that harvests all available free energy from the process using only classical memory. We establish an equivalence between qunifilarity, zero discord, and the existence of an efficient information engine. However, due to the asymmetry of discord, we see that there are quantum processes that can be optimally predicted from past to future but not in reverse order.

9:40 am – 10:00 am: Group picture and Coffee break

10:00 am – 10:40 am: The Thermodynamic Uncertainty Theorem

Kyle Ray
University of California, Davis

Thermodynamic uncertainty relations (TURs) express a fundamental lower bound on the precision (inverse scaled variance) of any thermodynamic charge—e.g., work or heat—by functionals of the average entropy production. Relying on purely variational arguments, these inequalities can be extended to analyze the impact of higher statistical cumulants of the entropy production itself within the general framework of time-symmetrically controlled computation. This perspective yields an exact expression for the charge that achieves the minimum scaled variance, for which the TUR bound tightens to an equality: the Thermodynamic Uncertainty Theorem (TUT). Importantly, both the minimum scaled variance charge and the TUT are functionals of the stochastic entropy production, thus retaining the impact of its higher moments. I will briefly explain how to derive the theorem and show, by example, several features that distinguish the TUT from previous TUR bounds.

10:40 am – 11:00 am: Coffee break

11:00 am – 11:40 am: Minimal entropy production in the presence of anisotropic fluctuations: an Optimal Mass Transport perspective

Olga Movilla Miangolarra
University of California, Irvine

Anisotropy in temperature, chemical potential, or ion concentration, provides the fuel that feeds dynamical processes that sustain life. At the same time, anisotropy is a root cause of incurred losses manifested as entropy production. In this talk, we consider a rudimentary model of an overdamped stochastic thermodynamic system in an anisotropic temperature heat bath, and study minimum entropy production when driving the system between thermodynamic states in finite time. While minimal entropy production in isotropic temperature environments can be expressed in terms of the length (in the Wasserstein W-2 metric) traversed by the thermodynamic state of the system, anisotropy complicates the mechanism of entropy production substantially since, besides dissipation, seepage of energy between ambient anisotropic heat sources by way of the system dynamics is often a major contributing factor. We show that in the presence of anisotropy, minimization of entropy production can once again be expressed via a modified Optimal Mass Transport (OMT) problem. However, in contrast to the isotropic situation that leads to a classical OMT problem and a Wasserstein length, entropy production may not be identically zero when the thermodynamic state remains unchanged unless one has control over non-conservative forces.

11:40 am – 12:20 am: Time-Asymmetric Protocol Optimization for Efficient Free Energy Estimation

Micheal DeWeese
University of California, Berkeley

The free-energy difference ΔF between two high-dimensional systems is an important yet computationally difficult quantity to compute. We demonstrate that the microscopic fluctuation theorem for an unconventional definition of work introduced by Vaikuntanathan and Jarzynski (2008) connects path ensembles that are driven by protocols unequal under time-reversal, allowing us to use a low-variance Bennett acceptance ratio ΔF estimator on bi-directional measurements from time-asymmetric processes. It has been shown before that counterdiabatic protocols give zero-variance work measurements for this definition. Motivated by this, we propose an on-the-fly adaptive importance sampling policy optimization algorithm that iteratively improves the efficiency of the time-asymmetric protocols. This algorithm requires minimal computational overhead, and uses all the samples collected in previous iterations to (1) update the protocol, and (2) provide a ΔF estimate. We test our algorithm on three models of varying complexity, finding that with just 1000 bi-directional work samples our algorithm yields ΔF estimates that are $\sim 100 - 10000$ times lower in mean squared error than the linear interpolation protocol with which it was initialized.

12:20 pm – 1:30 pm: Lunch

1:30 am – 2:10 pm: Quantum stochastic thermodynamics of relativistic systems

Sebastian Deffner
Department of Physics, University of Maryland, Baltimore County, Baltimore, MD 21250, USA

Physical scenarios that require a relativistic treatment are ubiquitous in nature, ranging from cosmological objects to charge carriers in Dirac materials. Interestingly, most of these situations have in common that the corresponding systems evolve very far from thermal equilibrium. Therefore, if and how the framework of stochastic thermodynamics applies at relativistic energies is a salient question. In this talk, I will survey our recent results on extending central notions of stochastic thermodynamics, such as fluctuation theorems and endoreversible heat engines, to classical as well as quantum dynamics at relativistic energies.

1. S. Deffner and A. Saxena, Phys. Rev. E 92, 032137 (2015)
2. S. Deffner, New J. Phys. 18, 012001 (2016)
3. A. Bartolotta and S. Deffner, Phys. Rev. X 8, 011033 (2018)
4. P. S. Pal and S. Deffner, New J. Phys. 22, 073054 (2020)
5. N. M. Myers, O. Abah, and S. Deffner, New J. Phys. 23, 105001 (2021)
6. E. E. Ferketic and S. Deffner, EPL (Europhys. Lett) 141, 19001 (2023)

2.12 Friday, July 27, 2022: Discussions

8:20 am – 9:00 am: Breakfast at TSRC

Breakfast at the Telluride Intermediate School

Session Chair: **KORANA BURKE**

9:00 am – 11:00 am: Scientific Ethics

11:00 am – 11:20 am: Coffee break

11:20 am – 12:20 pm: Discussion

12:20 pm – 1:00 pm: Lunch

3 Conference Venue and Maps

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

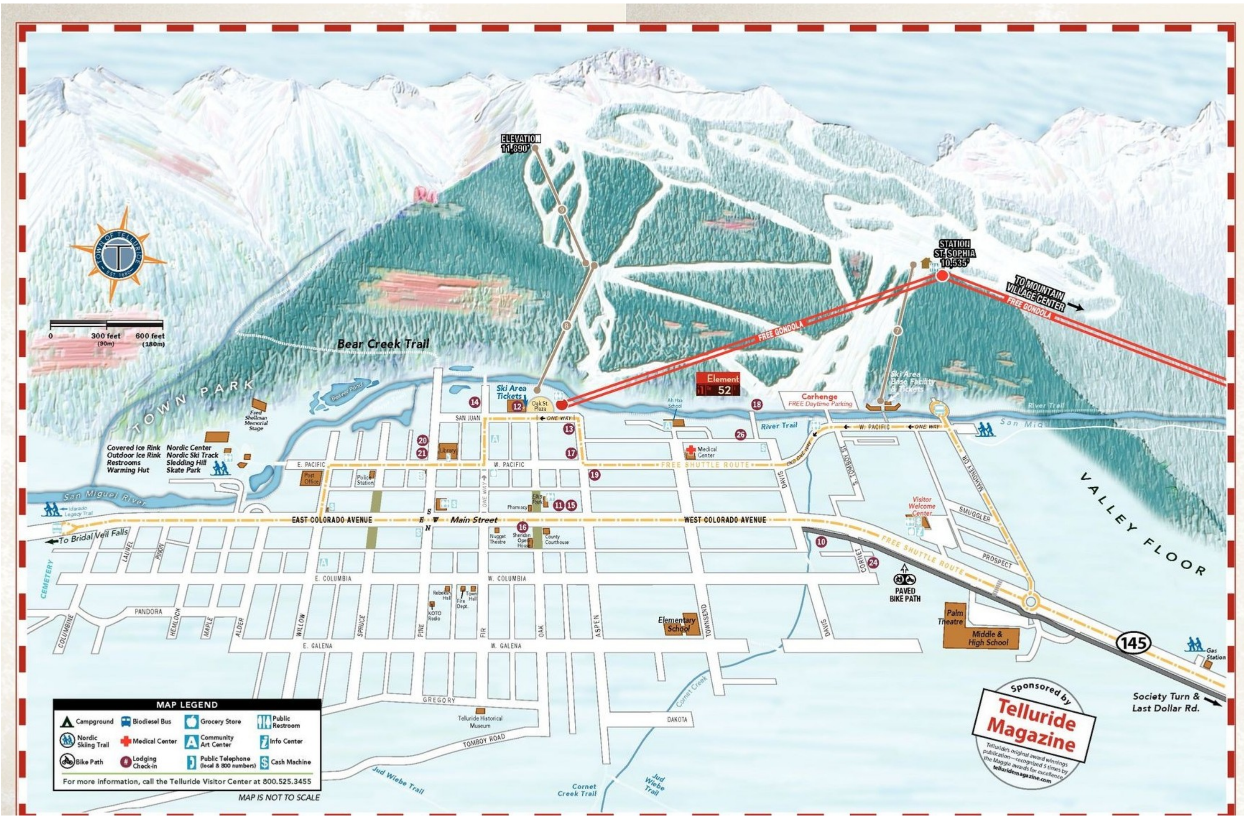

Figure 3.1: Map of the Town of Telluride

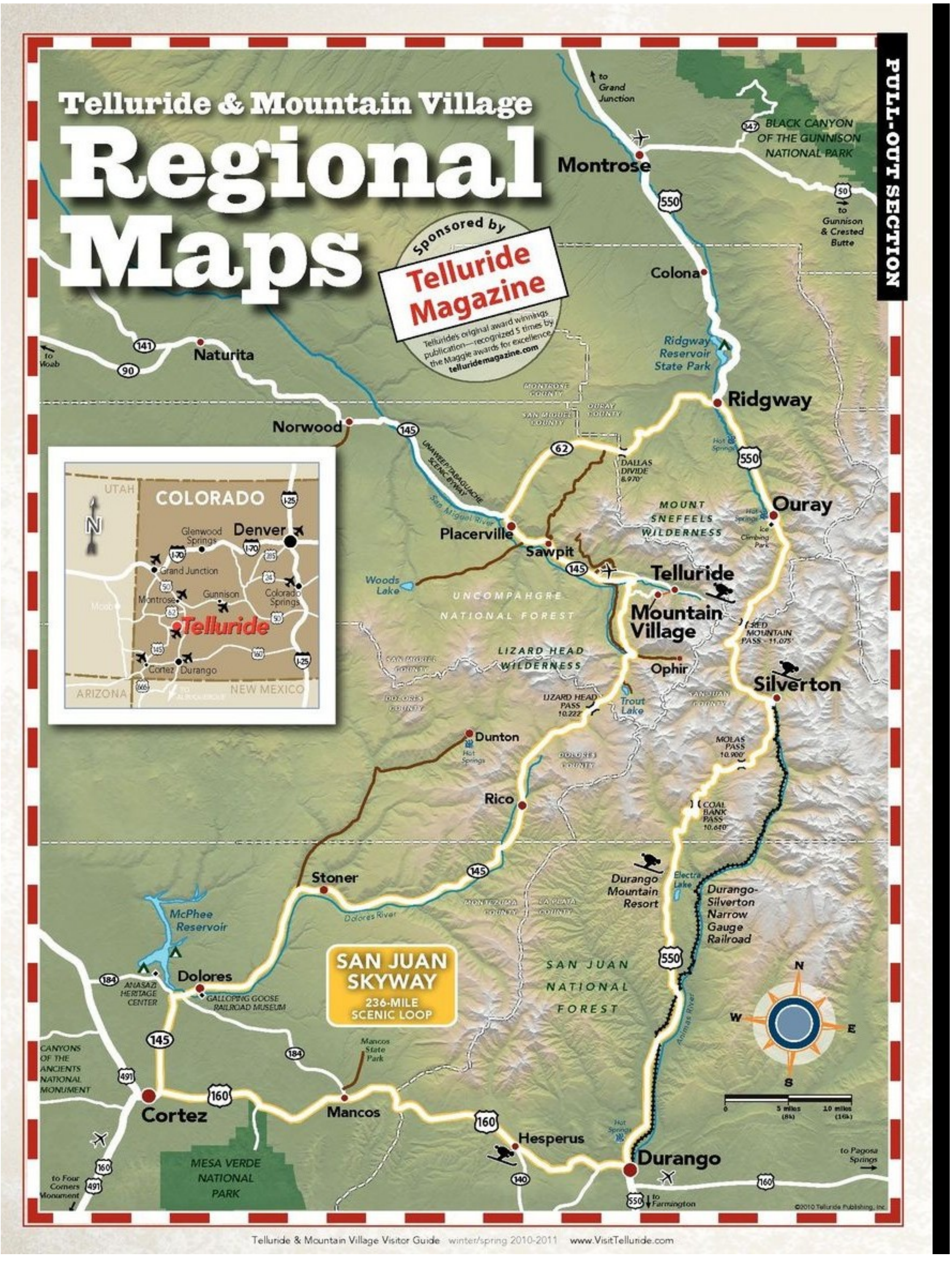

Figure 3.2: Regional Map

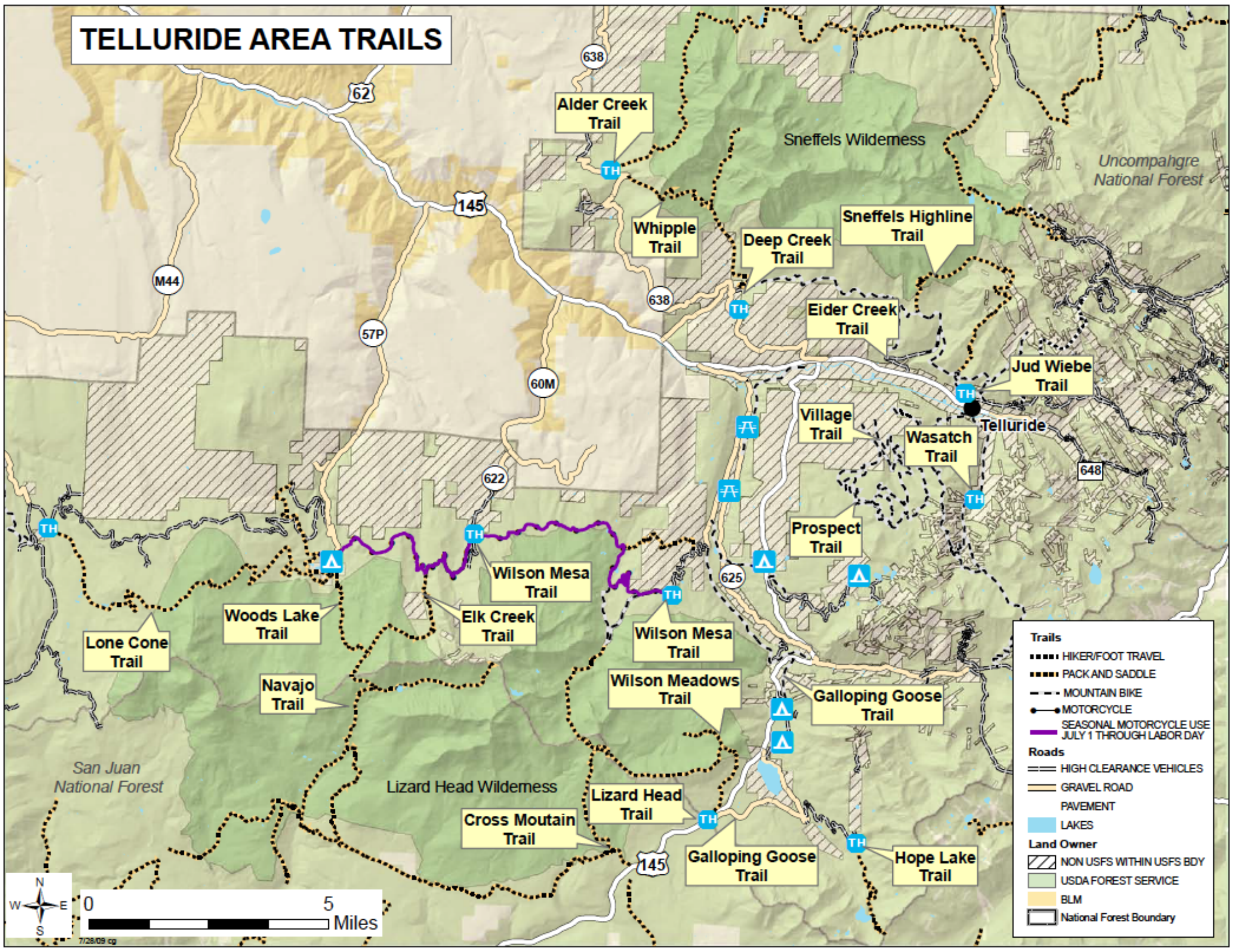

Figure 3.3: Telluride Area Trail Map