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Information Engines: Nanoscale Control, Computing, and Communication out of Equilibrium (Summary Technical Report, Sep 2013–Aug 2019)

by Dean Culver

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Information Engines: Nanoscale Control, Computing, and Communication out of Equilibrium (Summary Technical Report, Sep 2013–Aug 2019)

Dean Culver

Army Research Office, DEVCOM Army Research Laboratory

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14. ABSTRACT The FY13 Multidisciplinary University Research Initiative (MURI) effort titled “Information Engines: Nanoscale Control, Computing, and Communication out of Equilibrium,” led by Prof James Crutchfield at the University of California, Davis, was active from 1 September 2013 to 31 August 2019. The objective of the effort was to develop a unified framework for understanding, designing, and implementing micron-scale and nanoscale information-processing engines and to provide the scientific foundation for future nanoscale devices with groundbreaking capabilities.					
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1. Summary

The Multidisciplinary University Research Initiative (MURI) effort titled “Information Engines – Nanoscale Control, Computing, and Communication out of Equilibrium” led by Prof James Crutchfield at the University of California, Davis, was active from 1 September 2013 to 31 August 2019. The objective of the effort was to develop a unified framework for understanding, designing, and implementing micron-scale and nanoscale information-processing engines and to provide the scientific foundation for future nanoscale devices with groundbreaking capabilities. These ambitious goals were met and, in several cases, exceeded as attested by the project’s marked productivity (see <http://informationengines.org>, link:Research). These successes opened up a number of exciting future theoretical and experimental research avenues. The main efforts successfully developed methods to control nanoscale thermodynamic processes and, perhaps most importantly, culminated in successful detailed experimental tests and verifications of the team’s theoretical results. That said, looking beyond this MURI, much remains to do, and the core PI team continues to collaborate and make progress beyond the Information Engines MURI.

Any given natural process can be viewed in two complementary and equally valid ways: first, as a “physical” system that is controlled by, manipulates, stores, and dissipates energy and, second, as a “dynamical” system that generates, stores, transforms, and destroys information. When considering it and its physical implementation as a unitary system, we see that information processing requires energy to drive it forward. An immediate result is that this energy is not completely transformed into processed information. Energy is dissipated. Such limitations dominate on the nanoscale, in particular, where fluctuations out of equilibrium are the rule, and the distinction between organized and thermal energy, between heat and work, becomes ambiguous. The MURI’s principal goal, therefore, was to find the physical limits of nanoscale information processing and control.

The MURI team was led by Prof James Crutchfield at the University of California, Davis, with the following additional team members: Prof Michael DeWeese at the University of California, Berkeley; Prof Henry Hess at Columbia University; Prof Christopher Jarzynski at the University of Maryland at College Park; Prof PS Krishnaprasad at the University of Maryland at College Park; and Prof Michael Roukes at the California Institute of Technology. Total funding for the effort was \$6.88M. Project details are outlined in Appendix A, and the Final Report is presented as Appendix B.

The Information Engines MURI led to major advances in controlling nanoscale thermodynamic systems and in determining the thermodynamic constraints on nanoscale information processing. In parallel, the MURI's flux-qubit information-engine devices were extensively experimented on. The experimental results successfully validated key aspects of our theoretical predictions. The flux-qubit device was demonstrated to be markedly more appropriate for the project's goals than either the original molecular motor or nanoelectromechanical systems.

2. Overview of Results

This MURI was broken up into three primary thrusts: 1) control of nanoscale thermodynamic systems, 2) principles of information and thermodynamics, and 3) nanoscale information engines experiments. Results for each of these thrusts are summarized below.

Control of Nanoscale Thermodynamic Systems: Bringing together methods of geometric optimal control theory and nonequilibrium statistical physics, instantiated in concrete problems of designing working cycles for heat engines, has been a major goal of this part of the MURI project. The University of California Davis (UCD) and University of Maryland (UMD) teams focused on one of three previously developed approaches to controlling nanoscale thermodynamics systems: counterdiabatic control protocols for information processing tasks. Addressing very practical trade-offs in computing, counterdiabatic protocols provide finite-time “short-cuts” to what otherwise are adiabatic control protocols that require infinite time.

Principles of Information Thermodynamics: UCD determined the costs of thermodynamic controller's modular organization—the modularity dissipation—the first time thermodynamic costs have been associated with a system's structure and organization. This advances the team's suite of theoretical results to a design methodology for nanoscale devices with net positive thermodynamic benefit and, critically, it laid the foundation for an extensive suite of experimental tests that continue on under other projects.

Nanoscale Information Engines Experiments: Due to key theoretical insights, the flux qubit became the main experimental focus. In the process, UCD-Caltech discovered new ways—called the trajectory-class fluctuation theorems—to diagnose success and failure modes of microscopic behaviors that support information processing using the mesoscopic “observable” of the distribution of works expended over a repeated protocol.

The Information Engines MURI's productivity was sustained at a high level, indicating an intellectual maturation as the teams overcame previous theoretical and experimental challenges. The results were disseminated rather widely. This included over 100 manuscripts in peer-reviewed, high-profile journals.

3. Next Steps

The subjects and results of this MURI have accumulated attention in various DoD research laboratories and industrial partners. Specifically, advancements spearheaded by the Krishnaprasad lab have ignited a partnership with the Naval Research Laboratory modeling collective behavior in unmanned aerial and marine systems. Dr Krishnaprasad also engaged with DEVCOM Army Research Laboratory intramural researcher Dr Adam Svenkenson to develop a collaboration concerning theoretical foundations of modeling and controlling swarm behavior as well as phase transitions between individual agents and swarms. Finally, the MURI team has engaged with both Northrop Grumman and Ford in an effort to advance machine learning applied to control in noisy systems. Each lab has more specific steps forward, summarized in the following paragraphs.

Dr Crutchfield's newest efforts will merge novel theory on the thermodynamics of information engines and information ratchets with the experimental realizations developed by the Caltech team. This thrust will answer foundational questions on the limits, trade-offs, and capabilities of information engines in terms of fluctuations and large deviations from the thermodynamic functioning. Additionally, it will probe thermodynamic costs of modularity.

Dr Roukes and his team will pursue development of onboard bolometric thermodynamic measurements; a variety of structures based on both epitaxial Al/InAs (aluminum and indium arsenide, a common semiconductor) and single-layer graphene have already been designed and fabricated. The lab is performing calorimetric measurements to detect quantum transitions through the local heat bath. Construction of prototype calorimeters using superconducting-semiconducting-superconducting junctions to restrict the number of electron states to achieve very small energy resolutions is underway. Currently, the Roukes group is in the process of having these junctions grown (via epitaxy) in collaboration with the Palmstrom group at UC Santa Barbara and the Nadj-Perge group at Caltech. Designs that are compatible with bolometric measurements of classical logic erasure are underway. Caltech plans on performing thermodynamic measurements of quantum processes immediately following measurements of the classical counterparts.

Appendix A. W911NF1310390 Project Details

This appendix appears in its original form, without editorial change.

W911NF1310390: Information Engines, Nanoscale Control, Computing, and Communication out of Equilibrium

Reporting Period: SEP 01, 2013 to AUG 31, 2018

Date Received:

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Major Goals

The Information Engines MURI's original goal was to develop a unified framework for understanding, designing, and implementing micron-scale and nanoscale information-processing engines and to provide the scientific foundation for future nanoscale devices with groundbreaking capabilities. These ambitious goals were met and, in several cases, exceeded as attested by the project's marked productivity; see <http://informationengines.org> ==> Research. These successes opened up a number of exciting future theoretical and experimental research avenues. The main efforts successfully developed methods to control nanoscale thermodynamic processes and, perhaps most importantly, culminated in successful detailed experimental tests and verifications of our theoretical results. That said, looking beyond this MURI, much remains to do and the core PI team continues to collaborate on and extend the Information Engines MURI's progress. Putting the accomplishments in broad perspective, let's briefly review the overall project goals.

Any given natural process can be viewed in two complementary and equally valid ways: First, as a "physical" system that is controlled by, manipulates, stores, and dissipates energy and, second, as a "dynamical" system that generates, stores, transforms, and destroys information. When considering it and its physical implementation as a unitary system, we see that information processing requires energy to drive it forward. An immediate result is that this energy is not completely transformed into processed information. Energy is dissipated. Such limitations dominate on the nanoscale, in particular, where fluctuations out of equilibrium are the rule and the distinction between organized and thermal energy, between heat and work, becomes ambiguous. The MURI's principle goal, therefore, was to find the physical limits of nanoscale information processing and control. To this end, the MURI pursued a set of interdependent tasks:

Task 1: Intrinsic Computation in Nanoscale Substrates: Develop concepts and mathematical tools that identify how dynamical processes store and transform information.

Task 2: Nonequilibrium Information Processing by Nanoscale Machines: Develop thermodynamic and statistical mechanical principles that govern the operation of information engines and then synthesize these with the tools of intrinsic computation from Task 1.

Task 3: Control and Optimization at the Nanoscale: Integrate methods of geometric optimal control theory and nonequilibrium statistical physics, instantiating the synthesis in concrete control problems posed by information engines.

Task 4: Validation: Optimal, Controllable Nanoscale Information Processing Agents: Develop experimental platforms with which to test the information-engines thermodynamic principles developed in Tasks 1, 2, and 3. These came to include nanoelectromechanical systems (NEMS) and flux qubits.

The long-term scientific challenges, implicit in Tasks 1 – 3, were not only to pioneer theoretical foundations, but to also establish a research community in information engines. Looking back over the MURI's seven-year extended existence, there are two notable accomplishments on this score. The first is the annual workshop series on Information Engines at the Frontiers of Nonequilibrium Thermodynamics, co-organized by the Lead PI, held each summer at the Telluride Science Research Center, and sponsored by ARO; except in 2020 due to the pandemic. In lieu of an in-person workshop the co-organizers and past participants are assembling a special issue on Thermodynamic Computing with Information Engines for the well-known Journal of Statistical Physics.

The second is that the MURI's successes catalyzed the emergence of information engines as signaling the dawn of a new era of thermodynamic computing or, as we have come to frame it, low-kBT computing. The initial experimental successes and rapidly progressing theory led the Computing Community Consortium (CCC) in January 2019 to initiate a broad planning effort to develop this new paradigm, whose charge is to actively leverage and control inherent fluctuations in physical information-processing substrates. Note that in the 1990s and 2000s, CCC was a key convener for research in quantum computing, among many other nascent information technologies. The current CCC effort is destined to play a similar guiding role for thermodynamic computing. Its report on Thermodynamic Computing is found at <https://arxiv.org/abs/1911.01968>. For those interested in delving beyond this Summary Technical Report, we strongly recommend the CCC report as it paints a broad and bold picture of the path forward from this MURI.

Synopsis of Goals

The Information Engines MURI's led to major advances in controlling nanoscale thermodynamic systems and in determining the thermodynamic constraints on nanoscale information processing. In parallel, the MURI's flux-qubit information-engine devices were calibrated and extensively experimented on. The experimental results successfully validated key aspects of our theoretical predictions and led to new theoretical advances—e.g., the trajectory-class fluctuation theorems. The flux-qubit device was demonstrated to be markedly more appropriate for the project's goals than either the original molecular motor and NEMS systems. The following highlights our results.

- A. Control of Nanoscale Thermodynamic Systems: Bringing together methods of geometric optimal control theory and nonequilibrium statistical physics, instantiated in concrete problems of designing working cycles for heat engines, has been a major goal of this part of the MURI project. The UCD-UMD teams focused on one of our three previously-developed approaches to controlling nanoscale thermodynamic systems: counterdiabatic control protocols for information processing tasks. Addressing very practical trade-offs in computing, counterdiabatic protocols provide finite-time “shortcuts” to, what otherwise are, adiabatic control protocols that require infinite time.
- B. Principles of Information Thermodynamics: UCD determined the costs of thermodynamic controller's modular organization—the modularity dissipation—the first time thermodynamic costs have been associated with a system's structure and organization. This advances our suite of theoretical results to a design methodology for nanoscale devices with net positive thermodynamic benefit. And, critically, it laid the foundation (See Table I in the CCC report) for an extensive suite of experimental tests that continue on under other projects.
- C. Nanoscale Information Engines Experiments: Due to key theoretical insights, the flux qubit became the main experimental focus. In the process, UCD-Caltech discovered new ways—called the trajectory-class fluctuation theorems—to diagnose success and failure modes of microscopic behaviors that support information processing using the mesoscopic “observable” of the distribution of works expended over a repeated protocol.

Overall, the MURI was remarkably productive with well over 100 peer-reviewed published articles. Most all are available through arXiv.org and the project website: <http://informationengines.org>. Importantly, 13 appeared in physics' top journals: 6

in Physical Review X and 7 in Physical Review Letters. Thus, the MURI's efforts were recognized at the highest levels and had substantial impact.

Administratively, the Information Engines MURI (#W911NF-18-1-0340) complements the Lead PI's ARO project Functional Pattern Formation in Thermodynamical Systems (#W911NF-18-1-0028). The latter started in 2018 and focuses on spatially-extended engines with the unique goal of tracking the flow of thermodynamic resources.

Accomplishments Under Goals

(Citations are in the Bibliography, which is part of the Final Report in Appendix B.)

PI Crooks: Continued his signature geometric approach to thermodynamic control and also contributed fundamental theoretical work on strongly coupled thermodynamic subsystems:

1. Thermodynamic geometry of minimum dissipation driven barrier crossing [GEC1].
2. Near optimal protocols in complex nonequilibrium transformations [GEC2].
3. Geometric approach to optimal nonequilibrium control [GEC3].

PI Crooks left the MURI Project during 2017 to develop a start-up company developing quantum machine learning.

PI Crutchfield: The computational mechanics of information processing in thermodynamic systems is close to complete:

- Functional fluctuations [JPC1]: Large deviation theory and computational mechanics predict how the thermodynamic functioning of information engines fluctuates in response to environmental behaviors.
- Costs of modularity [JPC3]: The modular architecture of an information engine comes at a thermodynamic cost, demonstrating that inefficiency arises from modularity by destroying the ability to leverage environmental correlations.
- Powerful mathematical and calculation methods [JPC5]: Introduced new methods are sufficiently powerful to yield closed-form analyses in many previously-intractable cases.
- Computational mechanics of infinite-memory processes [JPC6]: Extended the analysis of intrinsic computation to such infinite-state systems.

- Multivariate mutual information [JPC7,JPC16,JPC18]: A comprehensive software package in Python was developed and is available as open source.
- Toward quantum information engines [JPC8]: Crutchfield that quantum information engines exhibit a surprising array of new thermodynamic behaviors.
- The Principles of Requisite Complexity [JPC10]: For an adaptive system to take maximum thermodynamic advantage of its environment, it must be internally organized to represent its environment's correlations.
- Bacteria as environmental prediction engines [JPC11]: Crutchfield explained the role of bacterial epigenetics as coding predictive ("causal") states of the environment.
- Causal asymmetry in a quantum world [JPC12]: Crutchfield showed that quantum structural complexity is time symmetric, raising fundamental issues about the origins of asymmetry in classical physics and so in thermodynamic information processing.
- Spacetime computational mechanics [JPC13]: This effort laid out the theoretical foundations for structure and causality in spacetime.
- Information theory software package [JPC17]: Open source Python library for discrete information theory.
- Fraudulent white noise [JPC18]: Crutchfield gave a new view of "unstructured" and "uncorrelated" processes that goes some distance to disabuse us of misinterpreting or even simply dismissing structure present in apparently-noisy observations.
- Information engine performance [JPC19]: Crutchfield developed new error-dissipation trade-offs in information engines controlled via time-symmetric protocols.
- Measurement-induced randomness and structure [JPC20]: Crutchfield developed close parallels and distinctions between quantum and classical physics in terms of randomness and structure that measurement can generate or remove.
- Harnessing fluctuations in thermodynamic computing [JPC21]: Crutchfield developed mesoscopic methods to track successful and failed microscopic information processing.

- Shortcuts to thermodynamic computing [JPC22]: Crutchfield and Jarzynski developed new counterdiabatic control methods that give much advantage in thermodynamic control.

PI DeWeese: Developed new approaches for understanding and controlling nonequilibrium systems and applied these insights to network theory, learning, engineered systems, and fundamental physics problems. DeWeese generalized the geometric framework for finding minimum dissipation protocols to include a systematic expansion of all terms beyond the second-order equations known previously, as well as a generalization of the “escorted dynamics” framework for transitioning the full distribution of a thermodynamic system from one state to another in finite time to the case of more than one control parameter [MRD1,MRD2,MRD3].

PI Jarzynski: Continued to pioneer novel control strategies for classical and quantum thermodynamic systems.

Thermodynamics of periodically-driven systems: Jarzynski showed for discrete-state Markov dynamics that such stochastic pumps—periodically driven stochastic systems—are able to mimic nonequilibrium steady states [CJ5] and extended this to diffusive motion in one degree of freedom [CJ1].

Programmable Maxwell’s Demon: Jarzynski developed a mechanistic model of a programmable Maxwell’s Demon [CJ2] that, interacting with a thermal bath, can raise a mass that against gravity.

Second Law violations: Jarzynski showed that it is possible, in principle, to design protocols in which most realizations give rise to Second Law violations [CJ3].

Shortcuts to adiabaticity: Jarzynski developed methods to construct shortcuts for a variety of systems—classical, quantum, and stochastic [CJ6]. Counterdiabatic erasure: Crutchfield and Jarzynski applied this to bit erasure [JPC22].

Quantum adiabatic control: For quantum systems, Jarzynski constructed local shortcuts to adiabaticity that rapidly drive a system from an excited state of an initial Hamiltonian to the corresponding state of the final Hamiltonian [CJ4].

PI Krishnaprasad: Developed approaches to control nonequilibrium processes, applying them to thermodynamic computation, collective motion, population dynamics, and interface growth.

1. Thermodynamic efficiency in a stochastic dissipative oscillator [PSK1]: Solved the design problem of a cyclic protocol (heat engine) that extracts a prescribed amount of work with maximal thermodynamic efficiency in a stochastic dissipative system.

2. Subriemannian geometry in collective motion [PSK3,PSK4,PSK5]: Extended collective subriemannian geometry to continuum settings with long-range propagation of information in collectives.
3. Population games and their control [PSK2,PSK4,PSK7]: Population games and their control formulated a variational principle for replicator.
4. Controlling KPZ interface growth [PSK6]: Control of the KPZ equation of interface growth via variance minimization problem.

PI Roukes: Roukes' Caltech team demonstrated that superconducting flux qubits can act as nanoscale switches displaying strong fluctuations at low temperatures. In particular, the flux qubits were validated as ideal classical double-well systems at temperatures near 500 mK. In collaboration with the UC Davis team, functional partitions within an erasure protocol were experimentally verified using the flux qubit [JPC21,MR1]. To monitor the thermodynamics, Caltech measured thermal conductance of suspended superconducting-normal-superconducting (SNS) thermometers and found a strong reduction of thermal conductance necessary for the thermodynamic measurements of information processing in flux qubits. Combining the SNS junction thermometers with the flux qubits on the same chip is underway in collaboration with Siyuan Han (University of Kansas). Roukes' Caltech team designed the flux qubit/SNS thermometer chip and reconfiguring the measurement equipment for thermodynamic measurements of operations within the flux qubit.

PI Hess: Explored how velocity fluctuations in microtubule transport by surface-adhered kinesin motors revealed key insights on how the degree of velocity fluctuations directly relates to a loss in efficiency and on how heterogeneity in motor attachment geometry and the anharmonicity in the tail stiffness conspire to dominate the velocity fluctuations at high motor densities. His Columbia University team left the MURI project during Fall 2016.

Plans Next Period

Results Dissemination

The Information Engines MURI's productivity was sustained at a high level, indicating an intellectual maturation as the teams overcame previous theoretical and experimental challenges. The results were disseminated rather widely. Annual summary:

2019: Thirty-eight manuscripts were in play, 19 appeared in peer-reviewed, high-profile journals, another 11 manuscripts were under review, and 8 were in preparation.

2018: 40 manuscripts, 25 appeared in peer-reviewed, high-profile journals and another 11 manuscripts under review.

2017: 52 manuscripts, 35 appeared in peer-reviewed, high-profile journals and another 17 manuscripts were under review.

2016: 40 manuscripts, 24 appeared in peer-reviewed, high-profile journals and another 21 manuscripts were submitted.

Each year during the MURI, the Lead PI co-organized the workshop on Information Engines at the Frontier of Nanoscale Thermodynamics, held at the Telluride Science Research Center, typically 10 days during July, and supported by ARO. The Lead PI also organized Beyond Shannon—The Structure and Meaning of Information, held at the Institute for Advanced Study, University of Amsterdam, 6-8 May 2019.

Space does not permit listing the hundreds of presentations—team colloquia, keynotes, lecture courses, invited presentations, and team-organized meetings and workshops. These are, however, documented in detail in the annual Interim Progress Reports.

Honors and Awards

Space does not permit listing the many dozens of PI honors, awards, and appointments. These are, however, documented in detail in the annual Interim Progress Reports.

Training Opportunities

The Information Engine MURI training effort was substantial with an average of half a dozen postdoctoral and two dozen graduate researchers, with 20 PhDs granted.

2019: 7 postdoctoral researchers, 18 graduate student researchers, and an undergraduate research intern. Five PhD degrees.

2018: 8 postdoctoral researchers, 20 graduate student researchers, and several undergraduate research interns. Three PhD degrees.

2017: 7 postdoctoral researchers, 20 graduate student researchers, and several undergraduate research interns. Six PhD degrees.

2016: 7 postdoctoral researchers, 29 graduate student researchers, and several undergraduateresearch interns. Five PhD degrees, one MS degree.

Ph.D. Degrees Earned

- Cina Aghamohammadi: “Memory and Thermodynamic Costs of Sampling and Biased Sampling”, Ph.D. Dissertation in Physics, University of California at Davis, August 2018.
- Mayur Mudigonda, “Inference algorithms and sensorimotor representations in brains and machines”, PhD dissertation in Vision Science, University of California at Berkeley, June 2019.
- Udit Halder: “Optimality, Synthesis and a Continuum Model for Collective Motion”, Ph.D. inEngineering, University of Maryland, College Park, April 2019.
- Vidya Radu: “Collective Behavior, Information Propagation, and Noise”, Ph.D. in Engineering,University of Maryland, College Park, May 2019.
- Eric Dodds: “Statistical learning models of sensory processing and implications of biological constraints”, PhD dissertation in Physics, December 2018.
- Alexander Boyd: “Thermodynamics of Correlations and Structure in Information Engines”, Ph.D.

Dissertation in Physics, University of California at Davis, December 2017.

- Ayoti Patra, “Bridging quantum, classical and stochastic shortcuts to adiabaticity”, PhD in Physics, University of Maryland, College Park, September 2017.
- Y. Huang: “Optimal control of heat engines in non-equilibrium statistical mechanics”, PhD inEngineering; August 2017.
- Nix Barnett: “Mechanisms within the Black Box: Prediction, Computation, Randomness, and Complexity of Input-Output Processes via the χ^2 -Transducer”, PhD in Mathematics, University ofCalifornia, Davis, August 2016.
- Sarah E. Marzen: “Bio-inspired Problems in Rate-distortion Theory”, PhD in Physics, Universityof California, Berkeley, August 2016. Now, Physics of Living System Fellow with Prof. Jeremy England, Physics, MIT.
- Paul Riechers: “Exact Results Regarding the Physics of Complex Systems via Linear Algebra,Hidden Markov Models, and Information Theory”,

Ph.D. Dissertation in Physics, University of California at Davis, December 2016.

- J. Demers, “Stochastic processes in physics: deterministic origins and controls”, PhD in Physics, University of Maryland, College Park, December 2016. Dr. Demers is now a postdoc in Prof. William Fagan’s group in the Department of Biology, University of Maryland, College Park.
- Amy T-C. Lam, “Assembly in Dynamic Nanoscale Systems”, PhD in Biomedical Engineering, Columbia University, New York, December 2015.
- Zhiyue Lu: “Topics in equilibrium and nonequilibrium thermodynamics: computing crystalline free energies and engineering Maxwell’s demon”, PhD in Chemical Physics, University of Maryland, College Park, December 2015.
- Biswadip Dey (UMD, 2014); Now, Postdoctoral Fellow in Mech & Aero Eng, Princeton University.
- Patrick Zulkowski (UCB, 2014) “The Geometry of Thermodynamic Control”; Now, Assistant Professor, Berkeley City College.
- Ofer Idan (Columbia, 2014) “Modeling Nanoscale Transport Systems”.
- Nick Travers (UCD, 2014); Now, Asst. Prof, Mathematics, University of Indiana, Bloomington.
- Ryan G. James (Physics, UC Davis) Ph.D. August 2013.
- Nicholas F. Travers (Mathematics, UC Davis) Ph.D. August 2013.

M.S. Degrees Earned During Reporting Period

- K. Miltenberger, MS thesis on collective behavior. April 2016.

Additional information on programs, students, and faculty of the Information Engines MURI project and the Complexity Sciences Center is available online at <http://informationengines.org/> and <http://csc.ucdavis.edu/>, respectively.

Technology Transfer

- PI Crutchfield: Continues to maintain and augment the MURI’s website <http://informationengines.org/> to facilitate team collaborations and outreach.
- PI Crutchfield: Continues to develop the open source Python package “Computational Mechanics in Python” (CMPy) consisting of most of

computational mechanics' constructive mathematical results and methods. Jupyter/Python notebooks continue to be developed to illustrate calculational details reported in our publications. A suite of over two-dozen Jupyter notebooks was developed as tutorials. CMPy has been ported to run on the Jupyter notebook service CoCalc.com. Efforts initiated to port CMPy from Python 2.7.X to Python 3.X.

- PI Crutchfield: Further developed the open source Discrete Information Theory Python package dit: <https://github.com/dit/dit>. Most notably, it was extended to include an even more complete suite of multivariate information measures for dynamical and stochastic networks. Including, in particular, new algorithms for secret key agreement measures of unique information [JPC17].
- PI Krishnaprasad: Transfer of knowledge to the Naval Research Laboratory through collaboration with Dr. Eric Justh has continued on a regular basis. Concrete applications of this transfer effort are expected in the area of collective behavior in unmanned aerial and marine systems. Other applications to development of machine learning algorithms are also under consideration.
- PI Krishnaprasad: There have been multiple interactions with Dr. Adam Svenkeson (Research Scientist at Army Research Laboratory, Aberdeen, MD) and these are expected to continue on a monthly basis, with the aim of developing collaborations.
- PI Krishnaprasad: Additional collaboration with Northrop Grumman Mission Systems (contact: Dr. Isidoros Doxas) has been initiated to allow further developments in the direction of adversarial learning modeled by controlled replicator dynamics subject to noise. Applications are being considered in agile surveillance systems capable of countering adversarial responses. PI Krishnaprasad will present new results at a Northrop Grumman Research Symposium in October 2019.
- PI Krishnaprasad: A new collaboration, including joint proposal development has been initiated with Ford in the area of autonomous systems and machine learning.

Participants

Name	Role	Person Months
Crooks, Gavin	Co-Investigator	1
DeWeese, Micheal	Co-Investigator	1
Hess, Henry	Co-Investigator	1
Jarzynski, Christopher	Co-Investigator	1
Krishnaprasad, P. S.	Co-Investigator	1
Roukes, Michael	Co-Investigator	1
Aghamohammadi,Cina	Graduate Student (research assistant)	6
Ara, Pooneh	Graduate Student (research assistant)	2
Armstrong, Megan	Graduate Student (research assistant)	3
Barnett, Nix	Graduate Student (research assistant)	6
Boyd, Alexander	Graduate Student (research assistant)	6
Brown, Benny	Graduate Student (research assistant)	1
Demers, Joseph	Graduate Student (research assistant)	6
Dey, Biswadip	Graduate Student (research assistant)	1
Dodds, Eric	Graduate Student (research assistant)	1
Emenheiser, Jeffrey	Graduate Student (research assistant)	1
Fang, Michael	Graduate Student (research assistant)	1
Frim, Nick CinkoAdam	Graduate Student (research assistant)	1
Frye, Charles	Graduate Student (research assistant)	1
Gier, David	Graduate Student (research assistant)	1
Halder, Udit	Graduate Student (research assistant)	1
Hodson, Wade	Graduate Student (research assistant)	6
Huang, Yunlong	Graduate Student (research assistant)	12
Idan, Ofer	Graduate Student (research assistant)	4
Jurgens, Alexandra	Graduate Student (research assistant)	3
Katti, Raj	Graduate Student (research assistant)	2
Kazeruni, Neda Bassir	Graduate Student (research assistant)	3
Klymko, Katherine	Graduate Student (research assistant)	1
Lam, Amy	Graduate Student (research assistant)	5
Lee, Steven	Graduate Student (research assistant)	1
Lei, Xincheng	Graduate Student (research assistant)	6
Li, Xincheng	Graduate Student (research assistant)	12

Ligeralde, Andrew	Graduate Student (research assistant)	1
Loomis, Samuel	Graduate Student (research assistant)	4
Lu, Zhiyue	Graduate Student (research assistant)	6
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Miltenberger, K.	Graduate Student (research assistant)	6
Mudigonda, Mayur	Graduate Student (research assistant)	1
Palacci, Henri	Graduate Student (research assistant)	6
Patri, Ayoti	Graduate Student (research assistant)	6
Prijatelj, Michael	Graduate Student (research assistant)	1
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Raju, V.	Graduate Student (research assistant)	1
Ray, Kyle	Graduate Student (research assistant)	6
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Rotskoff, Grant	Graduate Student (research assistant)	1
Rupe, Adam	Graduate Student (research assistant)	4
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Shemetov, Dmitry	Graduate Student (research assistant)	1
Smith, Andrew Mavin	Graduate Student (research assistant)	1
Tsitkov, Stanislav	Graduate Student (research assistant)	3
Venegas-Li, Ariadna	Graduate Student (research assistant)	3
Wadia, Neha	Graduate Student (research assistant)	1
Wimsatt, Greg	Graduate Student (research assistant)	12
Zarcone, Ryan	Graduate Student (research assistant)	1
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Boyd, Alexander	Postdoctoral (scholar, fellow or other postdoctoralposition)	1
Deffner, Sebastian	Postdoctoral (scholar, fellow or other postdoctoralposition)	1

James, Ryan	Postdoctoral (scholar, fellow or other postdoctoral position)	4
Kang, Louis	Postdoctoral (scholar, fellow or other postdoctoral position)	1
Katira, Parag	Postdoctoral (scholar, fellow or other postdoctoral position)	1
Mahoney, John	Postdoctoral (scholar, fellow or other postdoctoral position)	1
Mandal, Dibyendu	Postdoctoral (scholar, fellow or other postdoctoral position)	10
Marzen, Sarah	Postdoctoral (scholar, fellow or other postdoctoral position)	1
Riechers, Paul	Postdoctoral (scholar, fellow or other postdoctoral position)	1
Saira, Olli-Pentti	Postdoctoral (scholar, fellow or other postdoctoral position)	4
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Zulkowski, Patrick	Postdoctoral (scholar, fellow or other postdoctoral position)	6
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Mahoney, John	Staff Scientist (doctoral level)	1
Matheny, Matthew	Staff Scientist (doctoral level)	5
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Berger, Andrew	Undergraduate Student	1
Kim, Hyun Su	Undergraduate Student	1
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Pohland, Sara	Undergraduate Student	1
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Ruebeck, Joshua	Undergraduate Student	1
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**Appendix B. Final Report – Information Engines: Nanoscale
Control, Computing, and Communication out of Equilibrium**

This report appears in its original form, without editorial change.

Final Report
Agreement # W911NF-13-1-0390
Proposal # 63822EGMUR

Information Engines:
Nanoscale Control, Computing, and Communication
Out of Equilibrium

Reporting Period: 1 September 2013 – 31 August 2020
ARO FY2013 MURI Topic #6
Transforming Information within Nonequilibrium Nanosystems
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Submitted to
<https://extranet.aro.army.mil>

Per online length limits, abridged versions were uploaded of the following Major Goals, Major Accomplishments, Training, Results Dissemination, Plans, Honors, and Tech Transfer. This document provides the detailed information from which the summaries in the main sections were derived and the abridged uploaded versions extracted.

NOTE: Despite solicitations for additional funds to continue research under the Information Engines MURI during its last (seventh) year (August 2019 – 2020), no funds were forthcoming. Thus, the most recent Interim Progress Report filed on 31 August 2019 and this Final Report cover only work up to 31 July 2019. That said, this Final Report and associated filings update publication and personnel information current as of this 2020 filing.

Major Goals

The Information Engines MURI's original goal was to develop a unified framework for understanding, designing, and implementing micron-scale and nanoscale information-processing engines and to provide the scientific foundation for future nanoscale devices with groundbreaking capabilities. These ambitious goals were met and, in several cases, exceeded as attested by the project's marked productivity; see <http://informationengines.org> ⇒ Research.

These successes opened up a number of exciting future theoretical and experimental research avenues. The main efforts successfully developed methods to control nanoscale thermodynamic processes and, perhaps most importantly, culminated in successful detailed experimental tests and verifications of our theoretical results. That said, looking beyond this MURI, much remains to do and the core PI team continues to collaborate on and extend the Information Engines MURI's progress. Putting the accomplishments in broad perspective, let's briefly review the overall project goals.

Any given natural process can be viewed in two complementary and equally valid ways: First, as a "physical" system that is controlled by, manipulates, stores, and dissipates energy and, second, as a "dynamical" system that generates, stores, transforms, and destroys information. When considering it and its physical implementation as a unitary system, we see that information processing requires energy to drive it forward. An immediate result is that this energy is not completely transformed into processed information. Energy is dissipated. Such limitations dominate on the nanoscale, in particular, where fluctuations out of equilibrium are the rule and the distinction between organized and thermal energy, between heat and work, becomes ambiguous. The MURI's principle goal, therefore, was to find the physical limits of nanoscale information processing and control.

To this end, the MURI pursued a set of interdependent tasks:

Task 1: *Intrinsic Computation in Nanoscale Substrates:* Develop concepts and mathematical tools that identify how dynamical processes store and transform information.

Task 2: *Nonequilibrium Information Processing by Nanoscale Machines:* Develop thermodynamic and statistical mechanical principles that govern the operation of information engines and then synthesize these with the tools of intrinsic computation from Task 1.

Task 3: *Control and Optimization at the Nanoscale:* Integrate methods of geometric optimal control theory and nonequilibrium statistical physics, instantiating the synthesis in concrete control problems posed by information engines.

Task 4: *Validation: Optimal, Controllable Nanoscale Information Processing Agents:* Develop experimental platforms with which to test the information-engines thermodynamic principles developed in Tasks 1, 2, and 3. These came to include nanoelectromechanical systems (NEMS) and flux qubits.

The ultimate experimental goal in Task 4 was to fabricate nanoscale devices capable of storing, manipulating, and retrieving information, as well as exploiting information as an energy-catalyst to generate motion and to direct the flow of energy. The allied theoretical challenges were to lay the scientific and engineering foundations for a new generation of denser, faster, cheaper, and more energy-efficient computing device capable of manipulating large-scale, complex data structures and to point the way to a new generation of self-organizing nanoscale engines capable collectively interfacing with the physical world with maximum power and efficiency.

The long-term scientific challenges, implicit in Tasks 1 – 3, were not only to pioneer theoretical foundations, but to also establish a research community in information engines. Looking back over the MURI's seven-year extended existence, there are two notable accomplishments on this score. The first is the annual workshop series on *Information Engines at the Frontiers of Nonequilibrium Thermodynamics*, co-organized by the Lead PI, held each summer at the Telluride Science Research Center, and sponsored by ARO; except in 2020 due to the pandemic. In lieu of an in-person workshop the co-organizers and past participants are assembling a special issue on *Thermodynamic Computing with Information Engines* for the well-known Journal of Statistical Physics.

The second is that the MURI's successes catalyzed the emergence of information engines as signaling the dawn of a new era of *thermodynamic computing* or, as we

have come to frame it, *low- $k_B T$ computing*. The initial experimental successes and rapidly-progressing theory led the *Computing Community Consortium* (CCC) in January 2019 to initiate a broad planning effort to develop this new paradigm—whose charge is to actively leverage and control inherent fluctuations in physical information-processing substrates (<https://cra.org/ccc/events/thermodynamiccomputing/>). Note that in the 1990s and 2000s CCC was a key convener for research in quantum computing, among many other nascent information technologies. The current CCC effort is destined to play a similar guiding role for thermodynamic computing. Its report on *Thermodynamic Computing* is found at <https://arxiv.org/abs/1911.01968> and is uploaded with this Final Report. For those interested in delving further beyond this Final Report, we strongly recommend the CCC report as it paints a broad and bold picture of the path forward from this MURI.

Synopsis of Goals

NOTE: The MURI’s annual Interim Progress Reports, filed each August, give detailed synopses of each year’s goals. Here, limited space means that we can provide only the shortest summary of highlights. See also, the uploaded Final Report, which is not constrained by space.

The Information Engines MURI’s led to major advances in controlling nanoscale thermodynamic systems and in determining the thermodynamic constraints on nanoscale information processing. In parallel, the MURI’s flux-qubit information-engine devices were calibrated and extensively experimented on. The experimental results successfully validated key aspects of our theoretical predictions and led to new theoretical advances—e.g., the *trajectory-class fluctuation theorems*. The flux-qubit device was demonstrated to be markedly more appropriate for the project’s goals than either the original molecular motor and NEMS systems. And so, it became our primary experimental platform. As a broad-brush summary, the following highlights our results in thermodynamic control, principles of information thermodynamics, and nanoscale information-engines experiments.

- A. *Control of Nanoscale Thermodynamic Systems*: Bringing together methods of geometric optimal control theory and nonequilibrium statistical physics, instantiated in concrete problems of designing working cycles for heat engines, has been a major goal of this part of the MURI project. The UCD-UMD teams focused on one of our three previously-developed approaches to controlling nanoscale thermodynamics systems: counterdiabatic control protocols for information processing tasks. Addressing very practical trade-offs in computing, counterdiabatic protocols provide finite-time “short-cuts” to, what otherwise are, adiabatic control protocols that require infinite time.

PIs Crutchfield and Jarzynski continued to synthesize this control approach with the geometric and engineering control theories by analyzing all of the elementary bit manipulations (erase, create, swap, invert, and the like).

An additional goal for UMD (PI Krishnaprasad) was to make progress in collective dynamics (theory and data analysis) to incorporate symmetry, geometry, and information propagation through wave phenomena, learning, and the influence of noise. (Of particular interest was the subject of sub-Riemannian geometry, primarily as a tool for achieving these goals.)

- B. *Principles of Information Thermodynamics*: UCD determined the costs of thermodynamic controller's modular organization—the *modularity dissipation*—the first time thermodynamic costs have been associated with a system's structure and organization. This advances our suite of theoretical results to a design methodology for nanoscale devices with net positive thermodynamic benefit. And, critically, it laid the foundation for an extensive suite of experimental tests that continue on under other projects.
- C. *Nanoscale Information Engines Experiments*: Due to key theoretical insights, the flux qubit became the main experimental focus. In the process, UCD-Caltech discovered new ways—called the trajectory-class fluctuation theorems—to diagnose success and failure modes of microscopic behaviors that support information processing using the mesoscopic “observable” of the distribution of works expended over a repeated protocol. That is, the flux-qubit experiments demonstrated how a relatively-accessible thermodynamic observable (work) could be used to diagnose the success and failure of microscopic information processing trajectories. We proved that work distributions obey their own, characteristic Jarzynski integral and Crooks detailed fluctuation theorems and that the trajectory-class fluctuation theorems synthesize them both in a single family.

Critically, the experiments demonstrated that flux qubits offer a number of benefits for information-engine experimentation in terms of controllability, reliability, and speed of operation. These are particularly important when validating fluctuation theorems, as the latter require sampling extremely rare events and so many millions of experimental repetitions.

Finally, two experimental thermodynamic-measurement technologies were designed. For near-term experimentation this included bolometric measurements for acquiring average thermodynamic quantities using electron heat baths in normal metal islands. For the longer-term, this included calorimetric measurements for acquiring distributions of thermodynamic quantities in semiconducting islands using one-shot protocols. Preliminary data on normal metal islands showed that the

required sensitivity to make averaged measurements is attainable with next- round fabrication. First-round fabrication and testing of semiconductor platforms was completed. Moving forward to implement these experiments only relies on the PIs' ability to attract financial support, since this MURI established the necessary experimental infrastructure.

Overall, the MURI was remarkably productive with well over 100 peer-reviewed published articles:

2019: Thirty-eight manuscripts were in play: 19 appearing in peer-reviewed, high-profile journals, another 11 manuscripts under review, and 8 in preparation.

2018: Over 40 manuscripts were in play: 25 appearing in peer-reviewed, high-profile journals, another 11 manuscripts under review, and 4 in preparation.

2017: Over 52 manuscripts: 35 appearing in peer-reviewed, high-profile journals and another 17 manuscripts under review.

2016: Over 40 manuscripts: 24 appearing in peer-reviewed, high-profile journals and another 21 manuscripts submitted.

Most all are available through arXiv.org and the project website: <http://informationengines.org>. Importantly, 13 appeared in physics' top journals: 6 in *Physical Review X* and 7 in *Physical Review Letters*. Thus, the MURI's efforts were recognized at the highest levels and had substantial impact. Moreover, the high productivity and substantive results reflect a project-wide technical maturation and the close collaborations across the MURI teams. The statistics reveal that the MURI's previous years' exceptional productivity was sustained each year. Practically speaking, the MURI teams made good on all of the original proposal's four Tasks, excepting the early emphasis on molecular motors.

Administratively, the Information Engines MURI (#W911NF-18-1-0340) complements the Lead PI's ARO project *Functional Pattern Formation in Thermodynamical Systems* (#W911NF-18-1-0028). The latter started in 2018 and focuses on spatially-extended engines with the unique goal of tracking the flow of thermodynamic resources. In contrast, the MURI itself concerned individual engines and provided a wealth of new tools for analyzing spatially-distributed information engines. The two projects' conceptual and, even, algorithmic commonalities translated into quite a bit of conceptual exchange and synergistic progress.

Accomplished under Goals

The following reviews the PIs' efforts in turn. (Citations are listed in the Bibliography.)

PI Crooks: Continued his signature geometric approach to thermodynamic control and also contributed fundamental theoretical work on strongly coupled thermodynamic subsystems.

- 1. Thermodynamic geometry of minimum dissipation driven barrier crossing [GEC1]:** Explored the thermodynamic geometry of a simple system that models the bistable dynamics of nucleic acid hairpins in single molecule force-extension experiments. The analysis demonstrated that the friction coefficient of the driving protocols is sharply peaked at the interface between metastable regions, which leads to minimum-dissipation protocols that drive rapidly within a metastable basin, but then linger longest at the interface, giving thermal fluctuations maximal time to kick the system over the barrier. This provides a design principle for constructing thermodynamically efficient coupling between stochastic objects and predicts key aspects of evolved biomolecular motors.
- 2. Near optimal protocols in complex nonequilibrium transformations [GEC2]:** Crooks described a general method for sampling an ensemble of finite-time, nonequilibrium protocols biased toward a low average dissipation. As an application, Crooks sampled the ensemble of low-dissipation protocols that invert the magnetization of a 2D Ising model and explored how the diversity of the protocols varies in response to constraints on the average dissipation.
- 3. Geometric approach to optimal nonequilibrium control [GEC3]:** Optimal control of nanomagnets has become an urgent problem for the field of spintronics as technological tools approach thermodynamically determined limits of efficiency. Crooks provided a physically transparent derivation of a metric tensor for which the length of a protocol is proportional to its dissipation. Crooks then described a numerical method that computes geodesics even when the number of control parameters is large. Crooks' calculations revealed nontrivial protocols for magnetic-spin bit erasure and reversal, providing important, experimentally testable predictions for ultra-low-power computing.

PI Crooks left the MURI Project during 2017 to develop a start-up company developing quantum machine learning.

PI Crutchfield: Despite a number of focused technical questions still to analyze, computational mechanics' account of information processing embedded in thermodynamic systems is close to complete. In short, it can explain and analyze a broad array of thermodynamic information processing with mathematical and numerical precision. For example, Crutchfield developed the trajectory-class fluctuation theorems, synthesizing those of Jarzynski and Crooks, to delineate how engines function and fail on a given informational task. And, there is a new level of exact analysis of information engine operation that can be used to identify their possible thermodynamic functioning and how those functions fluctuate on the nanoscale. Here's brief summary that gives a sense of the depth and breadth of results:

- **Functional fluctuations** [JPC1]: Large deviation theory and computational mechanics predict how the thermodynamic functioning of information engines fluctuates in response to environmental behaviors. Previous conjectures have been rigorously established and the manuscript appropriately updated.
- **Costs of modularity** [JPC3]: Perhaps the most surprising and broadly applicable result to come out of the thermodynamic analysis of intrinsic computation is that the modular architecture of an information engine comes at a thermodynamic cost. In short, modularly-organized systems require more input work to run and they dissipate more energy in their operation. This goes far beyond Landauer's original argument, that only erasure of information implied a thermodynamic cost, to demonstrate that the very modular organization of information processing devices, whether digital circuits or biological organisms, extracts a thermodynamic cost. In short, inefficiency arises from modularity by destroying the ability to leverage environmental correlations.
- **Powerful mathematical and calculation methods** [JPC5]: Many results rely on our introducing wholly new mathematical tools. Without these, most results described here and their future generalizations would not be accessible. Moreover, the new methods are sufficiently powerful to yield closed-form analyses in many previously-intractable cases.
- **Computational mechanics of infinite-memory processes** [JPC6]: Many systems of interest in stochastic thermodynamics have continuous state spaces. Availing ourselves of the mathematical properties of computational mechanics' causal states led to our extending the analysis of intrinsic computation to such infinite-state systems. This opens up a vast array of future applications. The molecular sensors analyzed are just a first example.

- **Multivariate mutual information** [JPC7,JPC16,JPC18]: Computational mechanics' analysis of intrinsic computation relies critically on tools and concepts from information theory. As such, Crutchfield maintains an active research thrust in developing various kinds of information measures and algorithms to estimate them. For example, after calling into question many of the uses of mutual information to diagnose complex systems, he finally introduced a constructive approach for this important task. A key step in detecting that an information engine has formed patterns relies on using mutual information shared across a field of random variables. New information-theoretic methods were developed to handle this case. A comprehensive software package in Python was developed and is available as open source.
- **Toward quantum information engines** [JPC8]: With an eye to future directions for information engines, Crutchfield explored the structural complexity in quantum processes. The results suggest that quantum information engines will exhibit a surprising array of new thermodynamic behaviors. In particular, quantum models of stochastic processes can be smaller than classical. In contrast with the ϵ -machine's unique role in the classical setting, however, among the class of processes described by pure-state hidden quantum Markov models, there are those for which there does not exist any strongly minimal model. This hints at a fundamental ambiguity between classical and quantum physics.
- **The Principles of Requisite Complexity** [JPC10]: For an adaptive system to take maximum thermodynamic advantage of its environment, it must be internally organized to represent its environment's correlations.
- **Bacteria as environmental prediction engines** [JPC11]: Crutchfield developed a novel application of computational mechanics and information engines that explains the role of bacterial epigenetics as coding predictive ("causal") states of the environment.
- **Causal asymmetry in a quantum world** [JPC12]: Over two decades ago PI Crutchfield discovered the structural asymmetry in stationary processes "played" in forward and reverse time. It turns out that this is a classical phenomenon, as the quantum structural complexity is time symmetric. This raises fundamental issues about the origins of asymmetry in classical physics and so in thermodynamic information processing.
- **Spacetime computational mechanics** [JPC13]: Although the possibility and formal constructions of computational mechanics for spatially extended systems has been known for three decades, it has been left largely

unexplored. This effort laid out the theoretical foundations for structure and causality in spacetime, drawing connections with invariant-set theory of dynamical systems.

- **Information theory software package** [JPC17]: Crutchfield published an open source Python library for discrete information theory.
- **Fraudulent white noise** [JPC18]: Crutchfield gave a new view of “unstructured” and “uncorrelated” processes that goes some distance to disabuse us of misinterpreting or even simply dismissing structure present in apparently-noisy observations.
- **Information engine performance** [JPC19]: Crutchfield developed new error-dissipation trade-offs in information engines controlled via time-symmetric protocols.
- **Measurement-induced randomness and structure** [JPC20]: Measurement is a crucial act in both classical nonlinear dynamics and in quantum dynamics. Crutchfield developed close parallels and distinctions between quantum and classical physics in terms of randomness and structure that measurement can generate or remove.
- **Harnessing fluctuations in thermodynamic computing** [JPC21]: Crutchfield developed mesoscopic methods to track successful and failed microscopic information processing. This is a key step to adapting fluctuation theorems to spatially-extended information engines. This new approach was experimentally validated.
- **Shortcuts to thermodynamic computing** [JPC22]: Spatially-extended information engines present a particularly challenging spatiotemporal control problem. Crutchfield and Jarzynski developed new counterdiabatic control methods that give much advantage in this case.

PI DeWeese: Developed new approaches for understanding and controlling nonequilibrium systems and applied these insights to network theory, learning, engineered systems, and fundamental physics problems.

Geometric control and learning: DeWeese generalized the geometric framework for finding minimum dissipation protocols to include a systematic expansion of all terms beyond the second-order equations known previously, as well as a generalization of the “escorted dynamics” framework for transitioning the full distribution of a thermodynamic system from one state to another in finite time to the case of more than one control parameter. This included developing a technique to identify critical points in the loss surfaces explored during learning in dynamical

systems far from equilibrium [MRD1], a study comparing and contrasting the sparse structures of natural scenes versus natural sounds viewed as nonequilibrium physical systems [MRD2], and an analysis of fault tolerance in the design of optical neural networks that depend on various types of nonlinearities to overcome thermal fluctuations that limit performance [MRD3].

PI Jarzynski: Continued to pioneer novel control strategies for classical and quantum thermodynamic systems.

Thermodynamics of periodically-driven systems: When a stochastic system is perturbed by external, time-periodic forcing, it reaches a periodic state, characterized by currents and entropy production that are analogous to those that arise in nonequilibrium steady states. Earlier work funded by the MURI showed for discrete-state Markov dynamics that such *stochastic pumps*—periodically driven stochastic systems—are able to mimic nonequilibrium steady states, achieving the same time-averaged currents and probabilities at the same thermodynamic cost of entropy production [CJ5]. Jarzynski recently extended this to diffusive motion in one degree of freedom [CJ1]. In contrast to the discrete-state case, Jarzynski found that for a given average current and probability distribution, a periodically-driven diffusive system always generates more entropy than a nonequilibrium steady state (NESS). Additionally, Jarzynski showed how to construct both a stochastic pump and a NESS that support a given, desired current and probability distribution.

Programmable Maxwell’s Demon: Jarzynski developed a mechanistic model of a *programmable* Maxwell’s Demon [CJ2], which interacts with a thermal bath, a mass that can be lifted against gravity, and a sequence of *bits* implemented by paddles that rotate around a central axle. The model is programmable in the sense that it can be designed so that if the arriving bits encode a particular sequence—say the binary representation of $\pi=3.14159\dots$ —then the device extracts energy from the reservoir and delivers it to lift the mass. Conversely, if the mass is very large then the device systematically writes the digits of π onto the stream of bits, at a thermodynamic cost equal to that predicted for bit erasure by Landauer’s principle.

Jarzynski provided exact solutions for the behavior of the device in a particular limit and showed that our model can realize both autonomous and nonautonomous versions of Maxwell’s demon.

Second Law violations: One of the major themes explored over the MURI is that, for sufficiently small systems, fluctuations give rise to occasional “violations” of the Second Law of thermodynamics. In particular, for isothermal processes the Second Law inequality $W \geq \Delta F$ need not be satisfied for every realization of a given process, as long as it is satisfied on average. Jarzynski explored whether universal

bounds can be placed on the probability to observe such violations of the Second Law and showed that it is possible, in principle, to design protocols in which most realizations give rise to Second Law violations, but the inequality remains satisfied on average. Such protocols have recently been implemented experimentally using a single- electron transistor [CJ3].

Shortcuts to adiabaticity: These are control strategies for achieving adiabatic evolution under nonadiabatic (fast) driving. A major focus of Jarzynski’s research efforts developed methods to construct shortcuts for a variety of systems—classical, quantum and stochastic—thereby providing a robust and broadly applicable set of tools for controlling systems of interest. Earlier work funded by this MURI showed that a broad range of shortcuts to adiabaticity that can be unified within a single theoretical framework using *flow fields*, providing both intuition and a roadmap for further progress [CJ6].

Counterdiabatic erasure: Crutchfield and Jarzynski applied this approach to the problem of bit erasure, in which an overdamped Brownian particle evolves in a double-well potential and the aim is to design a protocol that rapidly forces the particle into one of the wells [JPC22].

Crutchfield and Jarzynski derived an exact expression for the additional work required to implement this protocol and clarified how this work scales with the protocol duration, the system size, and the implemented information processing. This project ties together a number of strands investigated over the course of the MURI: thermodynamics of information processing, geometric control, and shortcuts to adiabaticity.

Quantum adiabatic control: For quantum systems, we constructed local shortcuts to adiabaticity that rapidly drive a system from an excited state of an initial Hamiltonian to the corresponding state of the final Hamiltonian [CJ4]. This result solves an important open problem in the field, as previously local quantum shortcuts were available only for the ground state. Our strategy combines the flow field method mentioned above with a semiclassical analysis.

Periodically-driven Hamiltonian control: More recently, Jarzynski applied our flow field method to classical, Hamiltonian systems that are driven periodically with time. We showed how to construct a time-periodic potential that suppresses all excitations above a chosen value of energy, and we are currently exploring the quantum version of this problem.

Impulse-control of Hamiltonian dynamics: Finally, in the course of developing quantum shortcuts to adiabaticity, Jarzynski introduced a class of Hermitian operators that act as generators of spatial deformations. Jarzynski recently applied

these operators to explore how quantum systems can be controlled by the application of impulses—i.e., infinitely strong and infinitesimally brief perturbations. He found that such perturbations are naturally divided into first-order and second-order impulses, and we solved exactly for their effects.

PI Krishnaprasad: Developed approaches to control nonequilibrium processes, applying them to thermodynamic computation, collective motion, population dynamics, and interface growth.

Thermodynamic efficiency in a stochastic dissipative oscillator [PSK1]: A significant breakthrough was made in formulating and solving the design problem of a cyclic protocol (heat engine) that extracts a prescribed amount of work with maximal thermodynamic efficiency in a stochastic dissipative system (model problem: an oscillator coupled to a heat bath). The overdamped version (exemplified by a controllable capacitor in contact with a Nyquist-Johnson resistor in a heat bath of controllable temperature) is technically more complex and is being prepared for publication.

Subriemannian geometry in collective motion [PSK3,PSK4,PSK5]: Previous work on collective subriemannian geometry was further extended to continuum settings with a view towards understanding long-range propagation of information in collectives. Further development that incorporates stochasticity in collectives is expected.

Population games and their control [PSK2,PSK4,PSK7]: Significant progress was made in the area of population games and their control. Specifically, this took the form of investigating a variational principle for replicator dynamics on the probability simplex and new controllability results for such games when the associated payoff/fitness maps are modulated.

Controlling KPZ interface growth [PSK6]: Krishnaprasad made progress on control of the KPZ equation of interface growth, specifically to solve the variance minimization problem on a finite-time horizon.

PI Roukes: Roukes' Caltech team demonstrated that superconducting flux qubits can act as nanoscale switches displaying strong fluctuations at low temperatures. In particular, the flux qubits were validated as ideal classical double-well systems at temperatures near 500 mK. In collaboration with the UC Davis team, functional partitions within an erasure protocol were experimentally verified using the flux qubit [JPC21,MR1]. To monitor the thermodynamics, Caltech measured thermal conductance of suspended superconducting-normal-superconducting (SNS) thermometers and found a strong reduction of thermal conductance necessary for the thermodynamic measurements of information processing in flux qubits.

Combining the SNS junction thermometers with the flux qubits on the same chip is underway in collaboration with Siyuan Han (University of Kansas). Roukes' Caltech team designed the flux qubit/SNS thermometer chip and reconfiguring the measurement equipment for thermodynamic measurements of operations within the flux qubit. It also completed first-round fabrication of novel Superconductor-Semiconductor-Superconductor (S-Sm-S) junctions and Superconductor-Graphene-Superconductor (S-Gr-S) junctions for single-shot calorimetric detection of nanoscale information processes, in collaboration with the Palmstrom group (UCSB) and Nadj-Perge group (Caltech), respectively.

PI Hess: Explored how velocity fluctuations in microtubule transport by surface-adhered kinesin motors revealed key insights on how the degree of velocity fluctuations directly relates to a loss in efficiency and on how heterogeneity in motor attachment geometry and the anharmonicity in the tail stiffness conspire to dominate the velocity fluctuations at high motor densities. The experimental data led him to explore bounds on the entropy production rate as a function of the positional uncertainty. Second, Hess also initiated a detailed analysis of the information thermodynamics of the kinesin step to determine which fraction of the energy dissipated by kinesin is lost due to information processing. Finally, his work also investigated self-assembling, force-producing structures. His Columbia University team left the MURI project during Fall 2016.

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- [PSK4] V. Raju and P. S. Krishnaprasad “Lie Algebra Structure of Fitness, and ReplicatorControl,” 23 pages, **under review**.
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- [PSK6] Y. Huang and P. S. Krishnaprasad (2018) “Optimal Control of KPZ Equation using Deep Reinforcement Learning”, 11 pages; **under review**.
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Training

The Information Engine MURI training effort was substantial with an average of half a dozen postdoctoral and two dozen graduate researchers, with 20 PhDs granted.

2019: 7 postdoctoral researchers, 18 graduate student researchers, and an undergraduate research intern. Five PhD degrees.

2018: 8 postdoctoral researchers, 20 graduate student researchers, and several undergraduate research interns. Three PhD degrees.

2017: 7 postdoctoral researchers, 20 graduate student researchers, and several undergraduate research interns. Six PhD degrees.

2016: 7 postdoctoral researchers, 29 graduate student researchers, and several undergraduate research interns. Five PhD degrees, one MS degree.

Ph.D. Degrees Earned

- Cina Aghamohammadi: “Memory and Thermodynamic Costs of Sampling and Biased Sampling”, Ph.D. Dissertation in Physics, University of California at Davis, August 2018.
- Mayur Mudigonda, “Inference algorithms and sensorimotor representations in brains and machines”, PhD dissertation in Vision Science, University of California at Berkeley, June 2019.
- Udit Halder: “Optimality, Synthesis and a Continuum Model for Collective Motion”, Ph.D. in Engineering, University of Maryland, College Park, April 2019.
- Vidya Radu: “Collective Behavior, Information Propagation, and Noise”, Ph.D. in Engineering, University of Maryland, College Park, May 2019.
- Eric Dodds: “Statistical learning models of sensory processing and implications of biological constraints”, PhD dissertation in Physics, December 2018.
- Alexander Boyd: “Thermodynamics of Correlations and Structure in Information Engines”, Ph.D. Dissertation in Physics, University of California at Davis, December 2017.

- Ayoti Patra, “Bridging quantum, classical and stochastic shortcuts to adiabaticity”, PhD in Physics, University of Maryland, College Park, September 2017.
- Y. Huang: “Optimal control of heat engines in non-equilibrium statistical mechanics”, PhD in Engineering; August 2017.
- Nix Barnett: “Mechanisms within the Black Box: Prediction, Computation, Randomness, and Complexity of Input-Output Processes via the ε -Transducer”, PhD in Mathematics, University of California, Davis, August 2016.
- Sarah E. Marzen: “Bio-inspired Problems in Rate-distortion Theory”, PhD in Physics, University of California, Berkeley, August 2016. Now, Physics of Living System Fellow with Prof. Jeremy England, Physics, MIT.
- Paul Riechers: “Exact Results Regarding the Physics of Complex Systems via Linear Algebra, Hidden Markov Models, and Information Theory”, Ph.D. Dissertation in Physics, University of California at Davis, December 2016.
- J. Demers, “Stochastic processes in physics: deterministic origins and controls”, PhD in Physics, University of Maryland, College Park, December 2016. Dr. Demers is now a postdoc in Prof. William Fagan’s group in the Department of Biology, University of Maryland, College Park.
- Amy T-C. Lam, “Assembly in Dynamic Nanoscale Systems”, PhD in Biomedical Engineering, Columbia University, New York, December 2015.
- Zhiyue Lu: “Topics in equilibrium and nonequilibrium thermodynamics: computing crystalline free energies and engineering Maxwell’s demon”, PhD in Chemical Physics, University of Maryland, College Park, December 2015.
- Biswadip Dey (UMD, 2014); Now, Postdoctoral Fellow in Mech & Aero Eng, Princeton University.
- Patrick Zulkowski (UCB, 2014) “The Geometry of Thermodynamic Control”; Now, Assistant Professor, Berkeley City College.
- Ofer Idan (Columbia, 2014) “Modeling Nanoscale Transport Systems”.
- Nick Travers (UCD, 2014); Now, Asst. Prof, Mathematics, University of Indiana, Bloomington.

- Ryan G. James (Physics, UC Davis) Ph.D. August 2013.
- Nicholas F. Travers (Mathematics, UC Davis) Ph.D. August 2013.

M.S. Degrees Earned During Reporting Period

- K. Miltenberger, MS thesis on collective behavior. April 2016.

Additional information on programs, students, and faculty of the Information Engines MURI project and the Complexity Sciences Center is available online at <http://informationengines.org/and> <http://csc.ucdavis.edu/>, respectively.

The list of trainees—postdoctoral, graduate, and undergraduate students—follows. (0% FTE means a researcher substantially participated in advancing project goals, but did not receive direct financial support from the project.)

Research Scientists Involved

- Warren Fon (Physics, Caltech) 20% FTE.
- Matthew Matheny (Physics, Caltech) 50% FTE.
- Korana Burke (Lecturer in Mathematics, UC Davis).
- John Mahoney (Lecturer in Mathematics, UC Davis).
- Dowman Varn (Lecturer in Mathematics, UC Davis).

Postdoctoral Researchers Involved

- Fabio Anza (Physics, UCD) TWCF Fellow, 0% FTE.
- Alec Boyd (Center for Quantum Technologies, U. Singapore), TWCF Fellow, 0% FTE.
- Korana Burke (Physics, UCD) September 2012-2015, UC Davis Chancellor's Postdoctoral Fellowship. 0% FTE.
- Ryan James (Physics, UCD) 10% FTE.
- Sarah Marzen (Physics, MIT) Physics of Life Fellowship, 0% FTE.
- Paul Riechers (Center for Quantum Technologies, U. Singapore), 0% FTE.
- Olli-Pentti Saira (Physics, Caltech) 100% FTE.
- Cina Aghamohammadi (Woods Hole Oceanographic Institution), 0% FTE.
- Louis Kang (Physics, UCB) 0% FTE.
- Dibyendu Mandal (Physics, UCB) 100% FTE.

- Jascha Sohl-Dickstein (Google; Neuroscience, Stanford) 0% FTE.
- John Mahoney (Physics, UCD) 0% FTE.
- Parag Katira, Ph.D. (Associate Research Scientist, Columbia), 50% FTE.
- Patrick Zulkowski (Physics, UCB) 25% FTE.
- Sebastian Deffner (Chemical Physics, Maryland), 100% from 9/2013-8/2014; 100% FTE.

Graduate Students Involved

- Jeff Emenheiser (Physics, UCD), Ph.D. candidate. 0% FTE.
- David Gier (Physics, UCD), Ph.D. candidate. NSF Graduate Fellow. 0% FTE.
- Wade Hodson (Physics, UMD), Ph.D. candidate. 50% FTE.
- Xincheng Li (Engineering, UMD), Ph.D. candidate. 100% FTE.
- Alexandra Jurgens (Physics, UCD), Ph.D. candidate. 20% FTE.
- Raj Katti (Physics, CalTech), PhD candidate. 20% FTE.
- Xincheng Lei (Physics, UCD), Ph.D. candidate. 50% FTE.
- Sam Loomis (Physics, UCD), Ph.D. candidate. 25% FTE.
- Dani Masante (Physics, UCD), Ph.D. candidate, UCMEXUS Graduate Fellow. 0% FTE.
- Adam Rupe (Physics, UCD), Ph.D. student. 25% FTE.
- Pratik Sachdeva (Chemistry, UCB), Ph.D. student. 0% FTE.
- Ariadna Venegas-Li (Physics, UCD), Ph.D. candidate. 20% FTE.
- Kyle Ray (Physics, UCD), Ph.D. candidate. 50% FTE.
- Neha Wadia (Physics, UCB), Ph.D. student. 0% FTE.
- Greg Wimsatt (Physics, UCD), Ph.D. candidate. 100% FTE.
- Ryan Zarccone (Physics, UCB), Ph.D. student. 0% FTE.
- Michael Fang (Physics, UCB), Ph.D. student. 0% FTE.
- Andrew Ligeralde (Physics, UCB), Ph.D. student. 0% FTE.
- Charles Frye (Physics, UCB), Ph.D. student. 0% FTE.

- Steven Lee (Physics, UCB), Ph.D. student. 0% FTE.
- Mayur Mudigonda (Physics, UCB), Ph.D. student. 0% FTE.
- Tyler Maltba (Physics, UCB), Ph.D. student. 0% FTE.
- Nick CinkoAdam Frim (Physics, UCB), Ph.D. student. 0% FTE.
- Cina Aghamohammadi (Physics, UCD), Ph.D. student. 47% FTE.
- Alec Boyd (Physics, UCD), PhD candidate. 47% FTE.
- Eric Dodds (Physics, UCB), Ph.D. student. 0% FTE.
- Udit Halder (Engineering, UMD) Ph.D. candidate. 0% FTE. Ph.D. Expected April 2019: collective behavior, information propagation and noise.
- Yunlong Huang (Engineering, UMD) Ph.D. August 2017. 100% FTE.
- Katherine Klymko (Chemistry, UCB), Ph.D. student. 0% FTE.
- Vidya Radu (Engineering, UMD) Ph.D. candidate. 50% FTE. Expected April 2019: collective behavior, replicator dynamics and control, and noise.
- Andrew Mavin Smith (Chemical Physics, Maryland), PhD candidate. 50% FTE.
- Joseph Demers (Chemical Physics, Maryland), PhD candidate. 50% FTE.
- Nix Barnett (Mathematics, UCD), PhD candidate. 47% FTE.
- Paul Riechers (Physics, UCD), PhD candidate. 47% FTE.
- Dmitry Shemetov (Mathematics, UCD), Ph.D. student. 0% FTE.
- Henri Palacci (Biomedical Eng., Columbia), PhD candidate. 50% FTE.
- V. Raju (Engineering, UMD) Ph.D. 0% FTE.
- Michael Prijatelj (Physics, CalTech), Ph.D. Candidate. 0% FTE.
- Megan Armstrong (Biomedical Eng., Columbia), PhD candidate. 12% FTE.
- Ofer Idan (Biomedical Eng., Columbia), PhD candidate. 18% FTE.
- Amy Lam (Biomedical Eng., Columbia), PhD candidate. 17% FTE.
- Ayoti Patri (Chemical Physics, Maryland), PhD candidate. 50% FTE.
- Zhiyue Lu (Chemical Physics, Maryland), PhD candidate. 50% FTE.

- Biswadip Dey (Elec. Comp. Eng., Maryland), PhD candidate. 0% FTE.
- Patrick R. Zulkowski, (Physics, UCB) Ph.D. August 2013. 50% FTE.
- Pooneh Ara (Physics, UCD), PhD candidate. 47% FTE (NetControl MURI).
- Benny Brown (Physics, UCD), Ph.D. candidate. 0% FTE.
- Sarah Marzen (Physics, UCB), Ph.D. student. UC Berkeley & NSF Fellowships. 0% FTE.
- Grant Rotskoff (Chemistry, UCB), Ph.D. candidate. 0% FTE.
- K. Miltenberger (Elec. Comp. Eng., GSR) 50% FTE.
- Neda Bassir Kazeruni (Biomedical Eng., Columbia), PhD candidate. 17% FTE.
- Stanislav Tsitkov (Biomedical Eng., Columbia), PhD candidate. 16% FTE.

Undergraduate Students Involved

- Sara Pohland Huang (Engineering, UMD), B.S. student. 0% FTE.
- Hyun Su Kim (NSF REU undergraduate intern, Physics, UCD, 2017) 0% FTE.
- Bahti Zakirov (NSF REU undergraduate intern, Physics, UCD, 2017) 0% FTE.
- Josh Ruebeck (NSF REU undergraduate intern, Physics, UCD, 2016) 0% FTE.
- Brent Schlotfeldt (Engineering, UMD, 2017), pursuing PhD study in Electrical Engineering at the University of Pennsylvania.
- David Gier (NSF REU undergraduate intern, Physics, UCD, 2015) 0% FTE.
- Alexandra Nilles (NSF REU undergraduate intern, Physics, UCD, 2014) 0% FTE.
- Andrew Berger (Physics, UCB, 2015) 0% FTE.
- Brendan Roberts (NSF REU undergraduate intern, Physics, UCD, 2013).
- Greg Wimsatt (Undergraduate intern, Physics, UCD).

Results Dissemination

The Information Engines MURI's productivity was sustained at a high level, indicating an intellectual maturation as the teams overcame previous theoretical and experimental challenges. The results were disseminated rather widely. Annual summary:

2019: Thirty-eight manuscripts were in play, 19 appeared in peer-reviewed, high-profile journals, another 11 manuscripts were under review, and 8 were in preparation.

2018: 40 manuscripts, 25 appeared in peer-reviewed, high-profile journals and another 11 manuscripts under review.

2017: 52 manuscripts, 35 appeared in peer-reviewed, high-profile journals and another 17 manuscripts were under review.

2016: 40 manuscripts, 24 appeared in peer-reviewed, high-profile journals and another 21 manuscripts were submitted.

Each year during the MURI, the Lead PI co-organized the workshop on *Information Engines at the Frontier of Nanoscale Thermodynamics*, held at the Telluride Science Research Center, typically 10 days during July, and supported by ARO. The Lead PI also organized *Beyond Shannon—The Structure and Meaning of Information*, held at the Institute for Advanced Study, University of Amsterdam, 6-8 May 2019.

Space does not permit listing the hundreds of presentations—team colloquia, keynotes, lecture courses, invited presentations, and team-organized meetings and workshops. These are, however, documented in detail in the annual Interim Progress Reports.

Plans

The MURI, active over seven years, two over the usual duration of five years, has ended. Much remains to do, of course, despite the its marked accomplishments. The team was graced with discovering powerful theoretical results and a state-of-the-art experimental platform on which to test them and to explore additional ideas. It will continue to use its meeting-workshops in Telluride to monitor the coming challenges and to follow-through on our current research foci.

Appreciating future challenges requires recalling that it underwent a substantial change in organization, pivoting to the flux qubit devices of the Roukes group at Caltech. Our second “volunteer” experimentalist, Jukka Pekola (Aalto University, Finland), actively collaborated with the team on the challenges of designing devices for yoctojoule calorimetry and bolometry and for scaling up to coupled information engines.

Looking forward, beyond the MURI, several of the more specific plans the PIs will pursue are listed in the following.

PI Crutchfield: Our primary effort will merge our theoretical progress on the thermodynamics of information engines and information ratchets with the experimental realizations developed by the Caltech team. In fact, PI Crutchfield spent half a sabbatical year in the Roukes lab helping to drive this effort. Our theoretical efforts will also continue with foundational questions on the limits, trade-offs, and capabilities of information engines in terms of fluctuations and large deviations from thermodynamic functioning and also directly probing the thermodynamic costs of modularity. We are now actively designing information engines circuits and lattices and seeking financial support for these efforts.

PI Roukes: The team completed flux qubit thermodynamic experiments, extracting detailed data to validate the UC Davis fluctuation theorem predictions. This proved to be a rich system with many positive attributes for experiments on nanoscale information processing. We are continuing to pursue development of on-board bolometric thermodynamic measurements; a variety of structures based on both epitaxial Al/InAs and single-layer graphene were designed and fabricated. Additionally, we continue to advance our understanding of calorimetric measurements to detect quantum transitions through the local heat bath. Construction of prototype calorimeters using superconducting-semiconducting-superconducting (SNS) junctions to restrict the number of electron states to achieve very small energy resolutions is underway. Currently, the Roukes group is in the process of having these junctions grown (via epitaxy) in collaboration with the Palmstrom group at UC Santa Barbara and the Nadj-Perge group at Caltech. Designs that are compatible with bolometric measurements of classical logic

erasure are underway. There are only minor adjustments to the experimental platform to measure thermodynamic changes within quantum processes. Caltech plans on performing thermodynamic measurements of quantum processes immediately following measurements of the classical counterparts.

Honors, Awards, and Appointments

Space does not permit listing the dozens of PI honors, awards, and appointments. These are, however, documented in detail in the annual Interim Progress Reports.

Tech Transfer

- **PI Crutchfield:** Continues to maintain and augment the MURI's website <http://informationengines.org/> to facilitate team collaborations and outreach.
- **PI Crutchfield:** Continues to develop the open source Python package "Computational Mechanics in Python" (CMPy) consisting of most of computational mechanics' constructive mathematical results and methods. Jupyter/Python notebooks continue to be developed to illustrate calculational details reported in our publications. A suite of over two-dozen Jupyter notebooks was developed as tutorials. CMPy has been ported to run on the Jupyter notebook service CoCalc.com. Efforts initiated to port CMPy from Python 2.7.X to Python 3.X.
- **PI Crutchfield:** Further developed the open source *Discrete Information Theory* Python
- package dit: <https://github.com/dit/dit>. Most notably, it was extended to include an even morecomplete suite of multivariate information measures for dynamical and stochastic networks. Including, in particular, new algorithms for secret key agreement measures of unique information [JPC17].
- **PI Krishnaprasad:** Transfer of knowledge to the Naval Research Laboratory through collaboration with Dr. Eric Justh has continued on a regular basis. Concrete applications of this transfer effort are expected in the area of collective behavior in unmanned aerial and marine systems. Other applications to development of machine learning algorithms are also under consideration.
- **PI Krishnaprasad:** There have been multiple interactions with Dr. Adam Svenkeson (Research Scientist at Army Research Laboratory, Aberdeen, MD) and these are expected to continue on a monthly basis, with the aim of developing collaborations.
- **PI Krishnaprasad:** Additional collaboration with Northrop Grumman Mission Systems(contact: Dr. Isidoros Doxas) has been initiated to allow further developments in the directionof adversarial learning modeled by controlled replicator dynamics subject to noise. Applications are being considered in agile surveillance systems capable of countering adversarial responses. PI Krishnaprasad will present new results at a Northrop Grumman Research Symposium in October 2019.

- **PI Krishnaprasad:** A new collaboration, including joint proposal development has been initiated with Ford in the area of autonomous systems and machine learning.

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