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ORDER FROM DISORDER: THE ROLE OF NOISE IN CREATIVE PROCESSES. A SPECIAL ISSUE ON GAME THEORY AND EVOLUTIONARY PROCESSES – OVERVIEW

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The importance of applying game theory to the evolution of information in the presence of noise has recently become widely recognized. This Special Issue addresses the theme of spontaneously emergent order in both classical and quantum systems subject to external noise, and includes papers directly related to game theory or the development of supporting techniques. In the following editorial overview we examine the broader context of the subject, including the tension between the destructive and creative aspects of noise, and foreshadow the significance of some of the subsequent papers in the volume.

Keywords: Constructive role of noise; game theory; evolutionary processes; information theory.

1. Introduction

Perhaps the most depressing pronouncement in the history of science came in 1854 when the physicist Hermann von Helmholtz proclaimed that the universe is dying. The basis of Helmholtz's apocalyptic assessment was the second law of thermodynamics, according to which the entropy in a closed system would never decrease. Applied to the universe as a whole, the second law led to the prediction of a cos-

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mic heat death. Helmholtz declared that the entire universe is on a one-way slide toward a final state of thermodynamic equilibrium, following which further macroscopic change would be impossible.

The fact that the second law of thermodynamics implies an inexorable degeneration of the cosmic order exercised a profound influence over generations of scientists and philosophers. Thus Bertrand Russell was moved to reflect on the futility of human existence in the face of universal doom [1]:

'All the labors of the ages, all the devotion, all the inspiration, all the noonday brightness of human genius are destined to extinction in the vast death of the solar system, and the whole temple of man's achievement must inevitably be buried beneath the debris of a universe in ruins. All these things, if not quite beyond dispute, are yet so nearly certain that no philosophy which rejects them can hope to stand. Only within the scaffolding of these truths, only on the firm foundation of unyielding despair, can the soul's habitation henceforth be safely built.'

The second law of thermodynamics draws its potency from the elementary principle that common states are more likely to occur than rare ones, and that order is associated with the latter while disorder is associated with the former. Thus, there will be a tendency for physical systems to be shuffled from ordered states to less ordered states. The shuffling mechanism – the villain in the piece – is noise. The random agitation of microscopic degrees of freedom, for example the continual bombardment of an object by chaotically moving molecules, will remorselessly degrade the state of order, and shift the system down the road to thermodynamic equilibrium.

Peter Atkins eloquently describes this degenerative power of noise driving physical systems to higher entropy states [2]:

'We have looked through the window on to the world provided by the Second Law, and have seen the naked purposelessness of nature. The deep structure of change is decay; the spring of change in all its forms is the corruption of the quality of energy as it spreads chaotically, irreversibly and purposelessly in time. All change, and time's arrow, point in the direction of corruption. The experience of time is the gearing of the electro-chemical processes in our brains to this purposeless drift into chaos as we sink into equilibrium and the grave.'

The general conclusion that noise is a negative influence, equated with decay and destruction, was given a further twist by the pioneering work of Claude Shannon, who analyzed the propagation of signals in a noisy communication channel [3]. Inevitably, the presence of noise robs the channel of information and sets stringent limits on the rate of information transfer. Shannon's work provided a formal link between information and entropy, so that the second law of thermodynamics came to be associated quite generally with irreversible loss, not only of a physical system's structure, but its functionality, its information content and even its value.

In spite of the widespread association of noise with degeneration, it has long been apparent that the message 'noise is bad' is too simplistic. In fact, the first hint that noise has a creative aspect came almost simultaneously with Helmholtz's announcement. Six years later, Charles Darwin published *On the Origin of Species,* outlining a theory of evolution in which noise, in the guise of random mutations, was identified as the central engine that drives biological development. To harness the creative power of noise, however, Nature must augment it with an additional constraint, in the case of biological evolution that being natural selection. This enables biology to 'Climb Mount Improbable,' to use Richard Dawkins evocative description [4], i.e. to generate elaborate and unlikely structures against the general flow of probability. No conflict is implied with the second law of thermodynamics, because every instance of the increase in biological order, for example the appearance of a new, more complex, species of organism, or a genome with greater information content, has to be paid for by a concomitant rise in the entropy of the environment. There is always a cost-and-reward trade-off that, when the balance sheet is finally tallied, entails a net cost. Thus organized complexity, richness and diversity can increase even as the total entropy rises, so long at the universe retains a source of free energy.

We now recognize that noise plays an indispensable role in many creative processes by providing a disturbing or enervating influence that can shunt a physical system randomly through a selection of states. In many systems, living and non-living, there is an optimal state, defined according to some criterion of fitness (in the biological case that being the most suitable adapted organism). Noise will then enable the system to 'discover' the optimal state and maintain it. This principle of random shuffling toward an optimal state provides the basis for the powerful techniques of genetic algorithms, which have application to a wide range of practical design problems [5].

Random shuffling will be an especially creative process where some sort of ratchet mechanism is involved, as that will impose directionality on the change. This set of ideas has its origin in Smoluchowski and Feynman's famous example of the spindle with a vane and ratchet, in which molecular bombardment causes the spindle to rotate in one direction only [6, 7]. In this case, the all-important constraint that augments the noise, enabling its power to be creatively harnessed, is the ratchet's 'this-way-but-not-that' rule. Modern variants include the flashing ratchet of Ajdari and Prost [8]. These systems all provide mechanisms for undirected, random, activity to be converted into ordered, directional change 'against the thermodynamic tide.' No violation of the letter of the second law is involved, but the extraction of 'useful' non-random macroscopic activity from 'destructive' microscopic noise runs counter to spirit of the second law as it has been perceived since the time of Helmholtz and Russell.

Perhaps an even more dramatic example is provided by Parrondo's 'paradox' [9]. Here the added constraint is a subtle linkage between the cost-and-reward trade-off of two random processes that are linked in some way. These might be noise-dominated physical processes or games of chance. Each process considered individually implies a thermodynamically downhill, degenerative, 'losing' trend, but by coupling the processes together, the system can drive 'uphill' on a creative, 'winning' trend. Thus, counter-intuitively, two losses can make a gain.

In a deeper sense, the very existence of the quasi-classical universe we observe in daily life might be said to derive from the creative power of noise. First, it is now clear that the emergence of classicality in a large quantum system can be attributed to the coupling between the system and a noisy environment, a process known as decoherence [10]. Without a noisy, decohering environment, the material world would be stranded in a madhouse of quantum indeterminism, ghostly superposition and non-local entanglement, precluding the ordered development of complex systems, including observers such as ourselves.

More speculatively, the existence of the observed universe may itself be attributed to the role of noise. In Linde's chaotic cosmology [11], a scalar field drives the process known as inflation, causing the universe to expand exponentially at a frenetic rate. Quantum noise ensures that there will be random regions where the field will be intense enough to trigger inflation, and such regions will occupy an exponentially large fraction of the total space. Inflation is (according to the standard model of cosmology) the mid-wife of an ordered, coherent, long-lived, low-entropy cosmos that permits life and observers. And by setting the gravitational state to 'smooth,' inflation bestows upon the universe an arrow of time in the form of a gravitational entropy gap. This 'entropic credit' can be used to pay for all the creative activity in which Nature is currently engaged [12].

The most dramatic examples of the creative power of noise have come not from cosmology but from the physics and chemistry of pattern formation [13]. Numerous workers have shown how, in nonlinear systems driven far from thermodynamic equilibrium, molecular noise can be amplified and stabilized, leading to the formation of states of higher organizational complexity. A classic example is the Bénard instability in a fluid heated from below. The initial state is one of uniformity, and the higher organizational state contains hexagonal convection cells in an orderly array. Another famous example is the Belousov-Zhabatinski chemical reaction, where complex, ordered shapes emerge spontaneously from featureless states. Alternatively, the chemical mixture can undergo rhythmic oscillations, constituting a molecular clock. These famous examples are only two members of a vast family of self-organizing systems [13].

The papers in this volume explore aspects of the creative power of noise as demonstrated in simple mathematical models of dynamic and evolving systems. One thematic thread that runs through this Special Issue is the application of game theory to the process. Increasingly it is clear that in a certain sense many physical systems subject to noise and presented with a selection of different states can be considered as playing a sort of game. For example, in biological evolution the winners in the great genetic lottery are the survivors, the species that occupy the high peaks in the landscape of adaptive success.

2. Special Issue Perspective

The theory of games and evolutionary processes in many cases relies on random phenomena. Information theory in noisy channels and a number of other physical processes can also be described in these terms. Papers for this Special Issue were invited addressing all these areas as well as those providing supporting techniques. The advertised scope included key words such as: stochastic games, dynamic games, game-theoretic control problems, information theory, cellular automata, statistical decision theory, stochastic computation, computation with noisy information, optimization under noise, evolutionary games, evolutionary processes, evolutionary computation, information theory in genetic systems, evolutionary economics, emergence in noisy environments, noise induced patterns, biogenesis, noisy self-organisation, Parrondo's games, quantum games, quantum information, quantum communication, decoherence, self-organized biological dynamics.

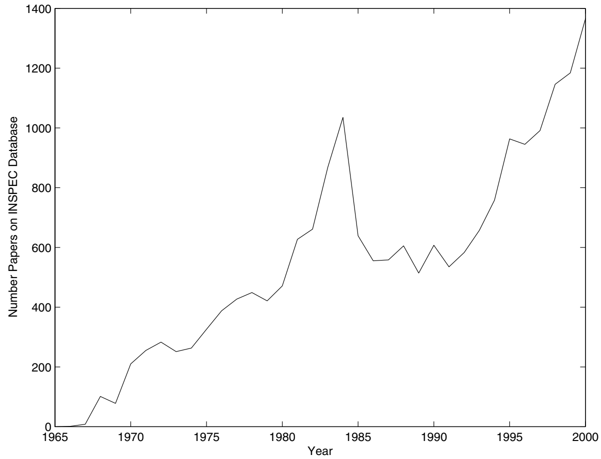

Fig. 1. This plot shows the number of game theory related papers per year appearing on INSPEC, which is primarily a physical/earth sciences database.

Game theory purists trace its roots, approximately two millenia, back to the Babylonian Talmud, which foreshadows the modern theory of cooperative games – solving such problems as how to divide a dead man's estate amongst three wives, when the property is not worth the amounts specified in the three marriage contracts [14]. In more modern times, game theory traces back to the works of Darwin [15], Lewontin [16] and Maynard Smith [17], in the context of animal competition. In an economic context, game theory was first formalized via the classic work of von Neumann & Morgenstern [18] and then immortalized through the work of Nash [19] and others. However, in this Special Issue we mainly focus on game theory and physical science, which may appear to be odd bed-fellows – where exactly is the connection? Moreover, looking at Figure 1 it is remarkable how the number game theory papers is rapidly increasing in the physical sciences realm – what is driving this trend? There are many answers to these questions and we shall briefly allude to but a few.

Beginning with the work of Szilard [20] and culminating in Landauer's mantra that 'information is physical' [21], the interaction between physical scientists and information theorists has burgeoned. In addition, following the pioneering work of von Neumann [22], theorists have used game-theoretic formulations, including simple coin tossing, as a vehicle to explore information theory. Coupling these two trends together connects game theory to physical science via information theory. Moreover, to paraphrase Landauer we might assert that 'games are physical.' In fact, statisticians have long viewed statistical inference as a 'game against nature' [23] and this point of view is increasingly influential among physicists.

Game theory has been successfully applied to both physical and biological control systems, all the way down to colonies of tiny *E. coli* [24]. Turner and Chao have even found that game theory can be applied on the scale of an RNA virus [25]. One might then be led to wonder about yet smaller scales at the molecular level where quantum rules might apply – as has been speculated by Eisert *et al.* [26]. This is hotly debated. On the one hand, decoherence times are very short, as molecules are coupled to an entirely classical environment. On the other hand, workers modeling proteins and other biomolecules are gradually turning to quantum mechanical descriptions in order to obtain accurate representations [27, 28].

Regardless of this debate, the theory of games with quantum rules is a rapidly growing field, launched by the seminal paper of Meyer [29]. As will be seen in the quantum game papers herein, there are a number of promising applications including (i) exploration of quantum information, (ii) the search for new quantum algorithms, (iii) trading with quantum protocols, (iv) cryptosystems and (v) decoherence control, to name but a few. For readers new to this area, we recommend some excellent popular review articles on quantum game theory for preliminary reading [30–32].

3. Papers in this Issue

In this section we provide a brief overview of the papers included in this Special Issue. Evolutionary change or innovation often spreads in the form of a traveling front. Examples are the replacement of one species by another and the invasion of a new territory or niche by a species. Spatial spread of populations is usually modeled by diffusive motion, where individuals undergo a simple random walk with no memory. However, micro-organisms and animals tend to continue moving in the same direction in successive time intervals, i.e., their motion displays memory or inertia. Inertial effects also play a role in other systems of interacting and dispersing particles, e.g., chemical reactions in the gas phase or turbulent flows. Populations and chemical reactions rarely, if ever, experience an environment that is completely free of random fluctuations.

In this issue, Horsthemke reviews the three main approaches used to describe systems of interacting and dispersing particles with inertia and derives analytical results for the effects of external spatial and temporal fluctuations on the mean speed of front propagation in such systems. While one approach concludes that external fluctuations have no effect, the other two predict that in a typical system external fluctuations play a positive and a negative role. They increase the mean speed of the traveling front and decrease the parameter range for which traveling fronts exist. The review suggests experiments to decide which of the approaches to reaction-transport systems with inertia best describes such systems under the influence of external noise.

Cartwright *et al.* review the work on embedding systems into larger systems to find special structures in the system of interest. The dynamics drive the system from chaotic into ordered states, and noise enhances this process. The work originated as an investigation of how small neutrally buoyant particles behave in fluid flows – the particles end up accumulating within vortices. The authors generalize this dynamical mechanism from 2D fluid flows, first to Hamiltonian systems, and then to other dynamical systems. Using chaos to find ordered states is a significant goal in itself. There may well be applications outside fluid mechanics and dynamical systems. One open question is the extension to spatially extended systems. Another is the potential application of these techniques to population dynamics and evolutionary game theory.

Buceta and coworkers introduce the so-called Brownian flashing ratchet, involving alternation between two configurations and illustrating how fluctuations can be 'captured' to produce systematic motion. More recently, this striking phenomenon has been extended to game theory by means of Parrondo's paradox, where alternation of two losing games turns into a winning outcome. In this review, the authors highlight that the message underlying the 'paradox' can be extended to pattern formation: they show how alternation, either random or periodic, of two dynamics, neither of which by itself leads to pattern formation, may produce patterns. One can envision biological situations, specifically in population dynamics and disease propagation, where this unexpected emergence of patterns may play a key role, leading to exciting advancements in the theory of evolutionary processes.

Karchenko deals with evolution of a system in the presence of a fluctuating environment. The main system assumption is that the evolution process is considered as diffusion with self-affine geometry of the phase space. Such a model may address economic systems where geometry of the phase space produces the transformation to the homogeneous function and finally stipulates the Pareto law to account for the wealth of the population, for example. Such kinds of systems show anomalous time behavior (different to the ordinary diffusion law). The author connects the tools of anomalous diffusion studies (super-diffusion) with the standard Langevin approach and presents the description of the system based on Gaussian processes. The article has an open question: is it possible to find an approximate model to represent subdiffusion processes in terms of Gaussian processes?

Rand introduces a Markovian model of literary style that allows for the question of authorship to be investigated by comparing underlying statistical regularities in the bodies of text. Results so far are successful and if this technique continues to succeed it could provide for an automatic identification of authorship, genre, or even 'moods' of texts. Moreover, it may also be possible to extend the technique to other areas of text examination and classification like genomics. These types of techniques are of great interest in tracking evolutionary change in both text and DNA sequences.

Living micro-organisms are able to transport nutrients and waste products. They are able to maintain non-equilibrium chemical potentials and to communicate. All these processes depend upon the selective transport of matter. A number of scientists, including Astumian, have used ideas from parlour games, such as 'craps', to allude to certain key transport processes. One advantage of this approach is that it is possible to make use of large bodies of existing theory, of games, of matrices and of Markov chains. The games are often so simple that analytical solutions can be found. These solutions often have very interesting symmetries. This naturally raises the question of whether these symmetries are part of natural processes in the world or whether they are artifacts of the way in which the natural processes have been formulated, as games. Allison *et al.* establish a completely rigorous, consistent and bi-directional mapping between a one dimensional stochastic transport process and a set of discrete games. The authors expect that symmetries found in the solutions to the discrete games will be found in the corresponding real physical processes. The technique used in the current paper is based on the method of finite differences. An important open question is to establish whether changes in these arbitrary choices would lead to significantly different sets of games with fundamentally different solutions. If we intend to use discrete games to represent continuous physical processes then we must require all finite difference models of a system to converge to the same solution, as the sampling distances and times are reduced to the limiting case of zero. Another well-known approach to the modeling of continuous systems is the method of finite elements, so another important open question is whether finite element models of a system would converge to the same solutions as the finite difference models. Finally, it is possible to speculate about the application of these processes to other stochastic systems. For example, we might want to study the dispersion of certain genes with respect to geographical location and time. If these processes could be formulated in terms of partial differential equations then the sampling techniques in this paper would be relevant and the probability of finding a gene at a particular location in space and time could be modelled using games of the type suggested by Parrondo. It is possible that fluctuations in the potential function (representing local fitness) could give rise to steady state flows in probability, and hence gene frequency, from one location to another. For example, it might be possible for annual fluctuations in fitness, due to the seasons, to give rise to permanent, non-cyclic, shifts in gene frequencies between two locations. This would have implications for evolutionary theory.

Parrondo's paradox demonstrates that the combination of two losing games can result in a winning game. One explanation is that one of the games has 'good' and 'bad' components and the introduction of the other game, although losing, inhibits the bad component in the first game. Toral shows that the same kind of results can be obtained when individual actions, which are bad on the average, combine with a neutral action such as an altruistic redistribution of money. The paper considers a set of agents of a society, which are playing a gambling game individually, in which all of them, on average, lose money. However, when their money is being redistributed randomly, the whole society (and each particular member of it) starts to win money. In other words, redistribution of money (in the form of taxes, for instance) can turn every individual losing player into a winning one. The key open issue, of course, is to establish if a similar scenario can happen within any of the general models of game theory as applied to social and economic behavior.

Rasmusson *et al.* analyse Parrondo's games, confirming previous results and furthermore produce an expression that predicts the performance of Parrondo's history-dependent games as a function of the mixing ratios of the games.

Melby *et al.* propose a very simple mechanism for adaptation in dynamical systems, based on a feedback from the fast dynamics of the system to the parameter's dynamics. Previously, they had found in numerical studies that systems with this type 'adapt to the edge of chaos' – that their long-term behavior places them on the boundary between chaotic and regular motion. In the present paper, the authors expand this work in two areas: (i) they show that adaptation to the edge of chaos is robust against a controlling force which seeks to make the system chaotic and (ii) they show that adaptation to the edge of chaos will occur in an experimental system with such feedback. This work addresses the general question, which many have asked about adaptive systems, of whether they will naturally evolve toward the transition point between chaos and order.

Flitney *et al.* give a brief description of the basic ideas and terminology of game theory before reviewing the protocol for combining the methods of quantum mechanics and game theory. They pull together ideas from various early papers on quantum games to present a concise introduction to the field, and briefly review the ideas in many of the published works. A full set of references for the field up to the time of writing is provided.

Patel suggests that Darwinian evolution can be quantified using just a simple linear evolutionary model. The model has similarities with extensively studied topics of zero-sum games and quantum computation. The crucial ingredient is that limited availability of a resource leads to destructive interference. This interference can be modeled, by analogy, using the mathematical machinery behind quantum computation. The model demonstrates that when one species snatches away the resource from another one, there is always instability and the weaker species is eliminated in a finite time. Detailed analysis of multi-species interactions in the model may shed more light on the variety of evolutionary instabilities seen in biology.

To date, quantum game models are based on complete information. Han *et al.* construct a quantum game subject to incomplete information and discuss how entanglement affects the Bayes-Nash equilibrium. Incomplete information models are very important for understanding quantum information processing and decoherence. How to construct an incomplete information quantum game corresponding to a given quantum process is an important open question.

Cellular function is the product of feedback-regulated biochemical reactions, which operate on the face of significant fluctuations in the internal and external environment. Along with homeostasis, cellular functions show many kinds of dynamics – periodic, chaotic, bistability, etc. Diverse cellular functions are sometimes controlled by a single biochemical oscillating in a robust manner with altered amplitude and frequency (frequency and amplitude coding). Many cellular processes also show noise-sensitive behavior, which have functional consequences. Suguna and Sinha address the question of noise sensitivity in a simple positive and negative feedback regulated model of a biochemical pathway to show that the same pathway can exhibit both robust and non-robust functional dynamics, under variation in both concentrations of biochemicals and parameters controlling rates of reactions. The phenotypic variation in the pathway dynamics under stochastic fluctuation in concentrations of substrates is a product of the fractal nature of the basin of attraction of the single positive unstable steady state. Much of the parameter space exhibits a variety of dynamics that are quite robust to fluctuations, indicating that robust behavior is the most common form under a wide range of mutational changes. Experimental biology has shown that cellular processes have evolved to evade or even exploit the fluctuations and noise pervasive in nature. The paper shows such properties can potentially give rise to the diversity and complexity observed in nature through evolutionary processes.

In their paper, Meyer and Blumer explain a quantum version of Parrondo's game. Just as the classical version models a particle diffusing in a flashing ratchet potential, their model describes a quantum particle evolving in the same potential. They show that even when there is a global bias, the expectation value of the position of the particle (which is the net capital of the gambler in the game), can be driven in the opposite direction. When the potentials are unbiased, the expectation value grows linearly with time. It would be interesting to implement recent suggestions for realizing quantum random walks experimentally [33–35] using the kinds of potentials that Meyer and Blumer consider – that is, to build a quantum Parrondo game! On the theoretical side, this paper illustrates one formalism for iterated play of a quantum game, a prerequisite for studying evolutionary processes in quantum games.

Lee, Johnson and coworkers examine the effect of correlated noise on the quantum coherence within a simple two-level system. This topic is important for the practical implementation of quantum information processing schemes, such as quantum computation, where decoherence is seen as the number one enemy. The main result is that such noise might not be as destructive as first imagined, and could even play a useful role in enhancing coherence phenomena. Their paper takes the viewpoint that the quantum system is effectively playing a game against the environment in order to retain its coherence. By adding a particular form of environmental noise and hence playing a particular form of game – the Parrondo game – they show that decoherence can indeed be reduced. An open question arises as to the generality of this result concerning robustness to correlated noise. The present results suggest that repeated games, and possibly even evolutionary games, may shed light on the task of quantum coherence control, and even the fundamental processes underlying decoherence itself.

Du *et al.* consider a multi-player version of Prisoner's dilemma and extend previous work by considering the full space of quantum strategies. They also give all the Nash equilibria for the 3-player game. As the degree of entanglement between players varies, very interesting effects emerge similar to phase transitions.

Doscher and Keyl review the quantum version of a well-known cryptographic protocol called 'coin tossing.' Roughly speaking, the problem is about two parties who distrust each other and try to agree about a random bit. This paper is the first detailed review of quantum coin tossing (QCT). To extract the rules of the game from the original publications and write them down in a clear way is in fact a hard task, and there was a great need for such a review. There are two major open problems: (i) find better bounds on the bias of QCT protocols and (ii) decide whether unconditional secure (with zero bias) coin tossing is asymptotically (i.e. in a game with infinitely many rounds) possible or not. Although it originates from quantum cryptography, QCT is a game. What makes it much more interesting than an ordinary coin flip, is the fact that 'cheating' is taken into account as an additional strategic option.

4. Quo Vadis?

Dramatic advances in science often stem from the mixing of ideas from different fields of enquiry. In this Special Issue, game theory, the physics of noise and fluctuations and the concept of information are tangled together in a promising and tantalizing way. On reviewing the papers herein, it is hard to escape the impression that a new sub-discipline is emerging that could have broad implications for physical science as a whole. Information theory is currently penetrating several branches of physics and biology, and information as a physical quantity is assuming the status once reserved for particles or energy, as foreseen by Wiener long ago [36]. Some even claim that the physical universe is fundamentally built from information, not matter [37]. Yet we lack anything like the laws of mechanics or thermodynamics for the dynamics of information. Indeed, physicists do not even agree whether information is a conserved quantity at the microscopic level, as might perhaps befit a fundamental entity. The development of quantum computation forces us to rethink of the very notion of information and the rules for its evolution, with implications that are at once vast and uncertain.

The physical universe is in a very remarkable state, poised exquisitely between tedious uniformity and directionless chaos. The richness of the world we observe has emerged spontaneously from the featureless primordial universe that followed the big bang [38]. Some physical systems, especially but not exclusively living ones, can harness randomness, and use it to build complex structures. Nature's innate creativity lies in this process of self-organization, whose highest peaks (to date) are beings able to comprehend the evolution of the universe, including, to a small extent, themselves.

Although many disciplines appreciate the fact that much of the world moves from 'simple and featureless' towards 'complex and intricate', none of them has a general principle to explain it. The application of game theory to self-organising phenomena will cast important new light on this aspect of our cosmos, giving us, perhaps of a glimpse of a deep unification of physics, biology and information.

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