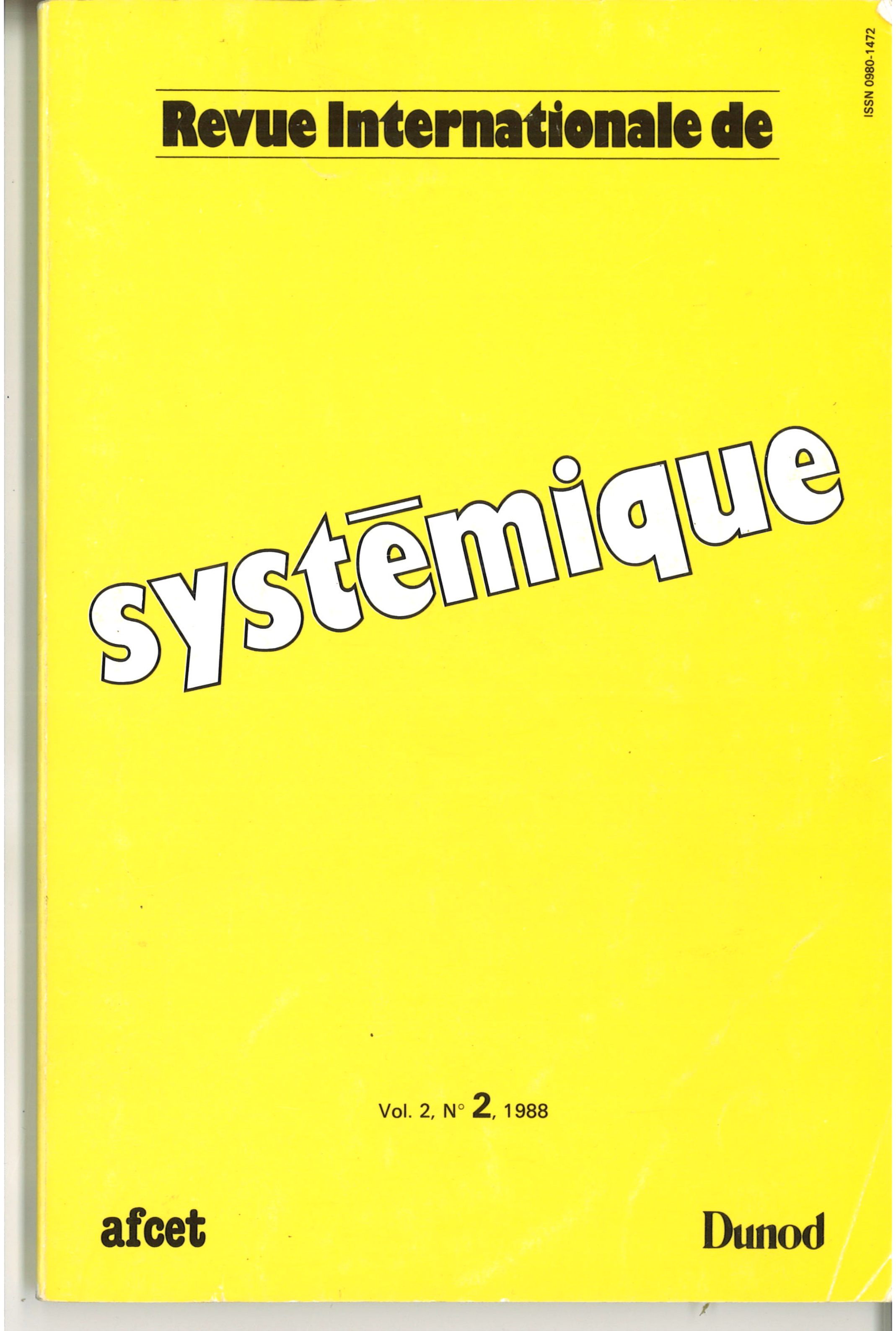

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EVOLUTIONARY DYNAMICS IN NATURE AND SOCIETY,

Steps Toward a Cross-Disciplinary Theory

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Abstract

A new paradigm, based on the sciences of complexity, allows the cross-disciplinary integration of natural and societal phenomena. The paradigm applies to complex systems far from equilibrium at all levels of organization. It includes general laws of system persistence, change and development, and links our understanding of physical evolution in the cosmos with biological and sociocultural evolution on Earth.

Résumé

Un nouveau paradigme, fondé sur les sciences de la complexité, permet l'intégration trans-disciplinaire des phénomènes naturels et sociétaux. Ce paradigme s'applique aux systèmes complexes loin de l'équilibre à tous les niveaux d'organisation. Il incorpore les lois générales de permanence, de changement et de développement des systèmes et relie notre compréhension de l'évolution physique dans le cosmos à l'évolution biologique et socio-culturelle sur la Terre.

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Introduction

Modern science, despite the proliferation of specialized branches and disciplines, exhibits a penchant for creating highly integrated and elegant theories within each of its domains of investigation. Newton's monumental work synthesized the myriad observations accumulated by physical scientists in the elegant general laws of classical mechanics. Darwin synthesized the countless observations of life scientists in a grand theory which came to be known as the synthetic theory of evolution. In the beginning of this century Einstein reformulated the Newtonian synthesis to integrate within the scope of the special and general theories of relativity more recent findings that were anomalous for classical physics. His attempts to create a further synthesis in the form of a unified field theory, though unsuccessful at the time, inspired a series of more successful recent attempts to integrate electromagnetism with the weak nuclear force and the resulting electroweak force with the strong nuclear force. These 'Grand Unified Theories' (or GUTs, as they have become known) encourage expectations that, in the not too distant future, we may see integrated physical theories which encompass all universal forces, including gravitation, within the postulate of a single 'grand unified' force.

In recent years new interdisciplinary sciences have made their appearance under the collective heading of 'sciences of complexity'. Cybernetics, general system theory, information and communication theory and allied disciplines investigate the processes and dynamics of control and change in complex systems of a great variety, from artificial servomechanisms to human societies. Contemporary monequilibrium thermodynamics undergirds these attempts by providing an empirically based and mathematically formulated description of the dynamics of system formation and maintenance in domains far from thermal and chemical equilibrium. And the new theories of biological macroevolution show that the logic of evolution manifest in the physical realms also appears, albeit in different forms and manifestations, in the realms of life.

In the 1980s cross-disciplinary theories have a solid and still growing scientific base to build upon. If rigorously pursued they can extend insights gained in the natural sciences to the sciences of society, bringing new understanding to the humanities and healing the 'two culture' split that divided Western civilization since the dawn of the modern age.

But,the application of a theory of evolution based on principles developed in the *natural* sciences to events and processes within the domain of the *social* sciences implies an insidous form of reductionism : it appears to suggest that, after all, society is 'nothing but' a kind of a natural (physical, chemical or biological) system. Nothing could be further from the intentions of this study than such an assumption. It does not assume that society is anything other than what social scientists themselves assume it to be : a complex entity made up of human beings and groups of human beings in a variety of relationships. It does suggest, however, that such an entity can be analyzed in terms of concepts that apply to complex systems whatever the nature of their parts or their place in the order of things. We can legitimately ask, therefore, whether the laws ans regularities that hold for complex systems in the realms investigated by natural science also hold for complex systems investigated by social science. This is not to reduce social scientific phenomena to the phenomena of natural science, but to explore the applicability and validity of a general theory of systems persistence and change across the disciplines.

Arguments for treating society as an entity radically different from natural systems have no *a priori* validity. A society is a dynamic structure composed of groups of human beings in specific relations. The social system, much as an organic population, a clade or an ecosystem, maintains itself or changes independently of the particular destinies of its individual members. Human beings pass through it in cycles of birth, maturation and death ; society persists, changes or decays according to processes that take place on its own, typically societal level. The fact that the individual members of human societies are conscious, language and toolusing persons introduces a good deal of noise into the system but it does not negate whatever dynamic properties it has of its own. All forms of reductionism can be firmly rejected. Society as a system is not reducible to an atom, a cell, an organism or an ecosystem, even if the same basic and general laws apply to all of them. Society is also not reducible to its parts or components. Just as a human being is 'more than' the sum of the cells in his body, so a human society is 'more than' the sum of its individual members. Each system derives its structural and dynamic characteristics from the kind of interactions and interrelations that obtain among its parts, rather than from the aggregate presence of its parts.

The application of contemporary theories of systems evolution to society does not imply or entail reductionism. Such application means the use of a general theory to fields that are encompassed by the range of validity of its postulates. That the fields happen to cross boundaries that arose in traditional science is not a shortcoming of the theory but evidence of the obsolescence of compartmentalizing the fields of scientific research.

A new paradigm

Until recently Western science viewed evolution as a basically deterministic process oriented toward equilibrium. Factors of chance and instability were underemphasized in favor of stability, control and predictability. Randomness was conceptualized in physics mainly within quantum mechanics through the uncertainty principle of Heisenberg. But the principle applies only to the realm of the microscopic ; at macroscopic levels phenomena were considered to be basically deterministic. The mechanistic worldview underlying Newtonian physics, and the Laplacian belief that, given enough information we could predict the position of every particle in the universe at any time, proved to be pervasive. The laws of nature had to be deterministic as well as universal ; exceptions to them were viewed with mistrust ans ascribed to flaws in the system of reckoning. The state toward which systems tend was conceptualized as a state of balance or equilibrium – although these terms were seldom precisely defined.

Concepts of equilibrium and dterminacy were dominant also in the sciences of life and society ; biologists concentrated on the determinsitic logic whereby natural selection brings about a proper balance between predator and prey and assures the survival of the fittest under predictable conditions, while economists, following in the footsteps of Adam Smith, sought equilibrium in economic processes through the self-regulating forces of the markett demand and supply are to balance each other through the mechanism of natural price. Neo-classical economics and neo-Darwinian biology loath to surrender the myths of equilibrium and determinacy, even if they did allow multiple forms and levels of equilibrium and a certain degree of 'noise' which distorts – but does not cancel – the basically predictable effects of the principal laws and regularities. Unexpected events are still abhorred ; in ecology they are sometimes designated 'Acts of God', disclaiming responsibility form them. That systems move in states of nonequilibrium through sudden and individually unpredictable stages toward states of greater and greater free energy, more and more complexity and less and less entropy has dawned on the scientific world only in recent years.

In light of the latest understanding generated by nonequilibrium thermodynamics together with physical cosmology, evolutionary chemistry, macrobiology and the related sciences of complexity, evolution unfolds, step by step and level, through alternating phases of determinacy and indeterminacy, through self-preservation amidst change, and random and possibly chaotic reorganization during phases of bifurcation generatd by critical instabilities. Evolution climbs the ladder of structural complexity and organization, committed to the maximization of free energy and the minization of entropy. This is the genuine logic of evolution and it is very different from the conceptions we entertained hitherto.

We can no longer conceive of the universe as an accidental combination of matter, life and consciousness. We now see that levels of reality are not radically distinct from each other ; they appear in successive evolutionary phases as nonequilibrium systems encounter points of bifurcation and move toward energetically more efficient and structurally more complex and differentiated forms of organization. Time enters into the very essence of the process : though individually random, evolutionary transformation is irreversible on the whole, moving from simple, microscopic and energetically bonded units to more complex, larger-scale and less strongly bound entities.

Our understanding of the nature of scientific laws is likewise in need of reassessment. The laws of science apply not merely to certain delimited classes of phenomena ; they map dynamic sequences of events which repeat in phenomenologically entirely different forms and variations, corresponding to the evolutionary levels of the evolving systems. The sequence mapped by the laws allow for randomness and even for chaos ; random and chaotic behavior contradict the laws of traditional mechanistic theories but not those of the new sciences of systems and complexity.

The emerging logic of evolution signifies the breakdown of the hitherto dominant mode of thinking and a breakthrough to a new scientific 'revolution'. Nature is not fixed ; it is actively altering, responding and creating itself in response to often unpredictable stresses and perturbations. This is a new scientific paradigm, and it can no longer be ignored. Those who make creative use of it will be the leading minds of our time, whose ideas and theories will open new vistas for science – and fresh opportunitis for people and for societies.

New concepts of evolution

Traditionally science has accounted for the emergence and evolution of systems on each level of the evolutionary hierarchy through a specific theory developed in the corresponding scientific discipline. The appearance and transformation of the atoms of the elements were explained in theories of cosmology and astrophysics, and in quantum and plasma physics. The reactions and reaction cycles responsible for the syntesis of molecules of various complexity were accounted for in chemistry and in organic chemistry ; the cellular and subcellular entities associated with life were investigated in microbiology ; while macro– or evolutionary biology concerned itself with the emergence of cellular and multicellular species. Ecology dealt with the origins and development of systems composed of diverse populations of organic species, and the human and social sciences concentrated on the emergence, behavior patterns and social relations of human beings.

These special concerns still exist, as each branch of empirical science pursues its investigations within relatively delimited domains, using its own theoretical concepts and languages. However, there is now also a cross-disciplinary trend which deals with the appearance, developmeent and functioning of complex systems as such, regardless of the domain of investigation to which they belong. The trend originated with the general system theory pioneered by von Bertalanffy, Paul Weiss, Anatol Rapoport and Kenneth Boulding, and was reinforced when Wiener, Ashby and Beer developped the science of cybernetics. Since the early 1970s, the thermodynamics of irreversible processes – non-equilibrium thermodynamics – has furnished rigorous empirically tested and mathematically formulated concepts to explain how order arises from disorder, and structure is created and maintained in the physically improbable state far from thermal and chemical equilibrium.

Contemporary nonequilibrium thermodynamics is perhaps the best source for the formulation of a cross-disciplinary theory of evolutionary change with scientific rigor : the basic, concepts of this theory can be extended from physical chemistry to the life and even to the social sciences and can give an account of the processes underlying the evolution of all varieties of complex systems. We first review, therefore, the pertinent features of this theory.

Following Prigogine, we distinguish three types of states in which systems in the real world can exist. Of the three, one is radically different and entirely remarkable : it is the state far from equilibrium unknown to traditional physics and thermodynamics. The traditionally known states are those in which systems are either *in* equilibrium, or *near* it. In a state of equilibrium energy and matter flows have eliminated differences in temperature and concentration ; the elements of the system are unordered in a random mix and the system itself is homogenous and dynamicaaly inert. The second state differs only slightly from the first : in systems near equilibrium there are small differences in temperature and concentration ; the internal structure is not random and the systems is not inert. Such systems will tend to move toward equilibrium as soon as the constraints which keep them in nonequilibrium are removed. For systems of this kind equilibrium remains the 'attractor, state which it reaches when the forward and reverse reactions compensate one another statistically, so that there is no longer any overall variation in the concentrations (a result known as the law of mass action, or Guldberg and Waage's law). The elimination of differences between concentrations corresponds to chemical equilibrium, just as uniformity of temperature corresponds to thermal equilibirum. While in a state of nonequilibrium the system performs work and therefore produces entropy, at equilibrium no further work is performed and entropy production ceases.

In a condition of equilibrium the production of entropy, and forces and fluxes (the rates of irreversible processes) are all at zero, while in states near equilibrium entropy production is small, the forces are weak and the fluxes are linear functions of the forces. Thus a state near equilibrium is one of *linear* nonequilibrium, described by linear thermodynamics in terms of statistically predictable behaviors, as the system tends toward the maximum dissipation of free energy and the highest level of entropy. Whatever the initial conditions, the system will ultimately reach a state characterized by the least free energy and the maximum of entropy compatible with its boundary conditions.

The third possible state of systems is different from the other two in that it is a state far from equilibrium. Here initial conditions have a critical role and the fluxes are no longer a linear function of the forces. Systems far from equilibrium are always nonlinear and occasionally unpredictable. They do not tend toward minimum free energy and maximum entreopy but may amplify certain fluctuations and evolve toward a new dynamic regime that is entirely different from stationary states at or near equilibrium.

Nonequilibrium thermodynamics together with physical and organic chemnistry can show systems in the third state evolved in the course of time from systems near equilibrium. *Prima facis* such a process appears to contradict thermodynamic's Second Law. The Second Law states that in any isolated system organization and structure tend to disappear, to be replaced by uniformity and randomness. But evolving systems are not isolated systems and thus the Second Law does not fully describe what takes places in them – more precisely, between them and their environment. The fact is that systems in the third state are open systems, and the change of entropy within them is not determined uniquely by irreversible processes within their boundaries. Internal processes within the system do obey the Second Law : free energy, once expanded, is unavailable to perform further work. But energy available to perform further work can be 'imported' by open systems from their environment. There can be a transport of free energy – or negative entropy – across the system boundaries. Thus change in the level of system entropy is given by the equation : dS = dˆ iS + dˆeS. (Here dS is the total change of entropy in the system, while dˆiS is entropy change produced by irreversible process within it and dˆeS the entropy entering across the system boundaries). In a closed system dS is always positive, for it is determined uniquely by dˆiS which necessarily grows as the system performs work. However, in an open system dˆeS can offset the entropy produced within the system and can even exceed it. Thus dS in an open system can be zero or negative : the system can be in a stationary state or it can grow and complexify, moving even further from equilibrium. Entropy change in a system maintaining itself far from equilibrium is described by the equation dˆeS = –dˆiS ⩽ 0 : the entorpy produced by irreversible processes within the system is shifted into the environment.

Systems that balance their internal entropy production with the importation of negative entropy from the environment are said to be in a steady state. These states are not entirely 'steady' but are merely stationary to the extent that the two terms, dˆiS and dˆeS, balance one another. In reality most systems fluctuate around certain typical states, returning to them as to a norm or standard following limited deviations. The 'normal' state for such systems is the theoretical steady state, and it is defined by the internal forces organizing the system. If the states of the system are mapped over time as a trajectory, the system appears to be 'attracted' by the normal steady state (or perhaps a series of cyclically repeating steady states) : this state (or states) will then appear to be within the 'domain of attraction' of the system.

The forces which seem to pull the system toward the steady state or states are known as the system's 'attractors'.

Thus steady state systems are necessarily open systems in the third state, far from thermodynamic equilibrium. They exist in an energy flow between an energy source and an energy sink. As the energy flows from source to sink it passes through the substances (particles or already organized systems of matter-energy) that constitute the open system. As experiments have shown, in such conditions the energy flow *organizes* the substances into structures capable of storing and using some part of the energy throughput. As a result the system adopts steady states progressively further from thermodynamic equilibrium.

The emergence of systems in the third state is now explained in reference to the fact that, under suitable conditions, a constant and rich energy flow passing through a system drives it toward states characterized by a higher level of free energy and a lower level of entropy. The terms, entropy and free energy, are related by the equation $F = E - TS$, where F stands for free energy, E for total energy, T for absolute temperature and S for entropy. Free energy equals the total energy content of the system, less its absolute temperature times its entropy. Consequently at any given temperature the smaller the system's entropy, the greater its free energy (and vice versa). Morowitz has shown that the more energy is stored by the system, and the longer the time during which it is stored, the greater the system's free energy and the smaller its entropy.

For example, a gas composed of monatomic molecules can store energy only for a short time by producing charged electrons and ions. A complex chemical system, on the other hand, can store more energy and for a longer time in covalent bonds, ionic bonds, weak interactions and in other ways. Such complex systems have not only more free energy and less entropy than simple monatomic gases, they are also more complex. A living system is likewise more complex than a chemical compound : its free energy content is correspondingly higher and its entropy is correspondingly lower.

The relationship between energy flow over time and change in entropy and free energy is essential for answering not only the question as to *how* systems in the third state evolve, but also whether they evolve *necessarily*, under certain conditions. Until the 1970s investigators leant to the view – exposed most eloquently by Jacques Monod – that evolution is due mainly to accidental factors. But as of the 1980s many scientists are becoming convinced that evolution is not an accident, but occurs necessarily whenever certain parametric conditions are fulfilled.

Laboratory experiments and quantitative formulations now corroborate the non-accidental character of evolutionary transformations. The experiments call for reproducing an energy flow from a source to a sink, and placing the test objects within the flow. The theoretical basis for the experiments is given by Prigogine's 'Brusselator', modelling a chemical auto-catalytic system. The Brusselator consists of the following series of reactions :

(1) $A \longrightarrow X$

(2) $B + X \longrightarrow Y + D$

(3) $2X + Y \longrightarrow 3X$

(4) $X \longrightarrow E$

The parameters of the system are given by the products A, B, D, and E. A and B are inputs and E is the output ; these represent the matter-energy flow through the system. When the concentration of B exceeds a critical threslhold, while A is kept constant, the system leaves the stationary states and reaches a limit cycle : the concentrations of X and Y begin to oscillate with a well-defined periodicity. The determining factor is the increase in the concentration of the input factor B beyond the critical threshold. This is the externally induced 'perturbation' that pushes the system into the oscillatory mode (other inputs and outputs being kept constant).

A large variety of chemical systems capable of oscillating between two or more steady states have been designed in the laboratory. The principles underlying the experiments are clear. The system must be in a flow : it must be fed initial reactants and allowed to discharge its final products. It must have sufficient complexity of structure to persist in two or more steady states when the values of the parameters – the boundary conditions – are suitably varied (i.e., it must have bi– or multistability). And, last but not least, the structure of the system must be maintained in the flow by feedback loops and catalytic cycles.

Auto– and cross–catalytic cycles in the test systems are essential in the experiments just as they are essential in nature. Catalytic cycles are the basic mechanisms maintaining nonequilibrium systems in a flow of energy. Already in 1931 Onsager could show that in a steady state system cyclic matter-energy flows are likely to arise. For example,

in a simple chemical system composed of three types of molecules, A, B, and C, in which both forward and reverse reactions of the following kind are possible $A \rightleftharpoons B$, $B \rightleftharpoons C$, $C \rightleftharpoons A$, the introduction of a continuous energy irradiation into one of the cycles, e.g. $A + hv \rightarrow B$ tends to move the system into a cyclic pattern $A \rightarrow B \rightarrow C \rightarrow A$.

It is logical that of the various types of reactions that organize the system so as to increase its capacity to absorb some portion fo the energy throughput, those reactions should be naturally selected which have the most stability and the fastest reaction rates. These are the catalytic cycles. There are two principal varieties : auto-catalysis, where a product of a reaction catalyzes its own synthesis, and cross-catalysis, where two different products, or groups of products, mutually catalyze each other's synthesis. In relatively simple chemical systems autocatalytic reactions tend to dominate, while in more complex processes, characteristic of living phenomena, entire chains of cross-catalytic cycles appear. For example, nucleic acid molecules carry the information needed to reproduce themselves as well as an enzyme. The enzyme catalyzes the production of another nucleic acid molecule which in turn reproduces itself, plus another enzyme. The loop may involve a large number of elements ; ultimately it closes in on itself, forming a cross-catalytic reaction cycle remarkable for its fast reaction rates and stability under diverse parametric conditions.

Given sufficient time, and an enduring energy flou acting on organized systems within permissible parameters of intensity, temperature and concentration, the basic auto-catalytic cycles tend to interlodk in a process known in molecular biology as convergence. This process does not lead to growing similarities among the converging systems and ultimately to uniformity (as it does in the 'convergence' of social and political systems), since the convergent systems complete and complement each other functionally. Convergence in this sense has general application in all realms of evolution ; it is the basic mechanism for the creation of the multiple levels of nonequilibrium systems, ranging from molecules to multicellular organisms and the ecologies and societies formed by such organisms.

In a convergent process previously autonomous self-maintaining systems are progressivily interlocked in cross-catalytic cycles. The continued persistence of the systems becomes dependent on the functioning of these embracing feedback loops. In time a new nonequilibrium system emerges, as convergent evolution lifts the organization of free energy maximizing and entropy minimizing systems to the next level of the evolutionary hierarchy.

Bifurcations

As the 'Brusselator' and other theoretical and experimental models demonstrate, systems maintained by catalytic cycles in an energy flow can be 'disturbed', i.e., moved out of their typical steady states, by changes in the energy inputs and other crucial parameters. The disturbance is critical for systems when it impairs the functioning of their catalytic cycles. When critically destabilized, systems in the third state appear to 'search' for, and if sucessful ultimately settle into, alternative steady states maintained by a new set of catalytic cycles.

This finding is, of great importance for the understanding of just how nonequilibrium systems evolve. Significant evidence is now accumulating in diverse branches of contemporary science underscoring the fact that nonequilibrium systems do not evolve smoothly and continuously over time, but do so in sudden leaps which intersperse relatively extended periods of stasis. At these critical junctures the system-maintaining catalytic cycles are destabilized, and the system moves into another steady state (or set of steady states). In general, the further a system is from thermodynamic equilibrium, the greater the number of possible steady states available to it.

In nonequilibrium thermodynamics the leaps into new steady states are termed 'bifurcations'. Although in reality the points of bifurcations, consisting of numerous alternatives, are polyfurcations, the term 'bifurcations' conserves its validity inasmuch as a system can settle into only one of the alternative steady states available to it. Hence its trajectory over time bifurcates.

The selection of alternative steady states at points of bifurcation is random. Even if the observer controls the perturbation that destabilize a system (e.g., the input from the energy source), the transformation of its state remains unpredictable. The system acts indeterminately, selecting among the steady states available to it by randomly amplifying some of its, internal fluctuations. The indeterminacy of the system's behavior during points of bifurcation contrasts with the overall determinacy and predictability of its behavior in stable periods regulated by dominant internal forces or 'attractors'.

The destabilization of individual systems at a specific point in space and time, i.e. bifurcation as a unique event, being indeterminate and random, is not necessarily a conduit to higher stages of organization with greater free energy and lesser entropy. Systems can also decay

and dissolve, or manifest states known to contemporary science as chaotic. Instead of more organized structures consisting of controlled oscillations and regular limit cycles, aleatory states may appear.

Transitions toward chaotic states are currently the subject of intense study ; they are investigated in a branch of mathematics known as nonlinear dynamics. Originally develope by Henri Poincaré at the turn of the century, nonlinear dynamics was largely ignored because it generated random results without clear-cut applications to the empirical world. However, in recent years chaotic and apparently random behavior have been discovered in a wide varisty of complex systems. Such behavior is exhibited by processes as varied as fluids in flow, and the blending of substances during solidication. The phenomenon of turbulence is a case in point : it has been known since the 19th century, but its origins have been imperfectly understood. It now appears that turbulence is an aspect of the tendency of nonequilibirum systems to evolve, under certain conditions, in a disordered manner.

Current work in nonlinear dynamics finds order even in chaos : it develops an 'encyclopedia of bifurcations' which shows that seemingly chaotic states have their inner logic. Chaotic systems can be steered through interventions at critical points. Even more important from the viewpoint of understanding evolutionary processes is the empirical finding that, within the sweep of large-scale evolutionary processes, the outcome of bifurcations, though traversing chaotic states, is not entirely random. The statistical average is biased toward the creation of structures that store more energy for a longer time, maximizing free energy and minimizing entropy. Without such a bias evolution would be a random drift between more and less organized states, instead of a generally one-way build-up of order and complexity through alternating phases of order and disorder, determinacy and indeterminacy.

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We now have good reasons to believe that there is a supremely harmonious and logical process underlying the evolution of complexity in the, universe. Thanks to nonequilibrium thermodynamics and the new sciences of complexity, we can look forward to a scientifically grounded cross-disciplinary theory that links our understanding of physical and chemical evolution in the universe with our knowledge of biological and historical evolution on Earth. The full and rigorous formulation of such a theory would surely rank among the greatest achievements of contemporary science.