Recent theoretical and experimental advances in nonequilibrium thermodynamics provide a new understanding of how “intelligent” control can convert information to energy. However, these approaches have yet to account for the diverse kinds of information that complex nonlinear systems are capable of producing and storing. This is particularly a concern regarding the diversity of differently structured irreversible processes, which play key role in limiting computation. Fortunately, computational mechanics accounts for this diversity, but in autonomous dynamical systems. Thermodynamic cycles that perform useful information processing are nonautonomous.
ABSTRACT

Recent theoretical and experimental advances in nonequilibrium thermodynamics provide a new understanding of how “intelligent” control can convert information to energy. However, these approaches have yet to account for the diverse kinds of information that complex nonlinear systems are capable of producing and storing. This is particularly a concern regarding the diversity of differently structured irreversible processes, which play key role in limiting computation. Fortunately, computational mechanics accounts for this diversity, but in autonomous dynamical systems. Thermodynamic cycles that perform useful information processing are nonautonomous systems. To analyze information processing in nonautonomous systems, computational mechanics must be extended to controlled dynamical systems. Additionally, it must be augmented to account for the energetics that support information generation and storage.

The project’s goal was to synthesize the new nonequilibrium thermodynamics and computational mechanics into a single framework. The project successfully reached this goal and, leveraging that success, the research effort continues under the ARO-based MURI "Information Engines" (W911NF-13-1-0390), under the PI's leadership. The framework now provides techniques to analyze and predict the mechanisms by which energy flows support information processing. Using these, we are developing broadly applicable principles of emergent organization and hierarchy in complex physical and biological systems, including new bounds on the minimum required energy dissipation.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper


08/27/2014  7.00 Virgil Griffith, Edwin Chong, Ryan James, Christopher Ellison, James Crutchfield. Intersection Information Based on Common Randomness, Entropy, (04 2014): 0. doi: 10.3390/e16041985

TOTAL: 5
### Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

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(c) Presentations
December 2013, Complexity Sciences Center, UC Davis.
Jee Boyd (UCD), “Information Engines”, 3 December 2013, Workshop on Information in Infinitary Processes, 3-4 December 2013, Complexity Sciences Center, UC Davis.
Korana Burke (UCD), reviewed PRE “Information Content in Turbulence”, 20 November 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
J. P. Crutchfield (UCD), reviewed “Learning in embodied action-perception loops through exploration”, 30 October 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
Korana Burke (UCD), reviewed Milnor and Thurston's “Kneading Calculus”, 25 September and 2 and 9 October 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

**Number of Presentations:** 48.00

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<td>Dibyendu Mandal, James P. Crutchfield, Alexander B. Boyd. Identifying Functional Thermodynamics in Autonomous Maxwellian Ratchets, PHYSICAL REVIEW X (06 2015)</td>
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<td>Ryan G. James, Korana Burke, James P. Crutchfield. Chaos forgets and remembers: Measuring information creation, destruction, and storage, Physics Letters A (06 2014)</td>
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<td>Nicholas F. Travers, James P. Crutchfield. Equivalence of History and Generator epsilon-Machines, J. of Theoretical Probability (08 2013)</td>
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<td>James P. Crutchfield, Christopher J. Ellison. The Past and the Future in the Present, Physical Review E (10 2012)</td>
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<td>Ryan G. James, John R. Mahoney, Christopher J. Ellison, James P. Crutchfield. Many Roads to Synchrony: Natural Time Scales and Their Algorithms, Physical Review E (02 2013)</td>
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| Patents Submitted |          |
| Patents Awarded   |          |

### Awards

- PI Crutchfield awarded two-year accelerated promotion due to research accomplishments supported by this grant.

- PI Crutchfield's publication "Regularities Unseen, Randomness Observed" was selected by American Institute of Physics journal Chaos---A Journal of Nonlinear Science as one of the top 10 publications in the journal's 25 year history.

- Kevin Taylor, “Extending Reinforcement Learning Methods with a Simple Robot”, Undergraduate Senior Thesis (June 2013), awarded Highest Honors by Physics Department.

- Korana Burke: Assumed UC Davis Chancellor Postdoctoral Fellowship, Complexity Sciences Center, Physics Department (September 2012).


Graduate Students

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Names of Under Graduate students supported

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Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period.

The number of undergraduates funded by this agreement who graduated during this period: ...... 3.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 3.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 3.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 3.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ...... 1.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 3.00
### Names of Personnel receiving masters degrees

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### Sub Contractors (DD882)

### Inventions (DD882)
Scientific Progress
Intrinsic Information Processing and Energy Dissipation in Stochastic Input-Output Dynamical Systems

James P. Crutchfield, Principal Investigator
Complexity Sciences Center, Department of Physics
University of California, Davis, California 95616

Statement of the Problem Studied

Recent theoretical and experimental advances in nonequilibrium thermodynamics provide a new understanding of how "intelligent" control can guide the flow of disorganized thermal energy to useful work energy. However, these approaches have yet to account for the diverse kinds of information that complex nonlinear systems are capable of producing and storing. This is particularly a concern regarding the diversity of differently structured irreversible processes, that play key role in limiting computation. Fortunately, computational mechanics accounts for this diversity, but in autonomous dynamical systems. Thermodynamic cycles that perform useful information processing, in contrast, are nonautonomous systems. To analyze embedded information processing, computational mechanics must be extended to controlled dynamical systems. Additionally, it must be augmented to account for the energetics that support information generation and storage.

The project's goal was to explore the mathematical and theoretical foundations necessary to synthesize the new nonequilibrium thermodynamics and computational mechanics into a single framework. The project successfully reached this goal and, leveraging that success, the research effort continues under the ARO-based MURI "Information Engines" (W911NF-13-1-0390), under the PI's leadership. The framework now provides techniques to analyze and predict the mechanisms by which energy flows support information processing. Using these, we are developing broadly applicable principles of emergent organization and hierarchy in complex physical and biological systems, including new bounds on the minimum required energy dissipation for different kinds of information processing.

Approach

The scientific approaches involved consist of:

--- Nonlinear complex dynamical systems: Gives a detailed and structural view of the state-space mechanisms in nonlinear systems that guide and constrain system behavior.
--- Nonequilibrium statistical physics and thermodynamics: Delineates the kinds of work and work cycles required to overcome irreversible processes.
--- Computational mechanics: Allows for the exact characterization of the intrinsic information processing in complex systems.

Several technical approaches will be used identify relevant structures in nonlinear complex systems—equilibria, limit cycles, invariant submanifolds, ε-machines, and measures of intrinsic computation. The approaches include:

--- Analytical methods to solve in closed-form for the simplest prototype system behaviors and emergent properties.
--- Symbolic computing to extend the range of closed-form analysis to nontrivial complex behaviors.
--- Large-scale simulation using high-performance computing to go beyond their limitations.

Typically, nonlinear systems admit analytical solutions only in special cases. HPC-based simulations allow one to explore physically realistic behaviors outside of analytically approximated regimes.

Relevance to Army

Success in these tasks will enhance a number of Army capabilities, including:

--- Fundamental science of nonequilibrium thermodynamics: This is key to understanding emergent organization in a wide range of mechanical, electronic, chemical, biological, and social processes of interest to the Army.
--- Fundamental science of physical information processing: We are developing methods to analyze the nonlinear dynamical mechanisms that underlie the coupling between energy and information flows in complex physical systems.
--- Minimum energy requirements: By setting new bounds on energy dissipation required for information processing, the results will allow for more accurate estimates of optimal energy efficiencies in a wide range of information processing and control systems of interest to the Army.
--- Design efficiency: Building on these bounds, the results will lead to new design paradigms for large-scale, complex systems of interest to the Army.

Summary of the Most Important Results

The original proposal’s research strategy was to synthesize the three scientific areas via the following tasks.
--- Task A: Energetics Introduce energetics into computational mechanics’ informational view of complex systems.
--- Task B: Input-Output Dynamical Systems Develop a symbolic dynamics appropriate to controlled (input-output) dynamical systems by extending computational mechanics from signal generators (ε-machines) to signal transducers (ε-transducers).
--- Task C: Efficiency of Thermodynamic Information Processing Cycles Perform detailed computational mechanics informational analysis of the cyclic process by which thermodynamic transformations convert control information to free energy.
--- Task D: Microdynamics Perform a detailed dynamical systems analysis of the state-space or ganization of the dynamics underlying this same cyclic process.

Though the original proposal was rather ambitious, we believe that each of the tasks was addressed. We also now know that there is much follow-up research to do. In particular, while Tasks A-C are being pursued via the follow-on “Information Engines” MURI, Task D seems particularly deserving future attention.

The Publications (P#), manuscripts Under Review (UR#), and Manuscript in Preparation (IP#) document the task accomplishments and scientific progress. Their publication data and associated reprints and preprints have been uploaded to https://extranet.aro.army.mil. They are listed again below in the Bibliography to provide references for the narrative summary of the accomplishments.

The main highlights for scientific progress and accomplishments over the project are:

--- Information control of thermodynamical systems: The project achieved its most important scientific goal to describe how two processes interact: the mathematical foundations of ε-transducers. In short, we successfully extended the computational mechanics of ε-machines to optimal minimal transducers (P8). This opens up a huge range of applications. For example, we now have the mathematical tools with which to analyze controlled nonlinear dynamical systems—what the original proposal called input-output dynamical systems. Another example is that we can exactly identify the informational contributions to the flow of information between two systems (IP3). A third, and perhaps the most concrete application, is to analyzing the informational properties of controlled thermodynamic transformations. We recast Szilard’s Engine, a version of Maxwell’s Demon, showing that (i) it is a chaotic dynamical system whose degree of instability determines its rate of converting thermal fluctuations to useful work (UR4). We also introduced a broad family of fully analyzable information ratchets that operate as engines, consuming random bits on a tape and using the information to guide converting thermal fluctuations to lift a weight against gravity (UR5).

--- Exact Complexity: A new level of analytical precision for all uses of information-theoretic measures of complexity was developed. All known complexity measures for stationary discrete-valued hidden processes and dynamical systems with generating partitions can now be calculated in closed form from their ε-machine, if the latter is finite. This has been critical to progress in a number of applications to calculating correlation functions, power spectral densities, and a wide range of information measures. We adapted and substantially extended the methods of holomorphic functional calculus to give closed-form expressions for all functions of ε-machine transitions matrices. The result is that quantities, previously analytically uncomputable, and those that required exponential computational resources are now given by exact, closed-form expression. In computational complexity terms, what were exponential complexity computations are now constant-time algorithms. This is a major advance in the computational efficiency of analyzing intrinsic computation in complex systems. It also gives much theoretical insight into the very nature of intrinsic computation. (UR3 and IP2)

--- Mixed-States as Efficient Representations: A key part of these advances was our extending the underlying representation, the so-called mixed states, beyond simple discrete-alphabet and symbolic-dynamic processes to vector-valued and high-dimensional dynamical systems. One practical consequence is that the computational efficiencies we now enjoy for analyzing the intrinsic computation in low-dimensional systems applies to arbitrarily high-dimensional systems, including spatially extended dynamical systems and dynamical networks. (IP4)

--- Information Processing in Multi-input, Multi-output Channels: We introduced a consistent set of measures of redundant, synergistic, and unique information in multi-input, multi-output channels. This gives a systematic way of decomposing shared or mutual information into unique “atomic” components and opens up a way to understand how state-space structures in nonlinear dynamical systems support distinct kinds of information processing. (P4)

--- Chaos Forgets and Remembers: This project’s most historically surprising result showed how chaotic systems create, destroy, and store information. For over a half century chaotic dynamical systems were characterized by a single “system invariant”, the rate at which they generated information, called the Kolmogorov-Sinai entropy rate. We showed that this rate consists of two radically distinct kinds of information processing: (i) a component that is created and dissipation and (ii) a component that is created but actively stored by the system. (P2, P3, and P9)

--- The foundational and insightful aspect of these results were acknowledged in a Nature News and Views commentary on (P2): P. M. Binder and R. M. Pipes, “How Chaos Forgets and Remembers”, Nature 510 (19 June 2014) 343-344.

--- Intrinsic Computation in Continuous Systems: Computational mechanics has been successfully extended to processes over continuous-time and continuous-state. Our first results showed how to calculate the information anatomy of continuous-state
random walks in nonlinear potentials (P3). The second results showed how to do this for continuous-time memoryful renewal processes—a well known class of processes that is widely used, from statistical mechanics to geophysics and neuroscience (P9). For example, using these results, we analyzed the effect of time coarse-graining on information measures of complexity (IP1). To illustrate those mathematical methods, as an application we analyzed the statistical complexity and other intrinsic computation measures for neural spike trains (P6).

Synchronization: A key property of controlling nonlinear dynamical systems is how the driven system becomes correlated, or not, to the imposed driving signal. To understand this and frame it information-theoretically, we analyzed in some detail and then provided exact calculational algorithms to determine the amount and kind of information and time required for an observer to synchronize to a structured process. (P1)

--- Structural Inference: We developed a complete Bayesian inference method to infer the structure of hidden processes from time series data. This goes substantially beyond statistical parameter estimation methods typical of modern machine learning to estimation and modeling in that it makes minimal assumptions about the model classes. The latter, it should be emphasized, is the key issue when attempting to discover structure and not merely verify a structural modeling assumption. That is, our methods determine the appropriate model class from data directly. (P5)

--- Nonergodic Processes: We successfully extended the computational mechanics of \(\epsilon\)-machines from describing the structure and intrinsic computation in stationary, ergodic processes to that in nonergodic processes. This opens up a much wider range of applications of computational mechanics to, for example, analyzing structural properties of ergodic decompositions, change-point processes, multi-arm bandit processes, and nonequilibrium steady states. (IP5)

Correlations in Finitary Processes: We showed how to calculate, exactly and in closed-form, the pairwise correlations for any stochastic processes generated by finite-state hidden Markov models. This extends our previous methods that required unifiarity of the generator to the general, unrestricted case of nonunifilar generators. To give a concrete application and physical meaning to the results we demonstrated how the methods provide new insights into the organization of chaotic one-dimensional crystals; that is, into those that have any degree of disorder. (P7)

--- Computational Mechanics Foundations: Several technical papers established critical and oft-assumed properties in computational mechanics. This first showed that the original “equivalence-class” or “history” definition of optimal, minimal unifilar predictors is equivalent to the “generator” definition (UR1). The second showed when it is possible, in working with information measures over semi-infinite pasts and semi-infinite futures, to replace them with \(\epsilon\)-machine forward-time and reverse-time causal states. (UR2)

\[\text{Bibliography}\]

Resulting Journal Publications During Reporting Period


Manuscripts under Review and Technical Reports


UR4. A. B. Boyd and J. P. Crutchfield, “Demon Dynamics: Deterministic Chaos, the Szilard Map, and the Intelligence of


Manuscripts in Preparation


Appendices

The bulk of the following information has been uploaded to the webforms at https://extranet.aro.army.mil. However, the following provides more detail.

Collaborations and Technology Transfer

Continued development of open source library “Computational Mechanics in Python” (CMPy) that consists of all of the project’s constructive mathematical results and methods. Planned release as open source software package slated for Winter 2016.

This project led to the PI being awarded a ARO-based MURI. The expanded effort greatly broadens the impact of the current project’s results in collaborations with other universities and via interactions with ARO and ARL (e.g., in Albuquerque, NM).

Ph.D. Degrees Earned During Reporting Period

--- Nicholas F. Travers (Mathematics) completed Ph.D. June 2013.
--- Virgil Griffith (Neuroscience, CalTech), Ph.D. Fall 2014.

Postdoctoral Researchers Involved During Reporting Period

--- Korana Burke: (Physics) September 2012-2014.
--- John R. Mahoney (Physics) January 2015-present.
--- Dowman P. Varn (Physics) August 2014-present.

Graduate Students Involved During Reporting Period

--- Jason (Nix) Barnett (Mathematics) Ph.D. Fall 2015, expected.
--- Sarah Marzen (Physics, UCB) Ph.D. Fall 2016, expected.
--- Alec Boyd (Physics) Ph.D. Spring 2016, expected.
--- Pooneh Mohammediari (Physics), M.S. Fall 2015, expected.
--- Benny Brown (Physics), M.S. Spring 2016, expected.
--- Greg Wimsatt (Physics) Ph.D. Spring 2016, expected.

Undergraduate Students Involved During Reporting Period

--- Alexandra Nilles (NSF REU undergraduate intern, Physics, 2014).
--- Greg Wimsatt (Undergraduate intern, Physics, 2013).
--- Kevin Taylor (Undergraduate intern, Physics, 2012-2013).
--- Brenden Roberts (NSF REU undergraduate intern, Physics, 2013).
Awards, Honors, and Appointments

--- PI Crutchfield awarded two-year accelerated promotion due to research accomplishments supported by this grant.
--- PI Crutchfield's publication "Regularities Unseen, Randomness Observed" was selected by American Institute of Physics journal Chaos—Journal of Nonlinear Science as one of the top 10 publications in the journal's 25 year history.
--- Kevin Taylor, "Extending Reinforcement Learning Methods with a Simple Robot", Undergraduate Senior Thesis (June 2013), awarded Highest Honors by Physics Department.
--- Ryan G. James: Assumed post-doctoral research position in Computer Science Department, University of Colorado, Boulder (September 2013-August 2014).
--- Ryan G. James: Assumed post-doctoral research position in Complexity Sciences Center, Physics, University of California, Davis (September 2014-present).
--- Nicholas F. Travers: Assumed post-doctoral research position in Mathematics Department, Technion University, Israel (September 2013-August 2015).
--- Nicholas F. Travers: Assistant Professor, Mathematics Department, University of Indiana, Bloomington. (September 2015-).
--- Korana Burke: UC Davis Chancellor Postdoctoral Fellowship, Complexity Sciences Center, Physics Department (2012-2014).
--- John Mahoney, Assumed post-doctoral research position in Complexity Sciences Center, Physics, University of California, Davis (September 2014-August 2017).
--- Sarah Marzen (Physics, UCB) UC Berkeley Chancellor’s Graduate Fellow (Fall 2013-present).
--- Sarah Marzen (Physics, UCB) National Science Foundation Graduate Fellow (Fall 2013-present).

Additional information on programs, students, and faculty of the Complexity Sciences Center is available online: http://csc.ucdavis.edu/.

Talks and Presentations: For those by group members see Presentations section filed at https://extranet.aro.army.mil.

Sarah Marzen (UCB) “Information Theoretic Methods of Time Series Analysis”, March 2014, Machine Learning seminar, Computer Science Department, University of Hawaii, Manoaa.
Training: JPC taught two graduate courses Winter and Spring 2014 on the physics of information and the physics of computation, respectively.
Benny Brown, review of D. Little and F. Sommer “Learning and exploration in action-perception loops”, 21 May and 18 June
2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Fritz Sommer (Redwood Ctr, UCB), "Predictive Information Gain for Adaptive Learning", 11 June 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Alec Boyd, review of Mlodinow and Brun, "Relation between the psychological and thermodynamic arrows of time", 14 May 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Amanda Young, "Quantum Spin Chains", 30 April and 7 May 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Sarah Marzen, "Information Anatomy of Continuous Stochastic Processes", 16 April 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.


Ryan James (U Colorado, Boulder), "Intersection Information", 2 April 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.


Alec Boyd, review's Kawaguchi et al "Fluctuation theorem for hidden entropy production", 19 February 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Katie Amrine (Dept Viticulture and Enology) on "Information in transfer-RNAs to detect and resolve inconsistencies in deep roots of the Tree of Life", 12 February 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Pooneh Mohammadiara on "Elusive Information", 5 February 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.


J. P. Crutchfield led discussion on research job prospects and planning scientific and academic careers, 22 January 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.


Alec Boyd, review of Klages et al Ch. 1 "Fluctuation Relations", 11 and 18 December 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

J. P. Crutchfield, "Information in Infinitary Processes", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.

Dave Feldman (College of the Atlantic), "2D Information Theory", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.


Sarah Marzen (UCB), "Continuous-Time Processes", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.

Chris Strelloff, "Inferring Infinite-State Processes", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.

Alec Boyd, "Information Engines", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.


Korana Burke, reviewed Physical Review E "Information Content in Turbulence", 20 November 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

J. P. Crutchfield, "Information in Infinitary Processes", 13 November 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

J. P. Crutchfield, review of "Learning in embodied action-perception loops through exploration", 30 October 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Dowman Varn, "MultiAgent Dynamical Systems", 23 October 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Korana Burke, reviewed Milnor and Thurston's "Kneading Calculus", 25 September and 2 and 9 October 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Chun-Biu Li (Hokkaido) "Single Molecule Spectroscopy and Computational Mechanics", 17 September 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.


Alec Boyd, "Information Engines: Parts I and II", 21 and 28 August 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
Meetings
--- UCD group (Crutchfield, Boyd, Riechers) weekly visits to Redwood Center for Theoretical Neuroscience, UC Berkeley.
--- Nonequilibrium discussion meeting, every two weeks at the Redwood Center for Theoretical Neuroscience, UC Berkeley. (Crutchfield meeting co-sponsor and co-organizer.) See http://csc.ucdavis.edu/~chaos/share/infoeng/InfoEng/Discussion.html.

Technology Transfer
This project lead to the PI being awarded a ARO-based MURI. The expanded effort greatly broadens the impact of the current project's results in collaborations with other universities and via interactions with ARO and ARL (e.g., in Albuquerque).

Continued development of open source library "Computational Mechanics in Python" (CMPy) that consists of all of the project's constructive mathematical results and methods. Planned release as open source software package slated for Winter 2016.
Statement of the Problem Studied

Recent theoretical and experimental advances in nonequilibrium thermodynamics provide a new understanding of how “intelligent” control can guide the flow of disorganized thermal energy to useful work energy. However, these approaches have yet to account for the diverse kinds of information that complex nonlinear systems are capable of producing and storing. This is particularly a concern regarding the diversity of differently structured irreversible processes, that play key role in limiting computation. Fortunately, computational mechanics accounts for this diversity, but in autonomous dynamical systems. Thermodynamic cycles that perform useful information processing, in contrast, are nonautonomous systems. To analyze embedded information processing, computational mechanics must be extended to controlled dynamical systems. Additionally, it must be augmented to account for the energetics that support information generation and storage.

The project’s goal was to explore the mathematical and theoretical foundations necessary to synthesize the new nonequilibrium thermodynamics and computational mechanics into a single framework. The project successfully reached this goal and, leveraging that success, the research effort continues under the ARO-based MURI “Information Engines” (W911NF-13-1-0390), under the PI’s leadership. The framework now provides techniques to analyze and predict the mechanisms by which energy flows support information processing. Using these, we are developing broadly applicable principles of emergent organization and hierarchy in complex physical and biological systems, including new bounds on the minimum required energy dissipation for different kinds of information processing.

Approach

The scientific approaches involved consist of:
1. Nonlinear complex dynamical systems: Gives a detailed and structural view of the state-space mechanisms in nonlinear systems that guide and constrain system behavior.
2. Nonequilibrium statistical physics and thermodynamics: Delineates the kinds of work and work cycles required to overcome irreversible processes.

3. Computational mechanics: Allows for the exact characterization of the intrinsic information processing in complex systems.

Several technical approaches will be used to identify relevant structures in nonlinear complex systems—equilibria, limit cycles, invariant submanifolds, $\varepsilon$-machines, and measures of intrinsic computation. The approaches include:

1. Analytical methods to solve in closed-form for the simplest prototype system behaviors and emergent properties.
2. Symbolic computing to extend the range of closed-form analysis to nontrivial complex behaviors.
3. Large-scale simulation using high-performance computing to go beyond their limitations.

Typically, nonlinear systems admit analytical solutions only in special cases. HPC-based simulations allow one to explore physically realistic behaviors outside of analytically approximated regimes.

Relevance to Army

Success in these tasks will enhance a number of Army capabilities, including:

1. Fundamental science of nonequilibrium thermodynamics: This is key to understanding emergent organization in a wide range of mechanical, electronic, chemical, biological, and social processes of interest to the Army.
2. Fundamental science of physical information processing: We are developing methods to analyze the nonlinear dynamical mechanisms that underlie the coupling between energy and information flows in complex physical systems.
3. Minimum energy requirements: By setting new bounds on energy dissipation required for information processing, the results will allow for more accurate estimates of optimal energy efficiencies in a wide range of information processing and control systems of interest to the Army.
4. Design efficiency: Building on these bounds, the results will lead to new design paradigms for large-scale, complex systems of interest to the Army.

Summary of the Most Important Results

The original proposal’s research strategy was to synthesize the three scientific areas via the following tasks.

**Task A: Energetics** Introduce energetics into computational mechanics’ informational view of complex systems.

**Task B: Input-Output Dynamical Systems** Develop a symbolic dynamics appropriate to controlled (input-output) dynamical systems by extending computational mechanics from signal generators ($\varepsilon$-machines) to signal transducers ($\varepsilon$-transducers).

**Task C: Efficiency of Thermodynamic Information Processing Cycles** Perform detailed computational mechanics informational analysis of the cyclic process by which thermodynamic transformations convert control information to free energy.
**Task D: Microdynamics** Perform a detailed dynamical systems analysis of the state-space organization of the dynamics underlying this same cyclic process.

Though the original proposal was rather ambitious, we believe that each of the tasks was addressed. We also now know that there is much follow-up research to do. In particular, while Tasks A-C are being pursued via the follow-on “Information Engines” MURI, Task D seems particularly deserving future attention.

The Publications (P#), manuscripts Under Review (UR#), and Manuscript in Preparation (IP#) document the task accomplishments and scientific progress. Their publication data and associated reprints and preprints have been uploaded to https://extranet.aro.army.mil. They are listed again below in the Bibliography to provide references for the narrative summary of the accomplishments.

The main highlights for scientific progress and accomplishments over the project are:

1. **Information control of thermodynamical systems:** The project achieved its most important scientific goal to describe how two processes interact: the mathematical foundations of $\varepsilon$-transducers. In short, we successfully extended the computational mechanics of $\varepsilon$-machines to optimal minimal transducers (P8). This opens up a huge range of applications. For example, we now have the mathematical tools with which to analyze controlled nonlinear dynamical systems—what the original proposal called *input-output dynamical systems*. Another example is that we can exactly identify the informational contributions to the flow of information between two systems (IP3). A third, and perhaps the most concrete application, is to analyzing the informational properties of controlled thermodynamic transformations. We recast Szilard’s Engine, a version of Maxwell’s Demon, showing that (i) it is a chaotic dynamical system whose degree of instability determines its rate of converting thermal fluctuations to useful work (UR4). We also introduced a broad family of fully analyzable information ratchets that operate as engines, consuming random bits on a tape and using the information to guide converting thermal fluctuations to lift a weight against gravity (UR5).

2. **Exact Complexity:** A new level of analytical precision for all uses of information-theoretic measures of complexity was developed. All known complexity measures for stationary discrete-valued hidden processes and dynamical systems with generating partitions can now be calculated in closed form from their $\varepsilon$-machine, if the latter is finite. This has been critical to progress in a number of applications to calculating correlation functions, power spectral densities, and a wide range of information measures. We adapted and substantially extended the methods of holomorphic functional calculus to give closed-form expressions for all functions of $\varepsilon$-machine transitions matrices. The result is that quantities, previously analytically uncomputable, and those that required exponential computational resources are now given by exact, closed-form expression. In computational complexity terms, what were exponential complexity computations are now constant-time algorithms. This is a major advance in the computational efficiency of analyzing intrinsic computation in complex...
systems. It also gives much theoretical insight into the very nature of intrinsic computation. (UR3 and IP2)

3. **Mixed-States as Efficient Representations**: A key part of these advances was our extending the underlying representation, the so-called mixed states, beyond simple discrete-alphabet and symbolic-dynamic processes to vector-valued and high-dimensional dynamical systems. One practical consequence is that the computational efficiencies we now enjoy for analyzing the intrinsic computation in low-dimensional systems applies to arbitrarily high-dimensional systems, including spatially extended dynamical systems and dynamical networks. (IP4)

4. **Information Processing in Multi-input, Multi-output Channels**: We introduced a consistent set of measures of redundant, synergistic, and unique information in multi-input, multi-output channels. This gives a systematic way of decomposing shared or mutual information into unique “atomic” components and opens up a way to understand how state-space structures in nonlinear dynamical systems support distinct kinds of information processing. (P4)

5. **Chaos Forgets and Remembers**: This project’s most historically surprising result showed how chaotic systems create, destroy, and store information. For over a half century chaotic dynamical systems were characterized by a single “system invariant”, the rate at which they generated information, called the *Kolmogorov-Sinaï entropy rate*. We showed that this rate consists of two radically distinct kinds of information processing: (i) a component that is created and dissipation and (ii) a component that is created but actively stored by the system. (P2, P3, and P9)


7. **Intrinsic Computation in Continuous Systems**: Computational mechanics has been successfully extended to processes over continuous-time and continuous-state. Our first results showed how to calculate the information anatomy of continuous-state random walks in nonlinear potentials (P3). The second results showed how to do this for continuous-time memoryful renewal processes—a well known class of processes that is widely used, from statistical mechanics to geophysics and neuroscience (P9). For example, using these results, we analyzed the effect of time coarse-graining on information measures of complexity (IP1). To illustrate those mathematical methods, as an application we analyzed the statistical complexity and other intrinsic computation measures for neural spike trains (P6).

8. **Synchronization**: A key property of controlling nonlinear dynamical systems is how the driven system becomes correlated, or not, to the imposed driving signal. To understand this and frame it information-theoretically, we analyzed in some detail and then provided exact calculational algorithms to determine the amount and kind of information and time required for an observer to synchronize to a structured process. (P1)

9. **Structural Inference**: We developed a complete Bayesian inference method to infer the structure of hidden processes from time series data. This goes substantially beyond statistical parameter estimation methods typical of modern machine learning to estimation and modeling in that it makes minimal assumptions about the model classes. The latter, it should be emphasized, is the key issue when attempting to discover structure and not merely verify a
structural modeling assumption. That is, our methods determine the appropriate \textit{model class} from data directly. (P5)

10. \textit{Nonergodic Processes}: We successfully extended the computational mechanics of $\varepsilon$-machines from describing the structure and intrinsic computation in stationary, ergodic processes to that in nonergodic processes. This opens up a much wider range of applications of computational mechanics to, for example, analyzing structural properties of ergodic decompositions, change-point processes, multi-arm bandit processes, and nonequilibrium steady states. (IP5)

11. \textit{Correlations in Finitary Processes}: We showed how to calculate, exactly and in closed-form, the pairwise correlations for any stochastic processes generated by finite-state hidden Markov models. This extends our previous methods that required unifilarity of the generator to the general, unrestricted case of nonunifilar generators. To give a concrete application and physical meaning to the results we demonstrated how the methods provide new insights into the organization of chaotic one-dimensional crystals; that is, into those that have any degree of disorder. (P7)

12. \textit{Computational Mechanics Foundations}: Several technical papers established critical and oft-assumed properties in computational mechanics. This first showed that the original “equivalence-class” or “history” definition of optimal, minimal unifilar predictors is equivalent to the “generator” definition (UR1). The second showed when it is possible, in working with information measures over semi-infinite pasts and semi-infinite futures, to replace them with $\varepsilon$-machine forward-time and reverse-time causal states. (UR2)
Bibliography

Resulting Journal Publications During Reporting Period

Manuscripts under Review and Technical Reports

Manuscripts in Preparation
Appendices

The bulk of the following information has been uploaded to the webforms at https://extranet.aro.army.mil. However, the following provides more detail.

Collaborations and Technology Transfer
- Continued development of open source library “Computational Mechanics in Python” (CMPy) that consists of all of the project’s constructive mathematical results and methods. Planned release as open source software package slated for Winter 2016.
- This project led to the PI being awarded a ARO-based MURI. The expanded effort greatly broadens the impact of the current project's results in collaborations with other universities and via interactions with ARO and ARL (e.g., in Albuquerque, NM).

Ph.D. Degrees Earned During Reporting Period
- Nicholas F. Travers (Mathematics) completed Ph.D. June 2013.
- Virgil Griffith (Neuroscience, CalTech), Ph.D. Fall 2014.

Postdoctoral Researchers Involved During Reporting Period
- Korana Burke: (Physics) September 2012-2014.
- John R. Mahoney (Physics) January 2015-present.
- Dowman P. Varn (Physics) August 2014-present.

Graduate Students Involved During Reporting Period
- Jason (Nix) Barnett (Mathematics) Ph.D. Fall 2015, expected.
- Sarah Marzen (Physics, UCB) Ph.D. Fall 2016, expected.
- Paul M. Riechers (Physics) Ph.D. Winter 2016, expected.
- Alec Boyd (Physics) Ph.D. Spring 2016, expected.
- Pooneh Mohammediari (Physics), M.S. Fall 2015, expected.
- Benny Brown (Physics), M.S. Spring 2016, expected.

Undergraduate Students Involved During Reporting Period
- Alexandra Nilles (NSF REU undergraduate intern, Physics, 2014).
- Greg Wimsatt (Undergraduate intern, Physics, 2013).
- Kevin Taylor (Undergraduate intern, Physics, 2012-2013).
- Brenden Roberts (NSF REU undergraduate intern, Physics, 2013).
Awards, Honors, and Appointments

- PI Crutchfield awarded two-year accelerated promotion due to research accomplishments supported by this grant.
- PI Crutchfield's publication “Regularities Unseen, Randomness Observed” was selected by American Institute of Physics journal *Chaos—Journal of Nonlinear Science* as one of the top 10 publications in the journal's 25 year history.
- Kevin Taylor, “Extending Reinforcement Learning Methods with a Simple Robot”, Undergraduate Senior Thesis (June 2013), awarded Highest Honors by Physics Department.
- Ryan G. James: Assumed post-doctoral research position in Computer Science Department, University of Colorado, Boulder (September 2013-August 2014).
- Ryan G. James: Assumed post-doctoral research position in Complexity Sciences Center, Physics, University of California, Davis (September 2014-present).
- Nicholas F. Travers: Assumed post-doctoral research position in Mathematics Department, Technion University, Israel (September 2013-August 2015).
- Nicholas F. Travers: Assistant Professor, Mathematics Department, University of Indiana, Bloomington. (September 2015-).
- Korana Burke: UC Davis Chancellor Postdoctoral Fellowship, Complexity Sciences Center, Physics Department (2012-2014).
- John Mahoney, Assumed post-doctoral research position in Complexity Sciences Center, Physics, University of California, Davis (September 2014-August 2017).
- Sarah Marzen (Physics, UCB) UC Berkeley Chancellor’s Graduate Fellow (Fall 2013-present).
- Sarah Marzen (Physics, UCB) National Science Foundation Graduate Fellow (Fall 2013-present).

Additional information on programs, students, and faculty of the Complexity Sciences Center is available online: [http://csc.ucdavis.edu/](http://csc.ucdavis.edu/).

Talks and Presentations: For those by group members see Presentations section filed at [https://extranet.aro.army.mil](https://extranet.aro.army.mil).

10. Training: JPC taught two graduate courses Winter and Spring 2014 on the physics of information and the physics of computation, respectively.
20. Amanda Young, “Quantum Spin Chains”, 30 April and 7 May 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
27. Katie Amrine (Dept Viticulture and Enology) on “Measuring ‘Functional’ Information in transfer-RNAs to detect and resolve inconsistencies in deep roots of the Tree of Life”, 12 February 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
30. J. P. Crutchfield led discussion on research job prospects and planning scientific and academic careers, 22 January 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
32. Alec Boyd, review of Klages et al Ch. 1 “Fluctuation Relations”, 11 and 18 December 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
34. Dave Feldman (College of the Atlantic), “2D Information Theory”, 3 December 2013, Workshop on “Information in Infinitary Processes”, 3-4 December 2013, Complexity Sciences Center, UC Davis.
42. J. P. Crutchfield, review of “Learning in embodied action-perception loops through exploration”, 30 October 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
44. Korana Burke, reviewed Milnor and Thurston’s “Kneading Calculus”, 25 September and 2 and 9 October 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Meetings
2. UCD group (Crutchfield, Boyd, Riechers) weekly visits to Redwood Center for Theoretical Neuroscience, UC Berkeley.
3. Nonequilibrium discussion meeting, every two weeks at the Redwood Center for Theoretical Neuroscience, UC Berkeley. (Crutchfield meeting co-sponsor and co-organizer.) See http://csc.ucdavis.edu/~chaos/share/infoeng/InfoEng/Discussion.html.