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Signatures of Learning by Information-Processing and Decision-Making Human Systems

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Abstract

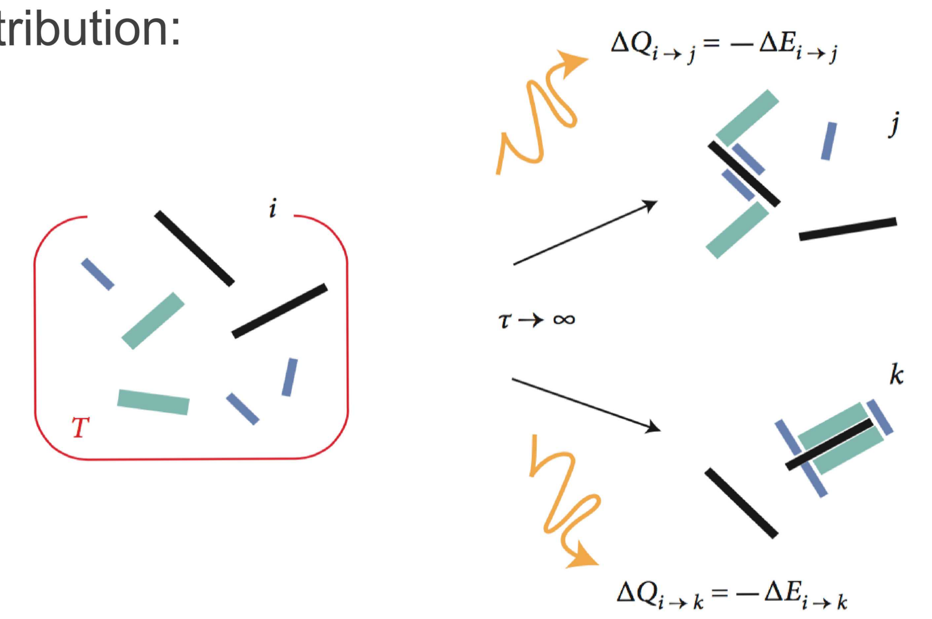
Human systems are constantly navigating problem-rich environments, ranging from soldiers navigating a battlefield to **scientific teams** navigating a research domain. As these systems navigate, they are constantly processing information, making decisions, and generating new knowledge. Perhaps as importantly, they are also *learning how to improve on information-processing and decision-making*. Understanding how these systems learn is non-trivial, however, not just because the environment itself is a moving target, but because information-processing and decision-making involve multiple time scales, heterogeneous implicit/explicit information, emotional factors, and complex feedback mechanisms.

We bring to this challenging problem perspectives from two distinct fields spanning our own research team. First, we are developing a model of a learning system based on an emerging theory of the statistical physics of adaptation [1,2]. Second, we propose that signatures of adaptation can be measured by changes in the information state of a learning system.

[1] N Perunov, R Marsland, and J England, "Statistical Physics of Adaptation." *Phys. Rev. X*, in press (2016)
[2] J England, "Dissipative Adaptation in Driven Self-assembly." *Nature Nanotech*, **10**, 920 (2015)

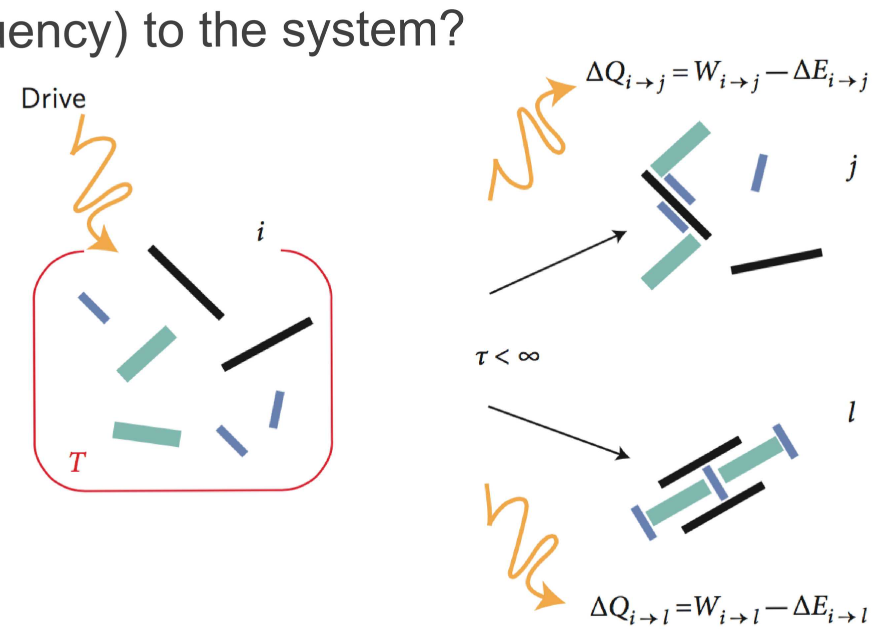
Adaptation as a Physical Process

Equilibrium probability to be in a state *j or k is* given by the Boltzmann distribution:



$$\frac{p(j)}{p(k)} = \exp\left[-\frac{E_j - E_k}{k_B T}\right]$$

What if we introduce an external drive (e.g. an optical stimuli at a specific frequency) to the system?

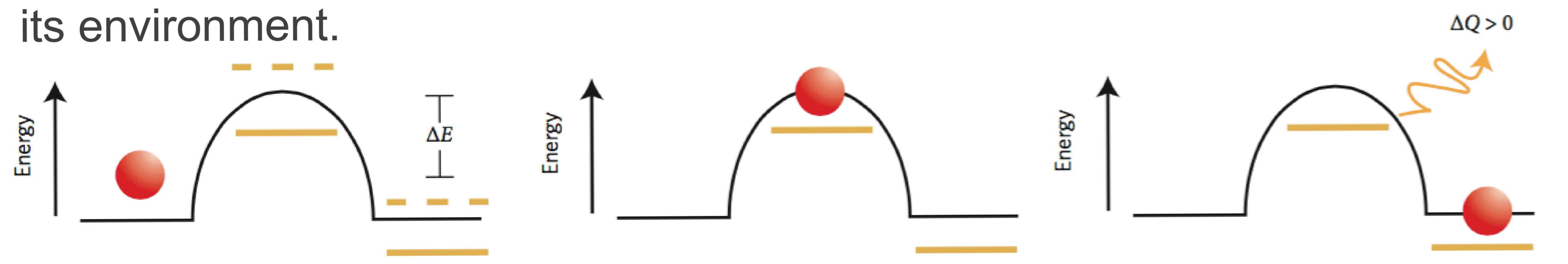


$$\frac{\pi(\gamma)}{\pi^*(\gamma^*)} = \exp\left[\frac{\Delta Q(\gamma)}{k_B T}\right]$$

A given **microtrajectory** is more likely than its time-reverse trajectory (i.e. irreversable) by an exponential factor of the heat dissipated into the environment [3, 4].

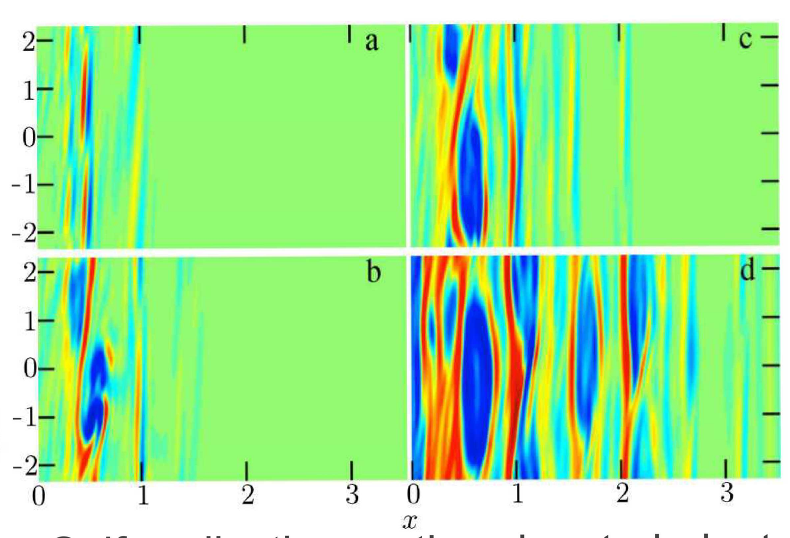
[3] G E Crooks, *Phys Rev E*, **60**, 2721 (1999)
[4] C Jarzynski , *Phys Rev Lett*, **78**, 2690 (2000)

What does this mean? The particular fluctuations which **absorb** and **dissipate** energy best are **driven** to accumulate, leading to a structure "well-adapted" to its environment.



And what better way to dissipate heat than to make many copies of yourself? Self-replication gives Nature what she wants: *more entropy, quicker*.


Two solar machines.

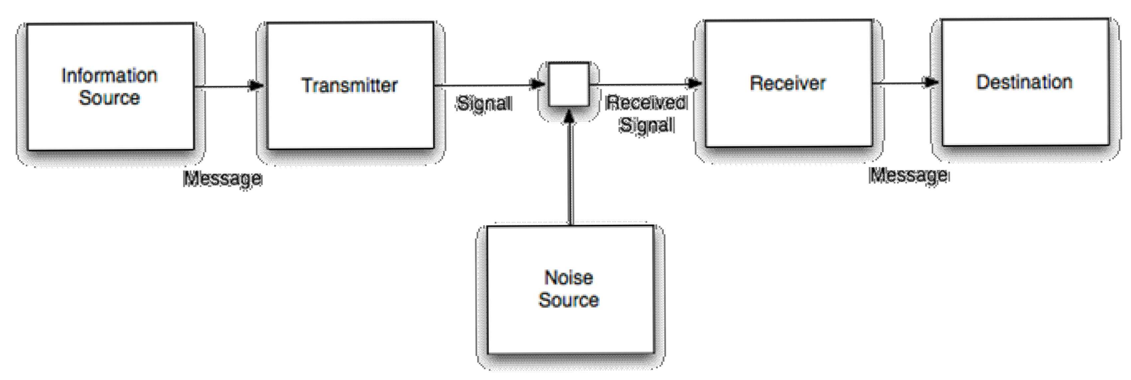


Self-replicating vortices in a turbulent fluid [5].

[5] P S Marcus, et al., *Phys Rev Lett*, **110**, 08451 (2013)

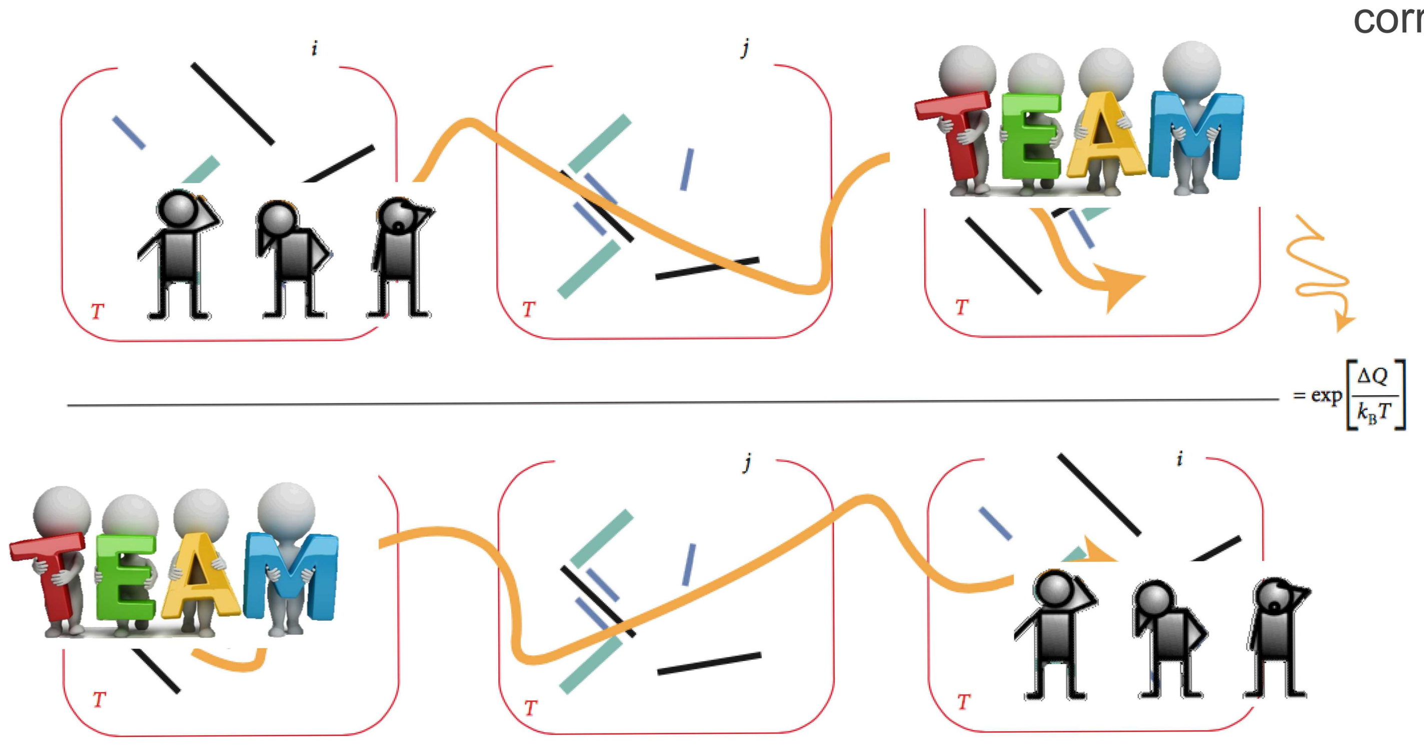
Information-processing systems (e.g. any scientific team!)

Goal of the information-processing system is to reduce the amount of uncertainty.
How can we quantify uncertainty?



Shannon's Problem: "The fundamental problem of communication is that of reproducing at one point, either exactly or approximately, a message selected at another point."

Shannon's Insight: Language can be modeled as a random process. Because of this, there are things we can say mathematically about the minimum number of bits needed to encode language. A high degree of uncertainty corresponds to a high volume of information.



Analogy to England's Dissipation-Driven Adaptation

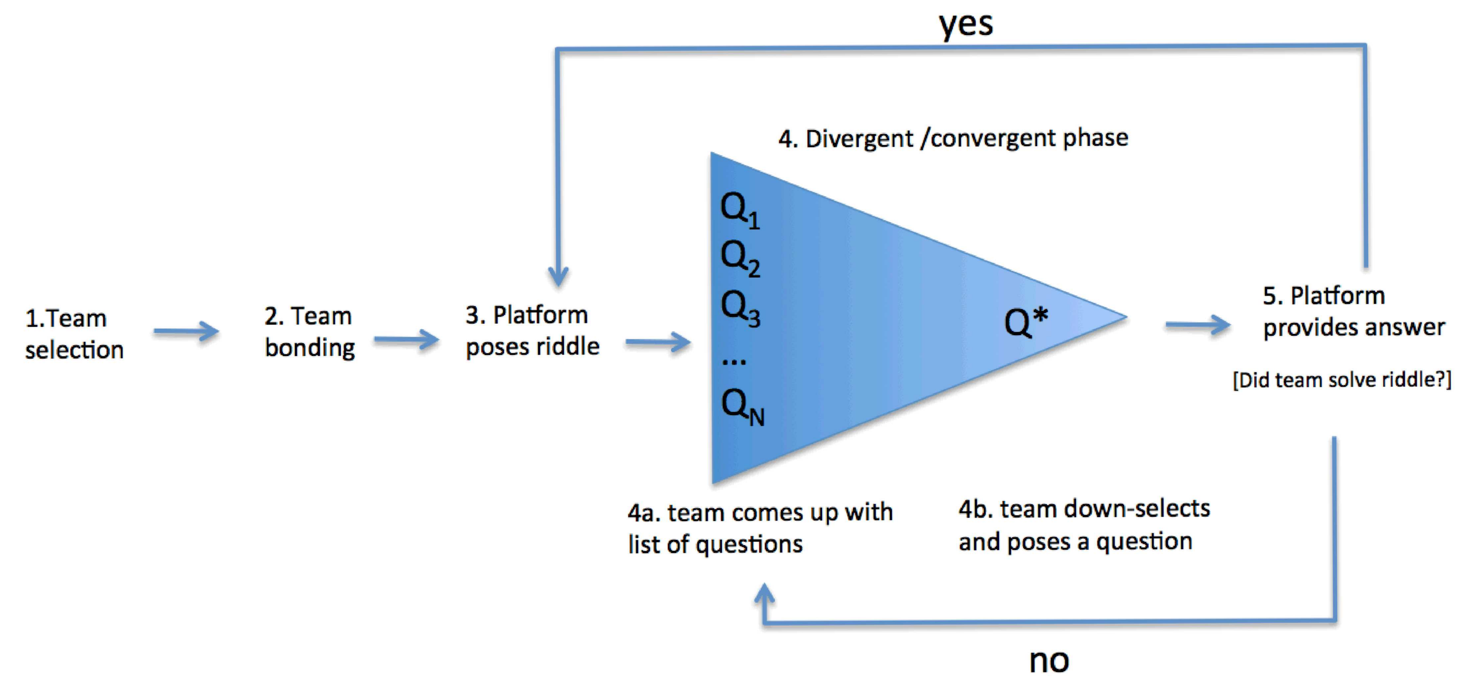
- External Drive: Data input
- Output: Information entropy
- Adaptation: System restructuring, reforming goals, or repositioning itself in its environment to *better* process information and dissipate entropy

Hypothesis 1 : The state of an information-processing system *adapts* to improve its ability to *reduce the information uncertainty* in a given problem space; the state of the system and the reduction of information [6] are *measurable*.

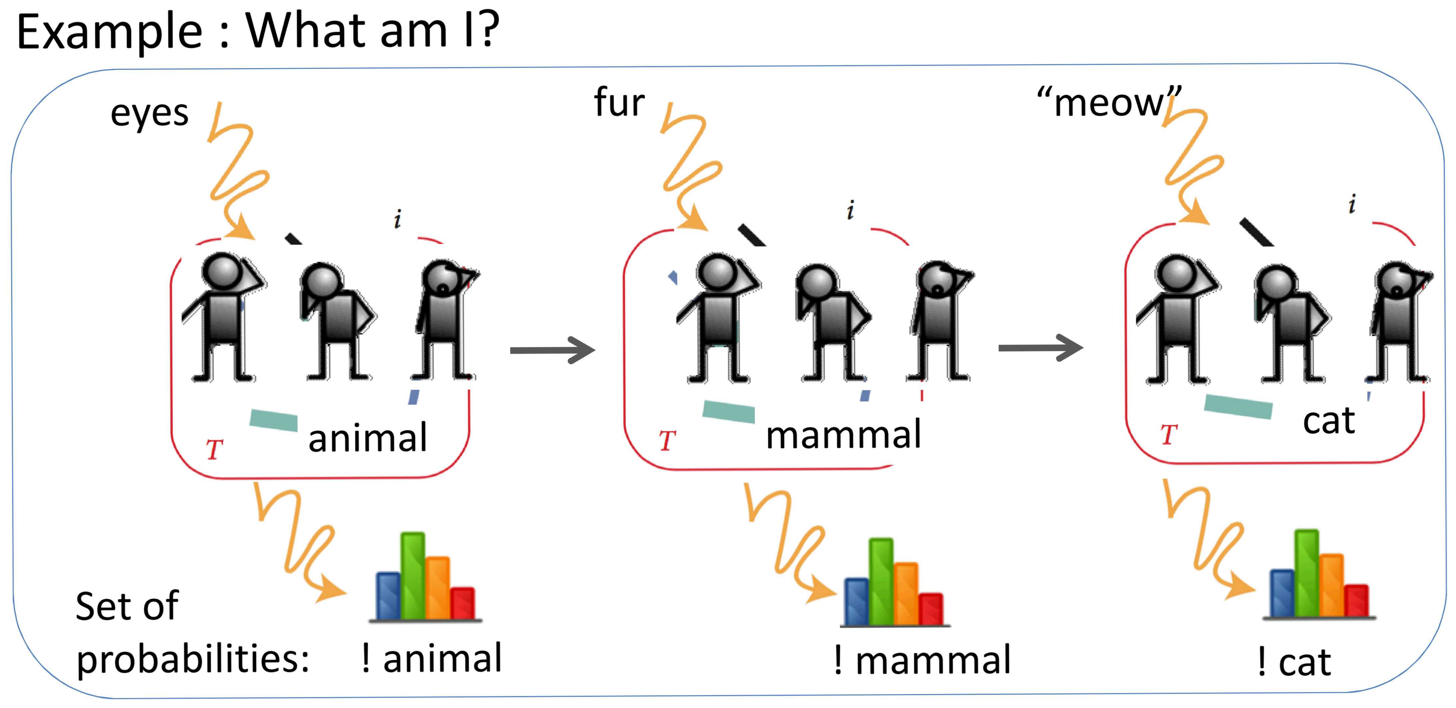
Hypothesis 2 : An potential underlying mechanistic process for the reduction of information uncertainty is divergent and convergent thinking: ideas must be generated (divergent thinking), then they must be tested and selected (convergent thinking), in iterative and nested microscopic loops which when assembled together result in high-level success or failure [7,8].

An understanding of how a system adapts to improve it's underlying mechanistic process of information reduction is of course directly related to how complex scientific teams adapt in a given problem space to better process information, to solve problems and make decisions.

Proposed adaptive experimental platform to monitor, measure, and/or manipulate the system state, and to measure the corresponding reduction in information:



Example : What am I?



Data input

Measurable changes in the system state

- Team composition
- Interactions, relationships, hierarchical structure
- Dynamics
- Communication tools
- Goals, motivation, feedback
- Emotions

Measurable changes in information entropy

[6] T Bauer and T Brounstein "Using Data Compression to Detect Inflection Points"
[7] "Art and Science of Science and Technology: Proceedings of the Forum and Roundtable" (2014) (posted on the Harvard Kennedy School Belfer Center for Science and International Affairs website).
[8] T Odumosu, J. Tsao, and V Narayanamurti. "Commentary: The social science of creativity and research practice: Physical scientists, take notice." Physics Today 68.11 (2015).

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