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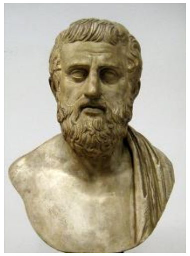
Sophocles



Self-Organised information PrOcessing, CriticaLity and Emergence in multilevel Systems

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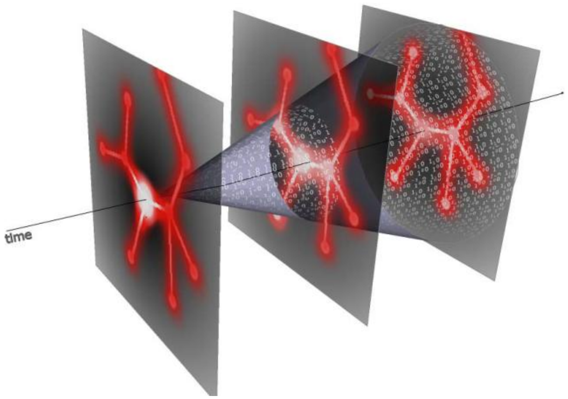
Nature processes Information



- Information is registered in the state of a system and its elements
- Information is transferred.
  - Bits of information about the state of one element will travel –imperfectly – to the state of the other element, forming its new state.
  - This storage and transfer of information is imperfect due to randomness or noise.
- A system can then be formalized
  - as a collection of bits
  - organized according to its rules of dynamics and its topology of interactions.
- Mapping out exactly how these bits of information percolate through the system could reveal new fundamental insights in how the parts orchestrate to produce the properties of the system.
- A theory of information processing would be capable of defining a set of universal properties of dynamical multilevel complex systems

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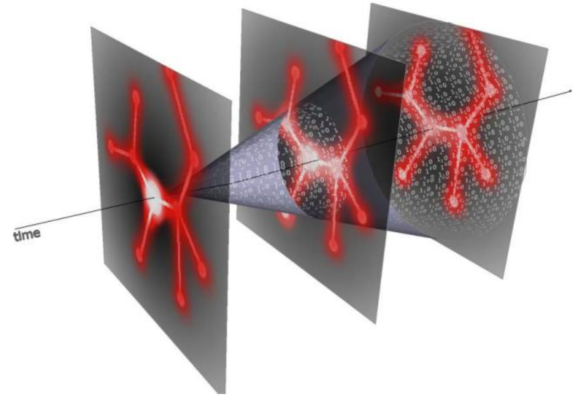
Nature processes Information



$\mathbb{I}(P\,|\,O)$ *returns* how many bits of information are stored about the predicted system state *P in the observed system* state *O.*

$$\mathbb{I}(P\,|\,O)\geq 0 \quad \mathbb{I}(P\,|\,\varnothing)=0$$
$$\Delta\mathbb{I}(P\,|\,O)\cdot\Delta H(P\,|\,O)\leq 0$$
$$\mathbb{I}(P\,|\,O_1,O_2)\leq\mathbb{I}(P\,|\,O_1)+\mathbb{I}(P\,|\,O_2)$$
$$\mathbb{I}(P\,|\,P)=\text{ max.}$$

The amount of information that a macroscopic system stores about a historic instance of a node *i after δ time steps*

$$\mathbb{I}(v_i(t-\delta)\,|\,\mathbb{N}(t),\xi(t))\ \text{for}\ \delta\geq 0.$$

The average time it takes to reduce to its minimum value is equivalent to how long the macroscopic system *remembers' the state of a microscopic state.* This the *information dissipation time of the node i*

$$\mathbb{I}(v_i(t)\,|\,\mathbb{N}(t),\xi(t))=\mathbb{I}(v_i(t)\,|\,\{v_0(t),\ldots,v_n(t)\},\xi(t))\leq\mathbb{I}(v_i(t)\,|\,v_i(t))=\text{ max.}$$
$$\mathbb{I}(v_i(t-\delta)\,|\,\mathbb{N}(t),\xi(t))=\mathbb{I}(v_i(t-\infty)\,|\,\mathbb{N}(t),\xi(t))\ \text{for all}\ \delta\geq\Delta.$$

Landauers principle, any logically irreversible transformation of classical information is necessarily accompanied by the dissipation of at least **kTln(2)** of heat per lost bit.

LETTER

doi:10.1038/nature10872

Experimental verification of Landauer's principle linking information and thermodynamics

Antoine Bérut[1], Artak Arakelyan[1], Artyom Petrosyan[1], Sergio Ciliberto[1], Raoul Dillenschneider[2] & Eric Lutz[3]†

In 1961, Rolf Landauer argued that the erasure of information is a dissipative process[1]. A minimal quantity of heat, proportional to the thermal energy and called the Landauer bound, is necessarily produced when a classical bit of information is deleted. A direct consequence of this logically irreversible transformation is that the entropy of the environment increases by a finite amount. Despite its fundamental importance for information theory and computer science[2–5], the erasure principle has not been verified experimentally so far, the main obstacle being the difficulty of doing single-particle experiments in the low-dissipation regime. Here we experimentally show the existence of the Landauer bound in a generic model of a one-bit memory. Using a system of a single colloidal particle trapped in a modulated double-well potential, we establish that the mean dissipated heat saturates at the Landauer bound in the limit of long erasure cycles. This result demonstrates the intimate link between information theory and thermodynamics. It further highlights the ultimate physical limit of irreversible computation.

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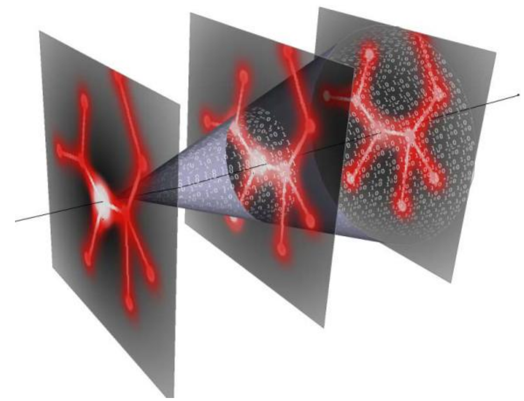
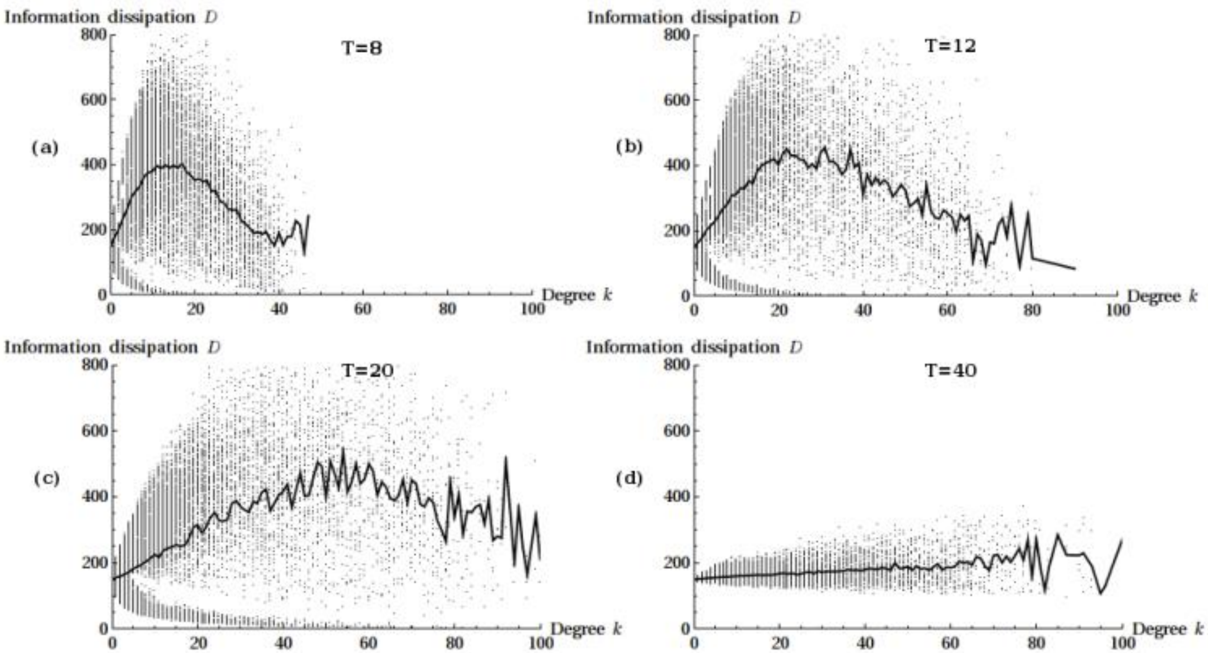
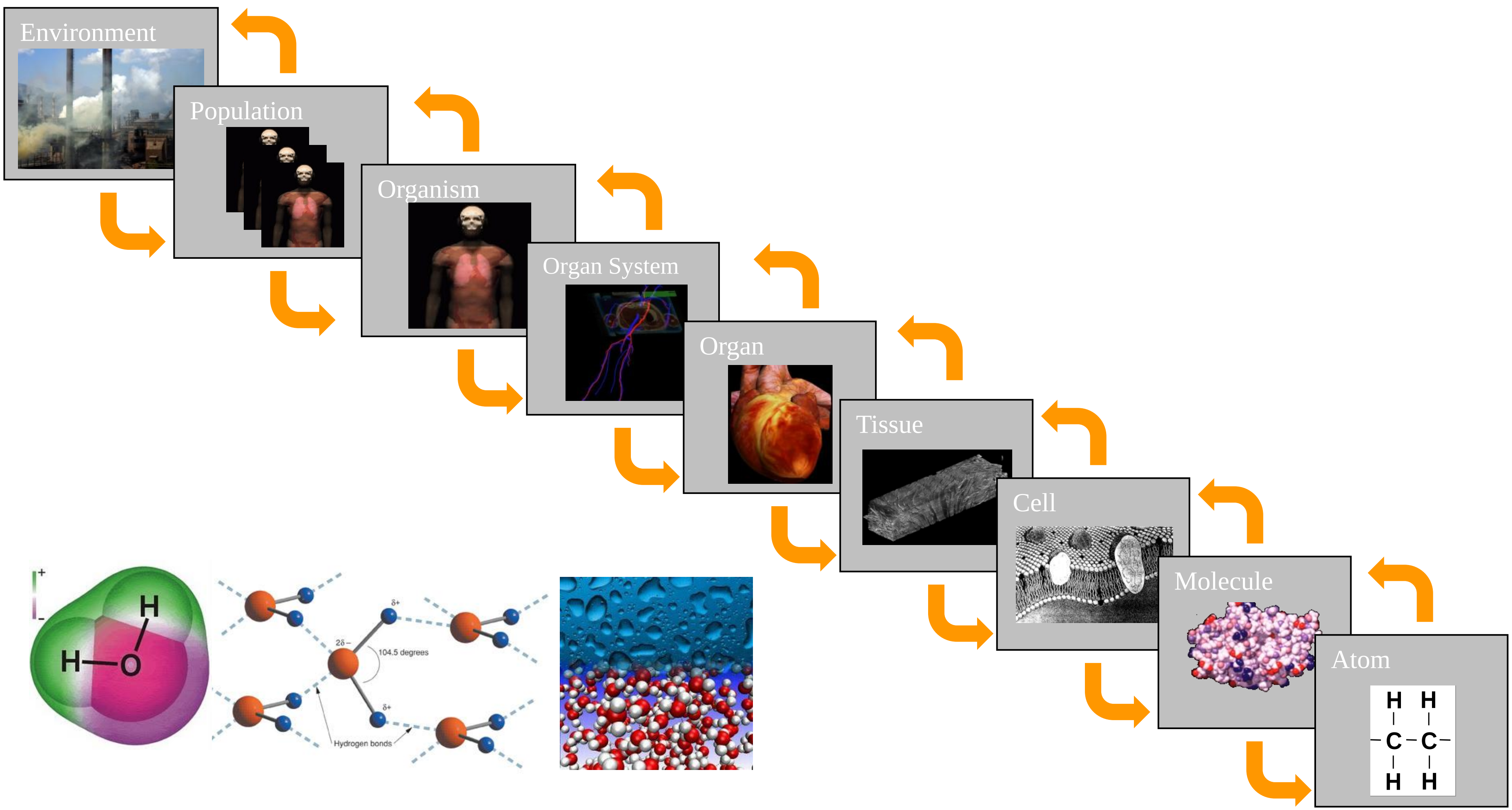
Nature processes Information



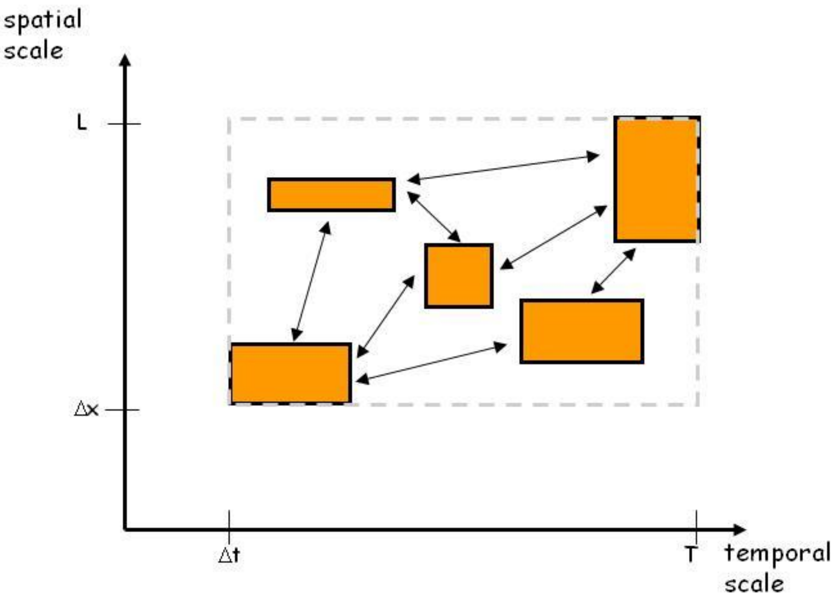


Scatter plots of information dissipation times of nodes as function of their number of connections, for different temperatures.

Nature is multi-scale



Nature is multi-scale



$$A(\Delta x, \Delta t, X, T, \mathbf{F}, \Phi, \mathbf{u})$$

$$f^{n+1} = \Phi(\mathbf{u}) f^n \quad \Phi : \mathbf{F} \to \mathbf{F}$$

$$\begin{array}{c} \downarrow \\ \mathbf{F}_1 \times \mathbf{F}_2 \end{array} \qquad \begin{array}{l} f_1^{n+1} = \Phi_1(\mathbf{u}_1) f_1^n \\ f_2^{n+1} = \Phi_2(\mathbf{u}_2) f_2^n \end{array}$$

$$\Phi_1(\mathbf{u}_1) = P \circ C(\mathbf{u}_1) \circ B(\mathbf{u}_1) \quad \mathbf{u}_1 = \mathbf{u}_1(f_2)$$

$$\Phi \longrightarrow (\Phi_1, \Phi_2)$$

Objectives

1. Develop mathematical and computational formalisms for information processing in multi-level complex systems, based on Information Theory.

2. Develop a theory of information processing in multilevel complex systems for study of criticality, emergence, and tipping points.

3. Develop a theory of self-organised information processing for multi-level systems that can emerge due to co-evolution of information processing and system topology.

4. Create an Computational Exploratory, an in-silico experimental facility that allows implementing our mathematical and computational framework of Information Processing in multi-level complex systems

5. Validate our theory using socio-economic datasets (tick-by-tick data from the Forex market, inter-bank interest rates, and social media). Study emergence of scales and tipping points in these datasets.

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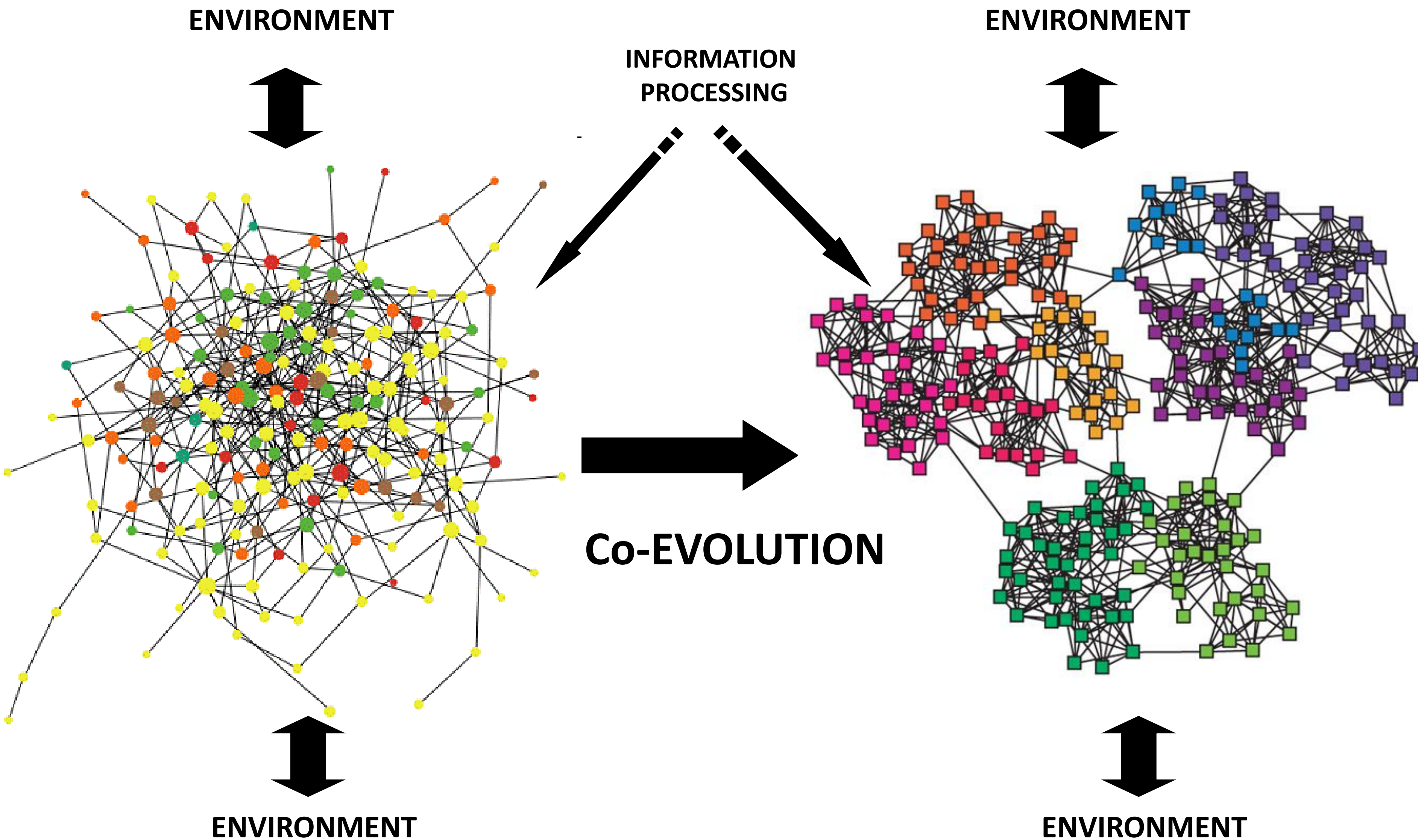
Information Processing
Real Data
Emergence, self organisation, Tipping Points

Coevolution of dynamics and topology due to internal and external stimuli



Tipping Points

Vol 461|3 September 2009|doi:10.1038/nature08227

nature

REVIEWS

Early-warning signals for critical transitions

…A. Brock[3], Victor Brovkin[5], Stephen R. Carpenter[4], Vasilis Dakos[1], …erk[7] & George Sugihara[8]

…ms to financial markets and the climate, can have tipping points at which …y occur. Although predicting such critical points before they are reached …lds is now suggesting the existence of generic early-warning signals that …l threshold is approaching.

considered to capture the essence of shifts at tipping points in a wide range of natural systems ranging from cell signalling pathways[14] to ecosystems[7,15] and the climate[6]. At fold bifurcation points (F_1 and F_2, Box 1), the dominant eigenvalue characterizing the rates of change around the equilibrium becomes zero. This implies that as the system approaches such critical points, it becomes increasingly slow in recovering from small perturbations (Fig. 1). It can be proven that this phenomenon will occur in any continuous model approaching a fold bifurcation[12]. Moreover, analysis of various models shows that such slowing down typically starts far from the bifurcation point, and that recovery rates decrease smoothly to zero as the critical point is approached[16]. Box 2 describes a simple example illustrating this.

The most straightforward implication of critical slowing down is that the recovery rate after small experimental perturbation can be used as an indicator of how close a system is to a bifurcation point[16]. Because it is the rate of change close to the equilibrium that matters, such perturbations may be very small, posing no risk of driving the system over the threshold. Also, models indicate that in spatially extensive systems at risk of systemic collapse, small-scale experimental probing may suffice to test the vicinity of the threshold for such a large-scale transition. For instance, it has been shown that recovery times after local perturbation increase in models of fragmented populations approaching a threshold for global extinction[17].

For most natural systems, it would be impractical or impossible to monitor them by systematically testing recovery rates. However, almost all real systems are permanently subject to natural perturbations. It can be shown that as a bifurcation is approached in such a system, certain characteristic changes in the pattern of fluctuations are expected to occur. One important prediction is that the slowing down should lead to an increase in autocorrelation in the resulting pattern of fluctuations[18] (Fig. 1). This can be shown mathematically (Box 3), but it is also intuitively simple to understand. Because slowing down causes the intrinsic rates of change in the system to decrease, the state of the system at any given moment becomes more and more like its past state. The resulting increase in 'memory' of the system can be measured in a variety of ways from the frequency spectrum of the system[19,20]. The simplest approach is to look at lag-1 autocorrelation[21,22], which can be directly interpreted as slowness of recovery in such natural perturbation regimes[16,18]. Analyses of simulation models exposed to stochastic forcing confirm that if the system is driven gradually closer to a catastrophic bifurcation, there is a marked increase in autocorrelation that builds up long before the

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LETTER

doi:10.1038/nature09389

Early warning signals of extinction in deteriorating environments

John M. Drake[1] & Blaine D. Griffen[2]

During the decline to extinction, animal populations may present dynamical phenomena not exhibited by robust populations[1,2]. Some of these phenomena, such as the scaling of demographic variance, are related to small size[3–6] whereas others result from density-dependent nonlinearities[7]. Although understanding the causes of population extinction has been a central problem in theoretical biology for decades[8], the ability to anticipate extinction has remained elusive[9]. Here we argue that the causes of a population's decline are central to the predictability of its extinction. Specifically, environmental degradation may cause a tipping point in population dynamics, corresponding to a bifurcation in the underlying population growth equations, beyond which decline to extinction is almost certain. In such cases, imminent extinction will be signalled by critical slowing down (CSD). We conducted an experiment with replicate laboratory populations of *Daphnia magna* to test this hypothesis. We show that populations crossing a transcritical bifurcation, experimentally induced by the controlled decline in environmental conditions, show statistical signatures of CSD after the onset of environmental deterioration and before the critical transition. Populations in constant environments did not have these patterns. Four statistical indicators all showed evidence of the approaching bifurcation as early as 110 days (~8 generations) before the transition occurred. Two composite indices improved predictability, and comparative analysis showed that early warning signals based solely on observations in deteriorating environments without reference populations for standardization were hampered by the presence of transient dynamics before the onset of deterioration, pointing to the importance of reliable baseline data before environmental deterioration begins. The universality of bifurcations in models of population dynamics suggests that this phenomenon should be general[10–12].

At present, habitat destruction and degradation are the major threats to viability for the majority of globally threatened or endangered bird (1,045), amphibian (1,641) and mammal (≥652) species[13]. The other leading threats to these groups are invasive non-indigenous species, exploitation for human use, emerging infectious diseases and pollution[13]. Each of these causes of extinction is an example of environmental deterioration, the effects of which are expected to be exacerbated by global changes in climate, land conversion and population density[14]. A central problem in the conservation of these species is the timing of interventions and the predictability of extinction[9], but the demographic properties of extinction in deteriorating environments remain poorly understood[15,16] and standard models are almost exclusively concerned with extinction due to demographic and environmental stochasticity and catastrophic events in stationary environments[3,17]. Understanding population dynamics under realistic expectations of future environmental conditions and improving capabilities to predict extinction are therefore priorities for research.

An important but overlooked aspect of environmental deterioration is that changes in environment-driven demographic rates such as reproduction, migration and survival can cause qualitative changes in patterns of population fluctuations. For instance, the same experimental plankton

…population in the deteriorating-environment group went extinct. The mean extinction time in deteriorating environments was 297 d (standard error, 16.4 d), and the effect of deterioration on extinction time was

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COMPLEX SYSTEMS

Foreseeing tipping points

Theory suggests that the risk of critical transitions in complex systems can be revealed by generic indicators. A lab study of extinction in plankton populations provides experimental support for that principle. SEE LETTER P. 456

MARTEN SCHEFFER

On page 456 of this issue, Drake and Griffen[1] show that subtle changes in the pattern of fluctuations in a population can indicate whether that population is close to extinction. This is a step forward for conservation biology, but the wider implications are even more profound. The symptoms detected belong to a family of generic leading indicators that may help to determine whether a complex system is on the brink of collapse.

Although mathematical models often predict gradual trends of change quite well, we are still badly equipped when it comes to foreseeing radical transitions such as the crash of financial markets, the onset of severe droughts, epileptic seizures or the collapse of coral ecosystems. However, a new development in our ability to predict such events[2] stems from the insight that some dramatic shifts in complex systems may be related to the existence of tipping points (or 'catastrophic bifurcations'). As a system comes close to such a critical point, even small perturbations can trigger a massive shift, much as capsizing becomes increasingly likely as more cargo is loaded onto the deck of a ship. It is notoriously hard to know if a system is close to a tipping point. We simply do not see the 'brittleness' of the situation unless the transition happens.

The new approaches for probing the vicinity of a tipping point are based on the idea that, whereas the equilibrium state reveals little at all, non-equilibrium dynamics should change in universal ways in the vicinity of tipping points[2–5]. Thus, rather than looking at the state itself, we may have to look at its fluctuations if we want to know how vulnerable a system is.

The main principle behind this theory (reviewed in ref. 2) is the fact that systems that are close to a tipping point become very slow in recovering from perturbations (Fig. 1), a phenomenon known as 'critical slowing down.' The most straightforward implication is that system fragility can in principle be probed by studying its recovery rate following experimental perturbations[6]. As the test perturbations can be tiny, this may be done with little risk of causing the actual transition. For large, complex systems, it will often be difficult to systematically test recovery rates. But there is a way around that problem. Virtually all systems are permanently subject to natural perturbations. In such situations, it can be shown that, as a critical point is approached, critical slowing down will be reflected in characteristic changes in the frequency spectrum and variance of the fluctuations in the system (Fig. 1).

One such change is an increase in autocorrelation: subsequent states in a time series will become more alike. This phenomenon has been found, for example, in models of the collapse of ocean thermohaline circulation — the

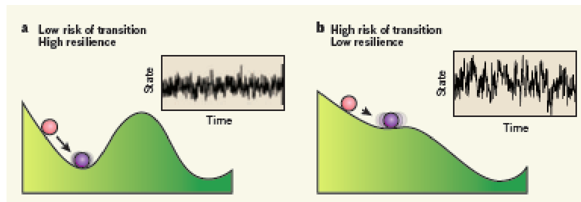
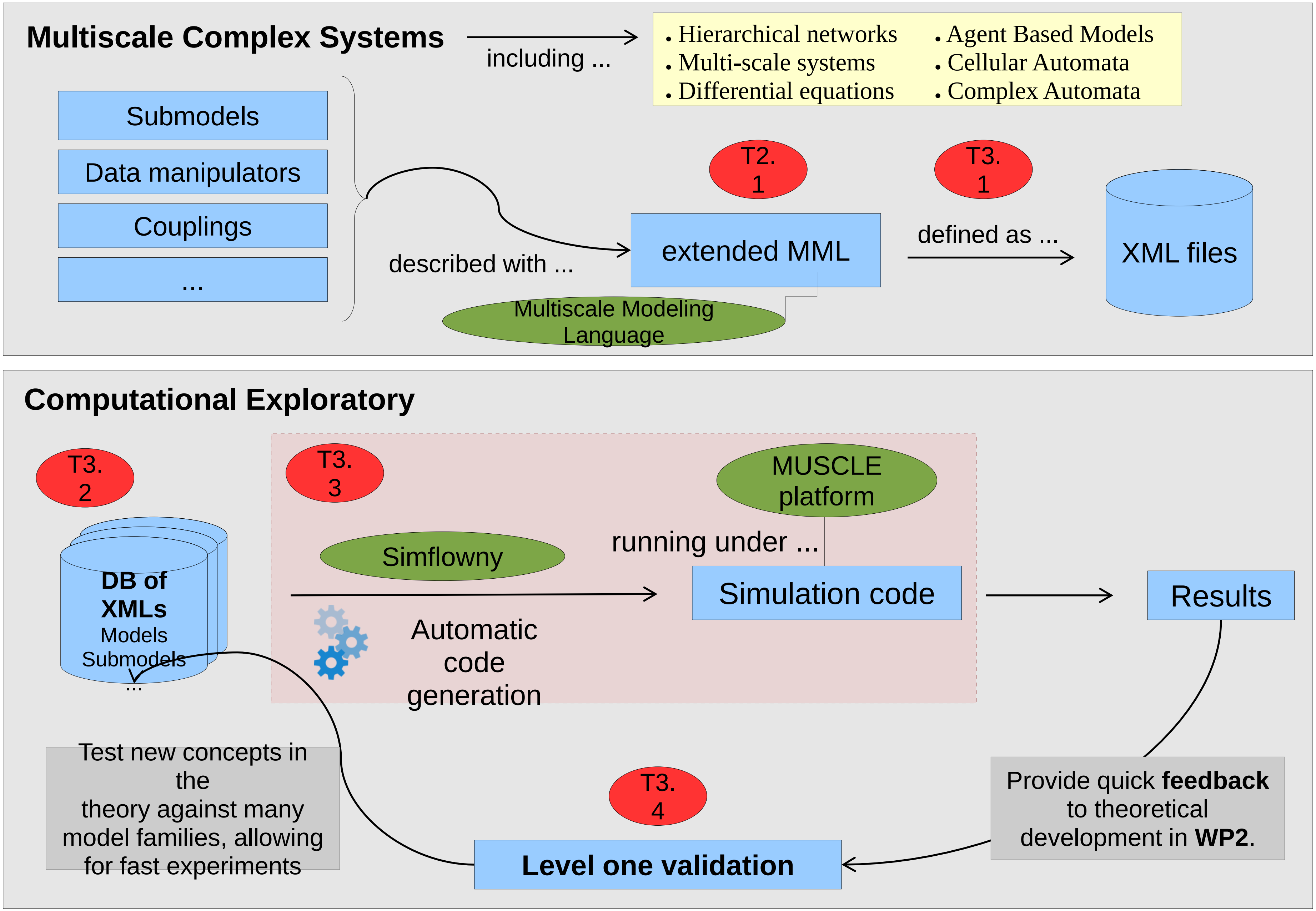


Figure 1 | Tipping points and leading indicators. The loss of resilience in the vicinity of tipping points can be understood from stability landscapes, shown here. a, Under conditions far from tipping points, a system is resilient: the basin of attraction is large, and perturbations will not easily drive the system towards an alternative state. b, If a system is close to a tipping point, the basin of attraction will be small, and a perturbation may easily push the system into an alternative basin. The state of the system by itself does not reveal such 'brittleness', but the system dynamics around the equilibrium differ in characteristic ways from those seen when the basin of attraction is large (as in a). In the risky state (b), the recovery rate from a small perturbation is slower (arrow), and the fluctuations in a stochastic environment will tend to be larger and more time-correlated, as shown in the insets. Such changes in dynamics are generic indicators for the proximity of tipping points, including those of the *Daphnia* populations investigated by Drake and Griffen[1]. (Modified from ref. 2.)

Computational Exploratory



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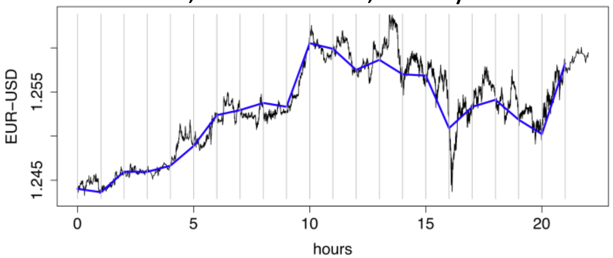
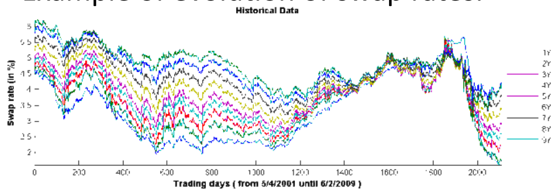
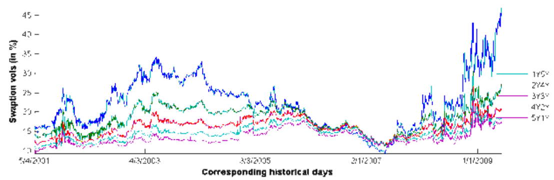
Datasets

EUR-USD, Nov 21 2008, hourly return

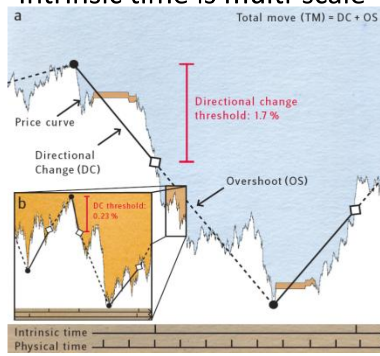


Example of evolution of swap rates.





Intrinsic time is multi-scale

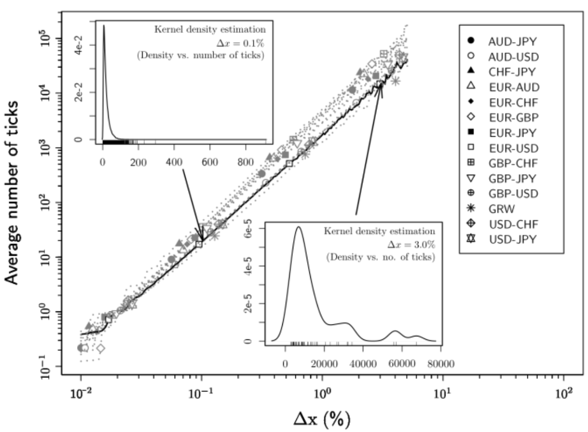


Semantic text enirchments

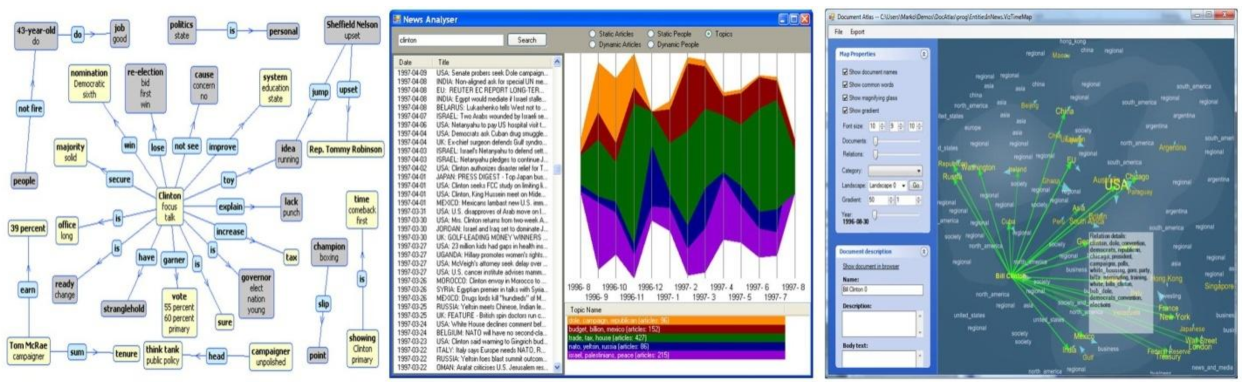
Monitoring global main stream news

Tick-count scaling law

$$\langle \mathrm{N}(\Delta x_{tck}) \rangle = \left(\frac{\Delta x}{C_{\mathrm{N},tck}} \right)^{E_{\mathrm{N},tck}} \quad \text{where } \Delta x_{tck} = 0.02\%$$



a) Semantic graph extracted from a news story on a Clinton's speech; (b) Story lines on Clinton in Reuters news (1996-1997); (c) Dynamic social network showing relationships between Clinton and related entities on a particular day (30th Aug 1996)



Collaborative tasks

ECCS '12 Satellites

European Conference on Complex Systems

ECCS'12: Satellite Meeting

INFORMATION PROCESSING IN COMPLEX SYSTEMS (IPCS'12)

Date

Thursday September 6th, 2012

Note

To attend the Satellite Meeting, it is mandatory to register to the European Conference on Complex Systems 2012 ECCS2012

Location

Universite Libre de Bruxelles

Summary

All systems in nature have one thing in common: they process information. Information is registered in the state of a system and its elements, implicitly and invisibly. As elements interact, information is transferred. Indeed, bits of information about the state of one element will travel – imperfectly – to the state of the other element, forming its new state. This storage and transfer of information, possibly between levels of a multi level system, is imperfect due to randomness or noise. From this viewpoint, a system can be formalized as a collection of bits that is organized according to its rules of dynamics and its topology of interactions. Mapping out exactly how these bits of information percolate through the system could reveal new fundamental insights in how the parts orchestrate to produce the properties of the system. A theory of information processing would be capable of defining a set of universal properties of dynamical multi level complex systems, which describe and compare the dynamics of diverse complex systems ranging from

Collaborative tasks

- Candidate joint publications
  - Special issues in a journal on Dynamics of Complex Systems
- Candidate joint events
  - Sophocles and TOPDRIM have taken initiative to organize a satellite event with ECCS2012 on Information Processing in Complex Systems,
  - see http://computationalscience.nl/ipcs2012/
- Future roadmap for DyM-CS, Impact assessment for DyM-CS (including how close we are getting to a general theory of CS)
  - Targeted consultation actions of experts, plus workshops to
- Joint Exploitation activities/events
  - Workshops, satellite events at conferences, such as ECCS, ICCS.
- Exchanges between projects (perhaps taking advantage of already existing overlaps)
  - TOPOSYS ⇔ Sophocles via partner JSI
  - TOPDRIM ⇔ Sophocles via partner UvA
- Common approach to international cooperation (e.g. workshops with other international related projects and with funding agencies)