Nonequilibrium Thermodynamics of Complex Agents: Information Processing from Nanophysics to Life

James Clerk Maxwell famously proposed that an intelligent demon can harness knowledge about its environment to produce useful work over 150 years ago. While this picture has been refined considerably in modern nonequilibrium thermodynamics, the field maintains that information processing allows agents to harness complex structure in their environment. This understanding of the energetic benefits of autonomous intelligence reveals a physical basis for the emergence of complex computing. And yet, these results only scratch the surface of the apparent hierarchy of complexity in nature. Here lies an opportunity to extend the scope of the physics of complexity. Whether a computation happens in a nanomechanical implementation of Maxwell's demon, an enzymatic manipulation of DNA, a bacterium as it navigates a nutrient landscape, an ant colony as individuals communicate through pheromones, or a trading algorithm that leverages fluctuating markets, energy and thermodynamic entropy are core concerns.

This workshop brings together experts in nonequilibrium information processing in its many forms and provides a platform for cross-disciplinary dialogue and collaboration. Together, we hope to synthesize our diverse expertise towards organizing principles of complex systems.

Workshop Programme

Format: Speakers will have 30 minutes for their talk and 5 minutes for questions.

Talk 1: 9:00 am - 9:35 am
Speaker: Alexander Boyd
Title: Maxwell's Demon and the Principle of Requisite Complexity
Abstract: Through his demon, James Clerk Maxwell showed that thermodynamic agents can harness information as a thermodynamic fuel. Conversely, Landauer showed that processing information comes at a cost. Modern nonequilibrium thermodynamics has synthesized these counterpoints into a unified understanding of the tradeoffs between information and energy in thermodynamic systems. For an agent that receives and processes a signal from its environment, this leads to the Information Processing Second Law of thermodynamics, which bounds the rate of work production during computation. However, the environment can have temporal correlations that may be inaccessible to simple agents. An agent operates on its input with temporal modularity, so it must dissipate energy when it is unable to store predictive information about the environment. Using this *modularity dissipation* we quantify how much must be dissipated due to the logical architecture of the agent, and we describe design principles for minimal dissipation. The result is the principle of Requisite Complexity: thermodynamically efficient agents must store enough memory to

match the statistical complexity of their environment.

Talk 2: 9:35 am - 10:10 am
Speaker: Paul Riechers
Title: The Error–Dissipation Tradeoff when Agents Compute
Abstract: We revisit the thermodynamics of computation in light of recent progress in nonequilibrium thermodynamics. Among several surprising new results, we discover a generic error–dissipation tradeoff whenever metastable memories are reliably transformed in time-symmetric environments. Energy consumption must diverge with increasing reliability of nonreciprocated transitions. This tradeoff is especially relevant to complex biological agents—whether they are behaving reliably at the nanoscale or are processing information in macroscopic meat computers. We consider the relevant energy scales and question if it is ever wise for agents to compromise their wit.

Talk 3: 10:10 am - 10:45 am
Speaker: Varun Narasimhachar
Title: Maxwell's Demon in a Quantum World
Abstract: Maxwell's demon epitomizes the intelligent thermodynamic agent that harnesses information to extract useful work. One might wonder: "What could the demon achieve if its machinations were enhanced by quantum information?" The resource theory of quantum thermodynamics provides ways of formalizing and answering this question. In this talk, we review some salient outcomes of our resource-theoretic work vis-a-vis the thermodynamics of agents: [1] thermodynamically-constrained manipulation of quantum coherence; [2] thermodynamics of classically-controlled quantum systems; [3] the thermodynamic advantage of a quantum memory over a classical one.

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[3] Narasimhachar, V., Thompson, J., Ma, J., Gour, G., and Gu, M. (2019). Quantifying memory capacity as a quantum thermodynamic resource. Physical review letters, 122(6), 060601.

Coffee: 10:45 am -11:15 am (Conference coffee officially scheduled 10:30 am - 11:00 am)

Talk 4: 11:15 am - 11:50 am
Speaker: Andrew Garner
Title: Oracular Information and the Second Law of Thermodynamics
Abstract: Devices that manipulate patterns one piece at a time in general require memory that contains information about both the input and output patterns. When considering the thermodynamics of pattern manipulation, the costs of updating this memory must also be taken into account. Typically, the

information in memory is determined by the history of these patterns ? but theoretically it can also contain oracular information ? correlations with upcoming parts of the pattern that cannot be accounted for by observation of the pattern?s history. In my talk, I will briefly review existing thermodynamic results about modular pattern manipulation. I then will comment on how the behaviour of oracular information is qualitatively different in devices that produce patterns than in devices that anticipate and consume patterns. In particular, though Landauer?s principle, I will discuss how oracular information in consumers of any pattern must be forbidden, by providing a constructive procedure that violates the second law of thermodynamics if oracular information is present.

Talk 5: 11:50 am - 12:25 pm
Speaker: Mikhail Prokopenko
Authors: Emanuele Crosato, Richard E. Spinney, and Mikhail Prokopenko
Title: On Thermodynamic Efficiency of Swarming Behaviour
Abstract: Self-organisation of coherent motion in systems of self-propelled particles (e.g., flocks, swarms, active matter) is a pervasive phenomenon [1, 2, 3, 4, 5, 6, 7], which may be explained by some underlying universal principles. We interpret self-organisation of collective motion as an example of collective and distributed computation, and study it as a thermodynamic phenomenon [8]. In this abstract we report on our investigation of key thermodynamic quantities such as free entropy and generalised work, using the dynamical model of collective motion proposed by Grégoire and Chaté [9]. This model exhibits a kinetic phase transition over the parameters controlling the particles' alignment, separating (i) the "disordered motion" phase, in which particles do not settle on a dominant direction while sharing a collective space, and (ii) the "coherent motion" phase, in which particles cohesively move in a common direction.

The Fisher information [10] measures the amount of information that an observable random variable X carries about unknown parameters $\theta = [\theta_1, \theta_2, ..., \theta_M]$. The probability of the states of the system, described by the state functions $X_m(x)$ over the configuration space and thermodynamic variables θ_m, in a stationary state, is given by the Gibbs measure:

$$p(x|\theta) = \frac{1}{Z(\theta)} e^{-\beta H(x,\theta)} = \frac{1}{Z(\theta)} e^{-\sum_m \theta_m X_m(x)} \tag{1}$$

where $\beta = 1/k_B T$ is the inverse temperature T (k_B is the Boltzmann constant), the Hamiltonian $H(x, \theta)$ defines the total energy at state x, and $Z(\theta)$ is the partition function [11, 12]. The Gibbs free energy of such system is:

$$G(T, \theta_m) = U(S, \phi_m) - TS - \phi_m \theta_m, \tag{2}$$

where U is the internal energy of the system, S is the configuration entropy and θ_m is an order parameter. For a physical system described by the Gibbs measure in Eq. (1), the Fisher information has several physical interpretations, e.g., it is equivalent to the thermodynamic metric tensor $g_{mn}(\theta)$, measures the size of the fluctuations about equilibrium in the collective variables X_m and X_n, is proportional to the curvature of the free entropy $\psi = \ln Z = -\beta G$, and to the derivatives of the corresponding order parameters with respect to the collective variables [11, 13, 14, 12, 15, 16]:

$$F_{mn} = g_{mn} = \langle (X_m(x) - \langle X_m \rangle)(X_n(x) - \langle X_n \rangle) \rangle = \frac{\partial^2 \psi}{\partial \theta_m \partial \theta_n} = \beta \frac{\partial \theta_m}{\partial \theta_n}, \qquad (3)$$

where the angle brackets represent average values over the ensemble.

It has also been argued that the difference between curvatures of the configuration entropy and the free entropy is related to a computational balance between uncertainty and sensitivity [17]. We established a thermodynamic basis for this relationship as follows [8]:

$$\frac{d^2 \langle \beta U_{gen} \rangle}{d\theta^2} = \frac{d^2 S}{d\theta^2} - \frac{\partial^2 \psi}{\partial \theta_m \partial \theta_n} = \frac{d^2 S}{d\theta^2} - F(\theta), \qquad (4)$$

where $\langle U_{\mathrm{gen}} \rangle = U(S, \phi) - \phi\theta$. This expression can be interpreted as the difference between the curvature of the free entropy, captured by the Fisher information (the sensitivity of the system), and the curvature of the configuration entropy (the uncertainty of the system). Under a quasi-static protocol, the first law of thermodynamics yields another important result for the generalised work W_{gen}:

$$F(\theta) = -\frac{d^2 \langle \beta W_{gen} \rangle}{d\theta^2}. \qquad (5)$$

Our results identify critical regimes and show that during the phase transition, where the configuration entropy of the system decreases, the rates of change of the work and of the internal energy also decrease, while their curvatures diverge.

We also consider a measure of the *thermodynamic efficiency of swarming behaviour* (treated as an example of distributed computation), defined, for a given value of the control parameter θ, as the reduction in uncertainty (that is, the increase in the internal order) that resulted from an expenditure of work:

$$\eta \equiv \frac{-dS/d\theta}{d\langle \beta W_{gen} \rangle / d\theta} = \frac{-dS/d\theta}{\int_{\theta}^{\theta'} F(\theta') d\theta'}, \qquad (6)$$

where θ^* is the zero-response point for which small changes incur no work [8]. This ratio can be considered entirely in computational terms as the ratio of increasing order, obtained at θ, to the cumulative sensitivity incurred over a process from the current state θ to the state of perfect order, identified by the zero-response point θ^*.

The *sensitivity* and the *uncertainty* are balanced in each phase (disordered motion or coherent motion). However, at criticality, i.e., during a kinetic phase transition, this balance is broken, and the ratio η, specified by Eq. (6), diverges or peaks in finite-size systems. This indicates that the maximal thermodynamical efficiency of swarming behaviour within the system of self-propelled particles is highest during the phase transition.

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[6] E. Crosato, L. Jiang, V. Lecheval, J.T. Lizier, X.R. Wang, P. Tichit, G. Theraulaz, and M. Prokopenko. Informative and misinformative interactions in a school of fish. *Swarm Intelligence*, 12(4):283-305, 2018.
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[16] M. Prokopenko, J.T. Lizier, O. Obst, and X.R. Wang. Relating Fisher information to order parameters. *Physical Review E*, 84:041116, 2011.
[17] M. Prokopenko and I. Einav. Information thermodynamics of near-equilibrium computation. *Physical Review E*, 91:062143, 2015.

Talk 6: 12:25 pm - 1:00 pm
Speaker: Oscar Dahlsten
Title: On Intelligent Energy Harvesting
Abstract: Pending

Lunch: 1:00 pm - 2:00 pm

Talk 7: 2:00 pm - 2:35 pm
Speaker: Joseph Lizier
Title: Universalities in Intrinsic Information Processing Properties Around Criticality in Many Systems?
Abstract: Complex systems scientists love a phase transition. More than that, we love observing that real-world complex systems often seem poised at a critical point or "edge of chaos" between ordered and chaotic behaviour. We also love speculating not only on how common this may be, but on what advantages criticality conveys that may lead this to be the case. Such speculation dating back to Langton relates phase transitions to changes in the underlying information processing structure of systems, and indeed often suggests maximisation of various information processing properties at criticality as underpinning its attractiveness. In this talk, I will review our work in information-theoretically characterising information storage and transfer in the intrinsic dynamics of complex systems, and how we have used this characterisation to study the information processing properties of various systems around criticality. This will cover work on random Boolean networks, the Ising model, echo state machines, neural cultures, Kuramoto oscillators and a neural mass model. Across all of these systems, we have observed that a balance in intrinsic information storage and transfer capacity is exhibited at or near criticality in general, offering a computational explanation for the utility of these type of dynamics. Yet there are subtle differences in such information dynamics across these systems, and here I will attempt to tease these out and relate them to underlying dynamics of the systems.

Talk 8: 2:35 pm - 3:10 pm
Speaker: Sarah Walker
Title: Can Life Be Quantified?
Abstract: The question 'what is life?' has evaded a concrete scientific answer for the better part of a century, since the quantum physicist Erwin Schrodinger first posed the problem as one for modern physics to solve. In this talk I discuss new inroads to the problem, taking steps to quantify life by its informational and causal properties. I illustrate the approach both on philosophical grounds and with concrete examples comparing informational architecture across biological examples and non-living examples. I discuss how this approach is directly toward developing a new physical theory for what life is, based on its informational properties, and how this might help us solve its origins.

Talk 9: 3:10 pm - 3:45 pm
Speaker: Kelly Finn
Title: Animal Behavior is Information Processing
Abstract: Sensory systems of animals evolved and developed to efficiently process patterns of information that commonly occur in their environments. Therefore the sensitivities and biases of sensory systems often correspond to statistical regularities of in natural environments. This allows animals to rapidly

detect stimuli that are important for their survival and reproduction. Tools derived from information theory now provide ways to precisely quantify the spatial and temporal configurations of physical objects and events in an animal's environment. In addition, we can also precisely quantify the spatial and temporal configurations of both individual and group-level behavior that occurs in response to environmental patterns. These tools allow us to measure the numerous sources of information that influence an animal and the subsequent behavioral effects, and thus study animals or groups of animals as information processors. I demonstrate the feasibility of this approach as empirical research with behavioral monitoring technologies. I suggest what behavioral ecology and the study of natural computing systems can offer the broader study of information processing. Finally, I invite us all to speculate how computing by an organism or social system could be analogous to information processing that occurs at other scales, and what common principles of information processing could offer to our understanding of the evolution of animal behavior.

Workshop Wrap-up Panel: 3:45 pm - 4:00 pm
Speakers: Organizing committee