



Life-like Self-assembly through Dissipative Adaptation

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| <p>14. ABSTRACT</p> <p>Since the last report submission, three manuscripts have been completed and submitted for publication. 1) A simulated model of a disordered mechanical network was studied. By subjecting this system to various kinds of external powered mechanical oscillations, it was shown that this model exhibits spontaneous adaptation behavior that is specific to its input driving signal and reduces work absorption from this signal across a range of different types of drive. Moreover, the system shows a lifelike ability to find attractor states that are robust against being rearranged by energy from the source that powered the attractor's emergence, much the same way that living things digest food from specific sources but are damaged by energy introduced through unfamiliar mechanisms. This was submitted to PRX. 2) A simulated model of a random spin glass in a complexly patterned sequence of 'barcoded' external fields exhibited a spontaneous novelty detection behavior, in that its energy absorption rate tended to spike when new force fluctuations never seen previously were introduced after a period of adaptation to fixed set of forcings. This finding indicated that a disordered many-body system can learn to predict the likely future of its environment simply by experiencing force fluctuations produced by that environment, and without any deliberate optimization or training or parameters. This was submitted to Nature Communications 3) The structure of this novelty-detecting spin glass system was studied using variational autoencoders and other bottlenecked neural nets. It was found that there is a regime where energy absorption does not act as a clear signature for learning, but where a neural net can detect lowdimensionality in the spin glass that indicates it has learned the pattern of its environment. This was submitted to PRX.</p> | | |
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AFOSR Progress Report for FA9550-17-1-0136
“Life-like Self-assembly through Dissipative Adaptation.”

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Outlook

This grant has funded two related, but separate lines of research studying the impact of time-varying external forces on many-body systems with disordered internal interactions that are coupled to an external heat bath. In both cases, the goal has been to discover and refine understanding of conditions under which patterned external driving in such a scenario gives rise to self-organized fine-tuning effects in the response properties of the driven system. We term such states “life-like” because living things are finely-tuned to environmental time-variations in multiple ways: they harvest energy from them, they are robustly structured against likely insults, and they sense, compute, and predict based on internal models of their world. One study described here has been carried out by Dr. Hriday Kedia, and has focused on simulations of a disordered mechanical network governed by Newtonian/Langevin equations. A second study, carried out by Jacob Mitchell Gold, has focused on a random spin glass, and has simulated a Gillespie algorithm to model stochastic dynamics.

Theory

Our original theoretical motivation for these studies was based in the “least-rattling feedback” idea put forward in our recent paper (Chvykov and England, *PRE*, 2018). In the original version of the idea, strong time-scale separation exists between two different subsets of degrees of freedom in a driven system where external driving only operates directly on the fast subset. In this case, one may show that the diffusion constant of the slow variables is dictated by the strength of fluctuations in fast variable motion, and therefore (typically) by the rate of energy absorption by these driven variables. Accordingly, one expects slow variables to fine-tune themselves to arrangements that reduce fluctuations and “cool down” the system.

We therefore undertook to study the impact of time-varying fields on two different types of systems in which such time-scale separation might strongly impact the dynamics. In the case of a random spin glass, at sufficiently low ambient temperature one expects glassy dynamics with a hierarchy of different time-scales for structural rearrangement. Meanwhile, in the disordered mechanical network project, we built slow motion into the Hamiltonian by making every bond in

the network bi-stable in a distance-dependent double-well shape, so that fast local oscillations could occasionally give rise to slower barrier-jumping bond lengthenings or shortenings.

In each of these systems, our hypothesis was that prolonged exposure to a patterned, time-varying field would lead to a fall in the rate of energy absorption over time, as a result of fine-tuned rearrangements in the response properties of the system that affect the ability of the system to absorb work from the drive pattern. Below, we discuss results.

Projects

Random Spin Glass

At the time of our last report, Jacob had just begun to identify the kind of numerical experiments to do where he could see an effect of interest. Since then, we have followed these first promising results up and carried out a thorough analysis. We indeed have found that random spin glasses reduce their rate of energy absorption (and, accordingly, dissipation) over time when driven by patterned time-varying fields. The scenario we have considered is one where a few hundred spins randomly coupled with Gaussian couplings in a sparse Erdos-Renyi graph are subjected to external fields that affect a subset of several dozen spins. Each state of the external field has a “fingerprint” in terms of how it pushes up or down on each spin, and this fingerprint changes over time by being selected, without replacement, from a finite set of such fingerprints. Once all such members of the set have been imposed, the group resets and is run through again, randomly and without replacement. In this way, the system sees an environment that is partly random, but partly predictable.

In this scenario, we find in general that the system experiences an early transient of high dissipation followed by a later decline to steady-state level. Interestingly, however, when a different set of fingerprints generated from the same random family is switched in, the dissipation spikes again, indicating that the steady-state behavior was robust only in a matter specific to the particular fingerprint pattern it had already experienced.

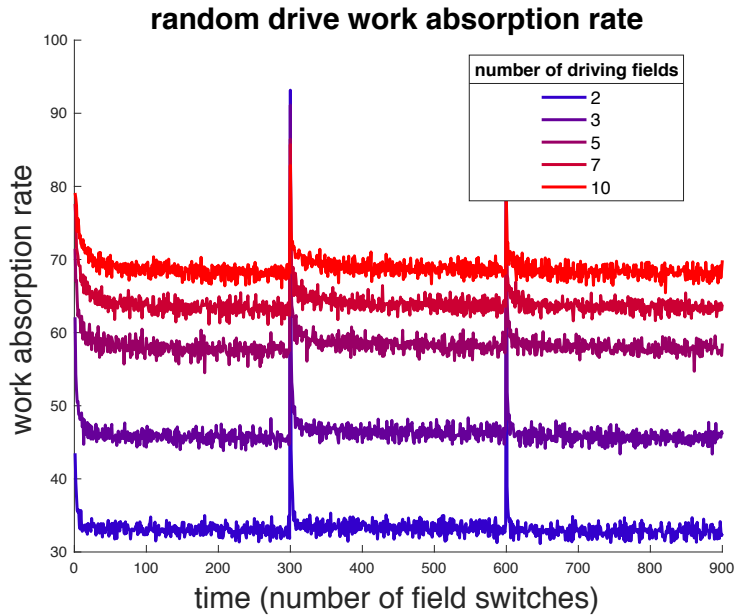


Figure 3: Since work is only absorbed when the system is rearranged, as the configuration evolves to a quasi-steady state fewer rearrangements will occur, resulting in a lower work absorption rate. The quasi-steady state reached is specific to the details of a particular drive, so when switching to a new drive the work absorption rate resets to behave as if the system had never been driven. Switching back to the first drive also resets this behavior.

This phenomenon has now been thoroughly analyzed and written up in a draft manuscript, which recently was submitted to *Nature Communications* [1]. In addition, we have also collaborated with MIT’s Ike Chuang and Harvard’s Nicole Halpern to take this project one more step down the road. The regime in which we identified the novelty detection phenomenon was one where work absorption acts as a strong indication that a new set of driving fields has been introduced after the system has adapted to a previously chosen one. However, it is also conceivable that there might be a regime where the work absorption rate does not act as a good indicator of this process of learning about environmental fluctuations, yet where the physical state of the system does embody a low-dimensional representation of the environment that has “learned” its pattern. To test this, we used autoencoders and other bottlenecked neural net architectures to generate a low-dimensional latent-space representation of the state of the spin glass. We found that even in a regime where the work absorption rate did not act as a useful novelty detector, there still was a clear adaptation of the physical state of the spin glass that reflected its capacity to learn and remember the possible states of the environment. This analysis has been written up and submitted to *PRX* [2].

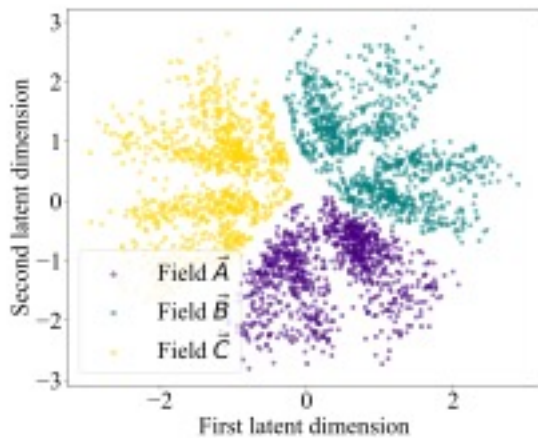


FIG. 2: Visualization of latent space: The latent space Z consists of two neurons, Z_1 and Z_2 . A variational autoencoder (VAE) formed this latent space while training on configurations assumed by a 256-spin glass during repeated exposure to three fields, A , B , and C . The VAE mapped each configuration to a dot in latent-space. We color each dot in accordance with the field that produced the configuration. Same-color dots cluster together: The VAE identified which configurations resulted from the same field.

Random Mechanical Network

In a second study, carried out by Dr. Hridesh Kedia in concert with an undergrad by the name of Deng Pan, we simulated a network of interacting masses connected by bi-stable interaction potentials acting along a random, sparse network of bonds connecting some pairs of masses. Each potential was W-shaped, which is to say it had local minima of similar energy at two different inter-particle distances, with a barrier of the same height in between. We computed the Newtonian dynamics of such networks in two dimensions in the low-temperature, high-viscosity limit while one particle in the network was subject to a sinusoidal force of fixed amplitude and frequency. The expectation is that that barrier jumping can be thought of as a set of slow degrees of freedom, and the local coordinate motion by contrast is “fast”.

The simulated dynamics in this system have over the last year demonstrated remarkable adaptability to different kinds of patterned driving. Typical “experiments” involve selecting one kind of external oscillation acting on a particle in the network (such as sinusoidal forcing) and then letting the system reach a steady-state in that condition before changing to a second external forcing (such as sinusoidal positioning of a particle in the network). As depicted in the figure, changing the drive leads to a transient spike in dissipation followed by adaptation to the new pattern, indicating specificity to the particularities of each pattern selected. Our study has spanned a range, from driving by tracing particles through different parametrized motions in space, to altering the type and direction of forcing, as well as introducing multiple particles coupled to different heat baths. We are currently composing a manuscript to be submitted soon presenting our findings.

The overarching point is that this disordered network is a highly adaptable self-fine-tuning system that reduces dissipation by reconfiguring its normal model response properties to be bad at absorbing drive energy.

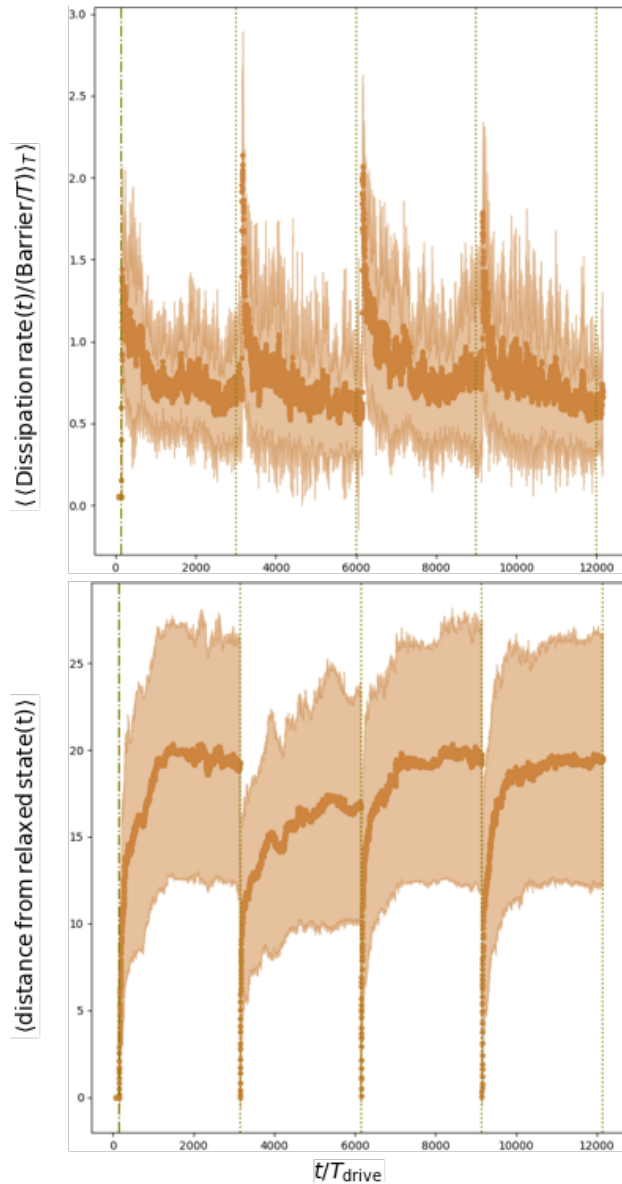


Figure 1 In the above system, which is representative of many realizations of this system, 25 particles are connected by a quenched, sparse graph of random bonds. Each bond experiences a potential that is a bi-stable double well, with local minima at two finite separations. A single anchored particle is driven first with sinusoidal forcing, and the “slow” bond lengths evolve over time with damping in the presence of fast local oscillations. At long times the system settles into a geometrically ordered quiescent state with low dissipation, after which the drive is switched to oscillation in particle position. After transient increasing of dissipation, the system adapts to the new forcing regime.

Aside from the empirical success in observing different adaptation effects of the response properties in this system, we have also gained new analytical understanding of the origins of

this effect. Prof. Slotine is an expert on contraction theory, which uses the eigenspectrum of the Jacobian for the first-order dynamical systems to prove theorems about convergence properties of dynamical trajectories. Analyzing our own system through this lens, we have established the hypothesis that in a rugged energy landscape like this with many degenerate global energy minima, there is a regime of moderate driving amplitude where particular local energy minima become the rare, absorbing attractors to the dynamics at long times because they contain stable periodic orbits that exploit their fine-tuned response properties. We are confident this contraction argument should apply to a broad class of dynamical systems, and have nascent collaborations at Harvard and Carnegie Mellon with experimentalists in soft and hard materials to test these ideas further. The paper [3] recently submitted to *PRX* will report the first empirical *in silico* success in seeing adaptation in these mechanical networks, and also will give an exposition of the analytical power of contraction theory in this system, with an eye towards other low-temperature, disordered many-body scenarios that might fall in the same class of behaviors.

References

[1] <https://arxiv.org/abs/1911.07216>

[2] <https://arxiv.org/abs/2001.03623>

[3] <https://arxiv.org/pdf/1908.09332.pdf>

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Abstract

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