The Emergence of Complexity in Physical Systems

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Abstract

Intrinsic determinism is a deep-seated concept in physics: a well-defined cause has a well-defined effect. Determinism leads to the concept of four-dimensional spacetime, in which the future, as well as the past, is set in stone, and there is no possibility for novelty. Applying determinism to an objective quantum reality leads to unresolved conceptual difficulties, most notably, nonlocality, which Einstein referred to as spooky action at a distance. These foundational questions have not held back physics' spectacular advance. However, intrinsic determinism of physical reality denies any description of evolution or emerging complexity in terms of fundamental physical principles.

We identify a deeply ingrained assumption that has led physics to reject fundamental irreversibility and randomness. We propose simple postulates that provide a consistent and objective interpretation of physical measurements, within a conceptual framework that embraces randomness and irreversible time as fundamental. Dissipative dynamics reconciles quantum nonlocality and relativity, and it provides a firm foundation for the Kelvin Selection Principle to guide the spontaneous emergence and evolution of complexity.

1. Introduction

The universe has evolved from a nearly homogeneous state early in its history, to its current state of extraordinary complexity; yet, physics provides no clear explanation for this. The block universe model regards the universe, its past, present and future, as a static block of four-dimensional spacetime. It describes time as a coordinate along the time axis and the evolution of the universe as the deterministic playing out of a script encoded at its creation. The block model accommodates neither the spontaneous generation of novelty nor the selection of possibilities. These are essential ingredients for any theory of physical evolution.

This article reviews physics' concepts of time and physical reality, and it integrates the empirical models of physics, thermodynamics, and evolution into a generalized conceptual framework. Dissipative dynamics provides for a principle of selection that guides the evolution of physical systems into the future by the irreversible selection of emerging possibilities.

2. Physics' Problem with Time

Physics regards time as a dimension of spacetime. Whereas spatial coordinates specify a body's position in space, the time coordinate specifies a body's position along the time axis. 'Here and now' marks our current position within spacetime, but unlike the spatial coordinates, we cannot move back and forth across the dimension of time. We can remember the past, but we cannot remember the future. Physics has a profound difficulty in rigorously explaining why this is so.

Our perception of time is clearly irreversible. If we release a drop of ink in swirling water, we see it disperse until it is uniformly distributed, but we will never see it unmix. We see friction dissipate kinetic energy into ambient heat, but we will never see ambient heat spontaneously accelerate a mass. Thermodynamics codified this asymmetry of time with its Second Law. The Second Law of thermodynamics describes the arrow of time by the increase in entropy. Increasing entropy describes both the irreversible dissipation of useful energy into waste heat and the dispersion of ink particles in water.

The laws of physics, however, are blind to the direction of time. Physics describes the physical world as microscopically reversible. If we could see individual water and ink particles interacting, we could not tell forward time from backward, and no laws of physics would be violated if the particles reversed their motions and the ink unmixed.

Ludwig Boltzmann sought to reconcile these disparate views of time. The background thermal noise of thermodynamic measurements precludes a precise determination of a system's actual physical state. Boltzmann defined heat and temperature as statistical descriptions of a system's particles, based on imperfect measurement. He then redefined entropy, from its original thermodynamic definition in terms of heat and temperature, to a statistical measure of our uncertainty of a system's actual physical state at any instant. Boltzmann managed to subsume thermodynamics as a statistical approximation of physics, and to firmly establish physical reality as defined by perfect measurement at absolute zero, in the absence of thermal noise.

A high uncertainty in a system's actual state means that there are many possible states available to the system. More possibilities mean a higher probability[1]. Boltzmann interpreted irreversible change as a progression from low probability to higher probability. According to physics, the only reason that we do not see the ink unmix and entropy decrease is that the disordered state is vastly more probable than the unmixed and ordered state. In physics, time marches forward because the universe started in a low-probability state and it has since drifted toward a higher probability state of higher entropy and disorder.

While all spontaneous processes produce entropy, the path toward higher disorder and higher probability can itself appear highly organized and improbable. At the onset of convection when we heat a liquid from below, molecules organize themselves and they start to circulate in coordinated convection cells. Convection is sustained by the flow of heat from high temperature to low temperature and by the production of entropy. This process illustrates a simple example of self-organization (Nicolis and Prigogine, 1977). Similarly, we can recognize Earth's biosphere as a self-organizing and evolving system, sustained by energy from the sun. The biosphere and associated global cycles constitute an exceedingly complex and efficient process of dissipating solar energy to the night sky. These examples do not violate the Second Law. The Second Law only says that a process proceeds in the direction of net entropy production. It says nothing about the actual process of entropy production. Prigogine documented that dissipative systems commonly self-organize into highly organized dissipative processes. We refer to this empirical tendency to self-organize as the arrow of emerging complexity (Crecraft 2017, 2018).

[1] This follows from the ergodic hypothesis of statistical mechanics, which says all available states are equally probable.

Physics acknowledges our perception of irreversibility and indeterminism, based on increasing entropy. It defines entropy as a probability, but in a deterministic world, a probability simply reflects an individual's assessment based on incomplete information. In a deterministic world, irreversibility and indeterminism are phenomenological properties, meaning that they apply only to our perception of reality and not to physical reality as it exists unobserved. Entropy, irreversibility and indeterminism have no foundational basis in physical reality.

Even as a phenomenological principle, the irreversible increase in entropy merely allows, but cannot explain, the empirical arrow of emerging complexity. The Second Law simply states that a low-entropy and ordered state evolves into a higher entropy and less ordered state; it says nothing of the process of change. Determinism requires that universe started in a low entropy state that was specifically configured to evolve into the high entropy state of extraordinary complexity and organization that we currently observe. Physics offers no explanation for such an extraordinary starting state. Yet, we see the emergence and evolution of complexity throughout the biosphere and throughout the universe. We see self-organization repeatedly and without fail, every time we heat a pot of water.

Physics focuses on states and being, and it consequently has had no problem rising above these foundational questions about time and change. Its inability to accommodate objective irreversibility and indeterminism, however, has prevented any general principle for the emergence of complexity. This has held back advances in the many sciences that focus on organization, function and the processes of becoming. Chemistry, biology, geological sciences, ecology, neuroscience, economics, social and political sciences—these all exhibit the arrow of emerging complexity.

3. Quantum Illusions

Physics also has a conceptual problem for any objective interpretation of quantum reality. Quantum observations and measurements are intrinsically random. Does the indeterminism of our observations mean that physical reality itself is random? We describe the quantum state by the wavefunction, which is fully deterministic. If the wavefunction is a complete description of physical reality, does this mean that the undisturbed physical state is also deterministic? Does mere observation trigger physical indeterminism? Can hidden variables, which would imply that the wavefunction is incomplete, explain the unpredictability of observations while maintaining determinism?

These questions are vigorously debated. The answers depend on our assumptions and on our interpretations of what quantum observations say about underlying physical reality. As an empirical description of measurements and observations, the wavefunction by itself is mute on the nature of quantum reality. We can only deduce the underlying quantum reality from our observations and from the assumptions that we make to interpret them.

Crecraft (2018) details the conceptual difficulties that physics' implicit definition of physical reality at absolute zero creates for quantum mechanics. Perhaps the most prominent is nonlocality.

Numerous experiments verify the prediction of quantum mechanics that simultaneous measurements on an entangled quantum state[2] are strictly correlated. These experiments and the assumption of an objective physical reality inevitably lead to quantum nonlocality (Bell, 1964; Mermin, 1981; Goldstein, 2017). Nonlocality means that a measurement on one part of an entangled quantum state instantly effects instantaneous correlation of measurements across the entire system, regardless of spatial extent. Albert Einstein referred to this as spooky action at a distance because it appears to violate relativity, which limits the propagation of effects to the speed of light (Einstein et. al, 1935).

Physics seems to leave us with two choices. We can have an objective physical reality if we accept quantum nonlocality and time, deterministically playing out a script encoded at the universe's creation. Alternatively, we can reject determinism and nonlocality, and reject the objective existence of physical reality. We choose a third option. We choose an objective reality that is local, that is intrinsically indeterminate, and that supports a fundamental model and principle for evolving systems.

4, Dissipative Dynamics

Physics defines physical reality by perfect measurement at absolute zero, where there is no heat or entropy. We refer any such interpretation of reality as a non-dissipative interpretation. This assumption underlies physics' claim that friction is just a messy detail that we can sweep away, and it logically implies reversibility, determinism, and quantum nonlocality. Dissipative dynamics (**DD**) (Crecraft, 2017, 2018) rejects this assumption. Dissipative dynamics is an integrated conceptual framework for interpreting classical mechanics, quantum mechanics, and relativity based on the following assumptions:

Postulate 1: No system has surroundings at absolute zero and no system can be perfectly isolated from its ambient surroundings.

Postulate 2: Perfect measurement is defined by a reversible process of transformation between a system's initial state and an equilibrium reference state at the ambient temperature.

Postulate 3: At perfect observation, there are no hidden variables.

Postulate 1 says that absolute zero can be approached, but it can never be attained, in practice or in principle. All systems exist and interact with surroundings at a positive ambient temperature. Even the universe itself has ambient "surroundings" defined by its cosmological background radiation at 2.7 kelvins.

Postulate 2 defines perfect measurement at the ambient temperature. The ambient temperature is a property of a system's actual ambient surroundings, but it is also the temperature of

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[2] An entangled quantum state has spatial separated parts within a single quantum state. A simple example is when an isolated and undisturbed particle emits two particles in opposite directions.

the perfect observer and measurement device. Perfect measurement is reversible. Reversing the measurement process restores the system's initial e-state as it existed prior to measurement.

Postulate 3 is a statement about DD's conceptual representation of physical reality. The conceptual model does not include any hidden properties that cannot be observed by perfect observation. It states that perfect observation completely describes the actual physical state.

Figure 1 illustrates DD's conceptual model of state.

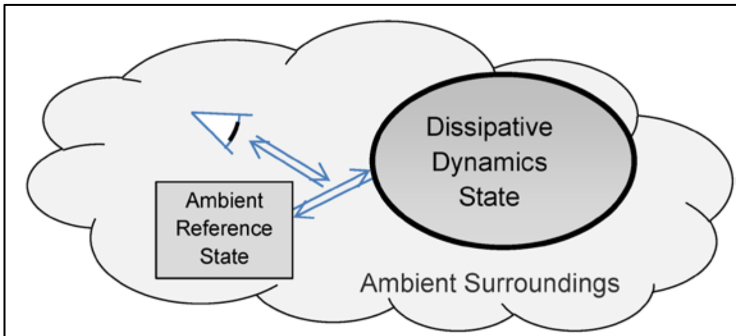

Figure 1. Dissipative Dynamics State

Perfect measurement is reversible transformation between the system and its ambient reference state (Postulate 2).

There are no hidden variables (Postulate 3). A perfect ambient observer's record of the measurement process is complete.

Reversible observation and measurement by an ambient observer completely defines the actual physical state.

Dissipative dynamics objectively defines ambient heat, exergy, and entropy relative to the ambient reference. Exergy is the potential work on an ambient reference. It includes the work potential of heat as measured on the ambient reference. Ambient heat is the heat reversibly measured at the ambient temperature; it is dissipated energy and has zero potential for work. Entropy is the ambient heat divided by the ambient temperature.

The dissipative dynamics state is independent of any particular ambient observer or the existence of an observer. This makes the physical state objective within the framework of dissipative dynamics. The state does depend on the ambient temperature of the surroundings, but this is not simply a property of the observer, as it is in non-dissipative interpretations of physics. It is an objective property of the system as it exists with respect to its actual ambient surroundings. The ambient temperature for the universe as a whole is objectively defined by the temperature of the cosmic background radiation at 2.7K.

Dissipative dynamics is premised on simple and straightforward postulates, but it has major implications. Thermalization describes the statistical distribution of energy over a system's available energy levels[3]. Dissipative dynamics asserts that the ambient temperature determines the system's thermalization. This is in distinct contrast to the local equilibrium hypothesis, which states that a system is locally thermalized at the local temperature. The difference between these interpretations leads to different definitions of a chemical component's reactive potential. Thermodynamics defines a component's potential by its chemical potential, which is the specific work potential as measured at the local temperature. Dissipative dynamics, in contrast, defines a component's potential by its

[3] The distribution of thermalized energy is given by the Boltzmann partition function, a function of temperature.

specific exergy[4], which is the work potential per unit of component as measured at the ambient temperature.

A simple experiment readily validates dissipative dynamics. A gas, distributed between two connected chambers maintained at different temperatures, approaches a uniform pressure. It follows from their respective definitions that specific exergy also approaches uniformity, whereas the chemical potential varies with the local gas temperature. These results demonstrate that specific exergy, and not chemical potential, drives this chemical process.

Figure 2 further illustrates the fundamental distinction between the dissipative dynamics and non-dissipative interpretations. Figure 2 shows a single-particle gas in a two-dimensional box. In Figure 2A, the particle is fully thermalized, meaning that its energy is all ambient heat. Measurement of the gas using a device at absolute zero would project the system onto an absolute zero ambient reference, and this would actualize a precise position for its single particle. We refer to a measurement at less than the ambient temperature as a phantom measurement, since it actualizes properties that do not exist at the ambient temperature, and we contrast this to perfect equilibrium measurement at the ambient reference temperature. For the hypothetical dynamic illustrated in Figure 2A, phantom measurement would most likely reveal a particle in the darker, central region. However, the gas is fully and completely described by the probability function defined by the statistics of phantom measurements. The gas, as it exists in thermal equilibrium at its ambient temperature[5], is fully thermalized and there is no well-defined position or trajectory.

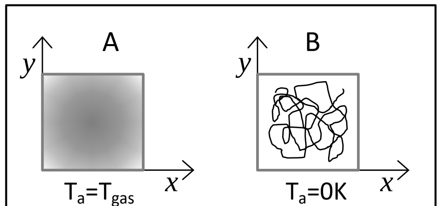

Figure 2. Configuration spaces for single-particle gas in 2D box.

2A. Gas at ambient temperature equal to gas temperature

2B. Gas at absolute zero ambient temperature.

The gas in both cases has the same energy and temperature.

If the same gas, at the same temperature and energy, exists with respect to an absolute zero ambient temperature, then there is no thermalization or ambient heat. The particle's energy is entirely mechanical (kinetic and potential). The gas particle has a precise position at any instant and a well-defined trajectory, as illustrated in Figure 2B. Perfect equilibrium measurement at absolute zero precisely reveals the position of the particle, as it actually existed at the instant of measurement. The gases represented by 2A and 2B have distinct physical realities, defined by their distinct ambient surroundings. Absolute zero, however, is an unattainable and unrealistic idealization that simply does not exist in reality.

The boxes in Figure 2 represent the two-dimensional volumes confining the gas. They also represent the configuration spaces for the single-particle gas in two dimensions. The configuration

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[4] Specific exergy is given by $\overline{X} = RT_a\ln(f)$ and chemical potential is given by $\mu = RT\ln(f)$, where f is gas fugacity (idealized pressure), R is the gas constant, T is the local gas temperature and T_a is the system's ambient temperature. $\overline{X}$ and μ are defined relative to a reference at unit fugacity and T_a or T.

[5] In dissipative dynamics, the ambient temperature of a particle in three dimensions is given by $T_a=Q/k_B$, where Q is thermalized energy and k_B is the Boltzmann constant.

space for an N-particle gas in three dimensions requires three dimensions for each of the N particles. For a gas that exists with respect to an absolute-zero ambient surroundings, configuration space is continuous and has infinite resolution. A point in its 3N-dimensional configuration space specifies the precise positions of all N particles in three dimensions. This is the idealized gas of classical statistical mechanics.

Dissipative dynamics describes a gas in thermal equilibrium with the ambient surroundings by perfect measurement by an ambient observer. It can equivalently describe the gas by the statistical distribution of phantom measurements at absolute zero. This defines a probability function over the 3N coordinates of its configuration space, and it represents a single "state-pixel" in configuration space. There is a striking similarity between this probability function and the quantum wavefunction, which is also statistically defined by phantom measurements. However, in DD, the representation of the equilibrium system as a probability function and a state-pixel is independent of the system's particular dynamics. It follows directly from the postulates of dissipative dynamics.

Dissipative dynamics resolves the dissipative dynamics entropy of an isothermal system into two components, shown in Figure 3. The first component (horizontal line) relates the system to its basis reference at the system temperature. This is a generalized thermodynamic entropy[6]. The second component (vertical line) is the basis entropy. This relates the basis reference at the system temperature to the same reference at the ambient temperature. The sum of these two components equals the total entropy. The total entropy is readily extended to non-isothermal systems by partitioning the system and its basis reference into isothermal zones, and summing over the parts. For the special case of absolute zero ambient temperature, the total DD entropy is equal to the Third-Law thermodynamic entropy, which also equals the Boltzmann entropy[7].

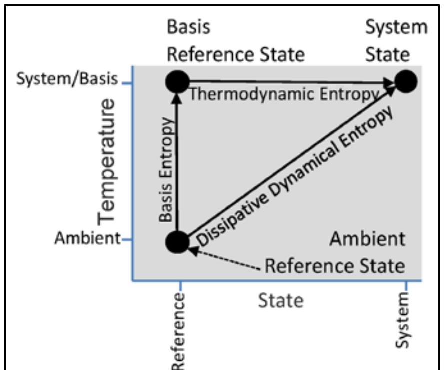

Figure 3. Two Components of Entropy. Dissipative dynamical entropy is resolved into the thermodynamic entropy, defined with respect to a basis reference at the system temperature, and the basis reference entropy, defined with respect to the ambient reference.

Figure 3 also reveals two paths toward higher entropy. The first is by dissipation of exergy to ambient heat. This increases the system's entropy relative to its reference at the system temperature. This defines the thermodynamic arrow of dissipation. The second path toward higher entropy results from a declining ambient temperature and the consequent refinement of configuration space. Refinement increases the number of state-pixel configurations and the Boltzmann entropy, leading to an increase in the basis entropy. This path defines the thermodynamic arrow of refinement.

[6] DD generalizes a system's thermodynamic entropy by the system's ambient heat, relative to the reference state at the system temperature, divided by the ambient temperature. This equals the equilibrium thermodynamic entropy when ambient and system temperatures are equal.

[7] Boltzmann entropy is defined by $k_B \ln(W)$, where W is the number of equally probable configurations.

The arrows of dissipation and refinement are two distinct arrows of thermodynamics, both leading toward higher entropy. Dissipation of exergy reserves, such as by fusion of hydrogen and release of energy, and a falling ambient temperature, such as by cosmic expansion, are two paths leading the universe toward higher entropy. Conversely, we can argue that the irreversible increase in total entropy drives both of these processes.

5, Time Reborn

In his 2014 book, *Time Reborn: From the Crisis in Physics to the Future of the Universe*, Lee Smolin presents a strong case against the block universe model, and he argued for a new concept of time that embraces fundamental irreversibility. Postulate 4 establishes irreversible time as an objective attribute of physical reality:

> **Postulate 4:** Any spontaneous process in nature is associated with the production of total entropy.

With entropy now objectively defined, Postulate 4 establishes the second law of thermodynamics as a fundamental law of physics. The irreversible production of entropy marks the irreversible passage of time as a fundamental attribute of physical reality. We will next see how this resolves the problem of nonlocality.

In the quantum limit, the dissipation of energy is discontinuous. An unstable particle can persist metastably for a period of time, but at some point, it transitions to a lower energy state, ejecting a quantum of energy and dissipating it to the ambient surroundings. During intervals of metastability, there is no entropy production. Zero entropy production means that forward and backward processes occur with equal probabilities. Time is reversible and symmetrical. Irreversible transitions segment time into intervals of metastability, reversibility, and time symmetry, separated by discontinuous increases in entropy marking advances in irreversible time. Each interval of time symmetry spans a discrete "instant" of irreversible time.

Pusey and Leifer (2017) argue that with time-symmetry, systems must be retrocausal. With time symmetry, there is no distinction between past and future, and effect can precede cause as easily as cause precedes effect. The delayed choice quantum eraser (Kim et al., 2000) provides an experimental demonstration of retrocausality within the framework of dissipative dynamics (Crecraft, 2017). Pusey and Leifer further argue that retrocausality can reconcile the instantaneous correlations of measurement with a local reality.

We previously asserted that instantaneous correlations and an assumption of objective physical reality inevitably lead to nonlocality. In making this assertion, however, we implicitly assumed the asymmetry of time. Physics defines reality at absolute zero, which implies microscopic reversibility. Microscopic reversibility, however, does not mean that the forward and reverse directions are equally probable. Reversibility only means that a process can be reversed without violating physical laws. Physics acknowledges, in fact, that the direction of increasing entropy is more probable and that time is asymmetrical. Time asymmetry does not apply to intervals of metastability and time-symmetry.

Figure 4 illustrates how dissipative dynamics reconciles local reality with instantaneous correlation of measurements within an interval of time symmetry. The vertical axis is time and the horizontal axis is spatial position. The shaded triangles illustrate light cones, which show the cones of locality propagating at the speed of light outward from their spontaneous events.

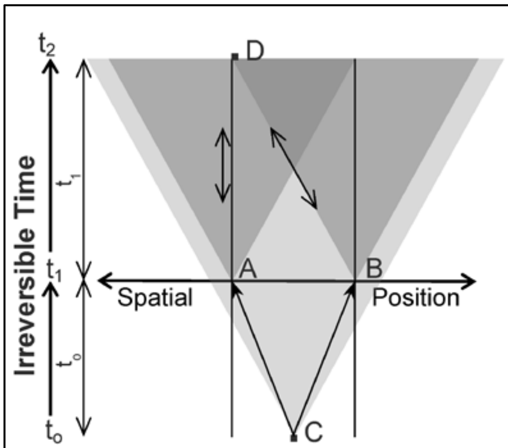

Figure 4. Not-so Spooky Action at a Distance

Two light cones are shown for simultaneous events A and B at time t_1. Each future light cone shows the cone of possible effects expanding outward at the speed of light. Both are within the light cone of event C.

In Einstein's space-time, the time axis is a single continuous dimension of reversible but asymmetrical time. Dissipative dynamics recognizes that time is partitioned into intervals of time-symmetry, separated by discontinuities marking irreversible and spontaneous events. Each event marks a new "instant" of irreversible time. Each spontaneous event is a new cause without a prior cause. Each spontaneous event generates a new light cone of potential effects.

If separate events A and B are linked within their intersecting future light cones and within an interval of time-symmetry, the events are deterministically correlated through a chain of forward and retro-causality.

At point C, a pair of electrons is emitted horizontally in opposite directions. This is a spontaneous event, marking the beginning of a reversible interval of metastability at time t_o. The electrons are entangled as parts of a single quantum state. The electrons travel toward Alice (point A), and Bob (point B), at less than the speed of light. At time t_1, the electrons simultaneously and irreversibly interact with Alice's and Bob's detectors at points A and B.

An electron has a property of spin. Quantum spin is quantized, with two possible measurement values, which we can designate as spin up and spin down. Conservation of spin requires that if the original particle had zero spin, then the electrons must have opposite spins and a net-zero spin for the pair. If Alice's and Bob's spin detectors are oriented parallel to each other, then if Alice measures an up spin on her entangled electron, she instantly knows that Bob measures a down spin. This instantaneous correlation of measurements has been experimentally confirmed numerous times. The measurements are made in spatially separated light cones, so locality means that there is no way that one measurement can directly influence the other at the instant of their measurement.

Each measurement marks a local spontaneous event, a new interval of time symmetry, and the start of a new light cone of locality. As soon as Bob detects his electron, he transmits his results to Alice at the speed of light, and she receives his results at time t_2 (point D), when she intersects his light cone (point D). Between times t_1 and t_2, there is no dissipation and the system evolves within an interval of time-symmetry. If Alice receives Bob's result and compares it with hers, and she maintains time symmetry throughout, then their individual measurement results are correlated through a chain of forward and retro-causality. The instantaneous correlation of events at A, B, and D is instantaneous, but only in the "instant" of irreversible time, t_1, spanning these events.

Dissipative dynamics provides a conceptual framework that accommodates classical mechanical, quantum mechanical and thermodynamic states as special cases. It provides a model of quantum reality that is objective, local, embraces irreversible time and randomness, and is consistent with experimental results. More importantly, it provides the starting point for a description of spontaneous organization and emergence of complexity in biological, physical, social, and economic systems in terms of fundamental principles. In the next sections, we introduce the dissipative dynamics of non-equilibrium and evolving systems.

6. Homeostates

Figure 1 previously presented the dissipative dynamics model for states. Figure 5 illustrates the DD model for a stationary non-equilibrium system. The model assumes a stationary environment, and it includes one or more exergy sources. Over time, the system converges to a stationary process of dissipation, sustained by its stationary environment. Stationary simply means that time-averaged properties are constant. The system is stationary, but it is not microscopically static and it is not an actual state, as its constituents are constantly reorganizing and dissipating exergy. Crecraft (2017) refers to these stationary non-equilibrium systems as homeostates.

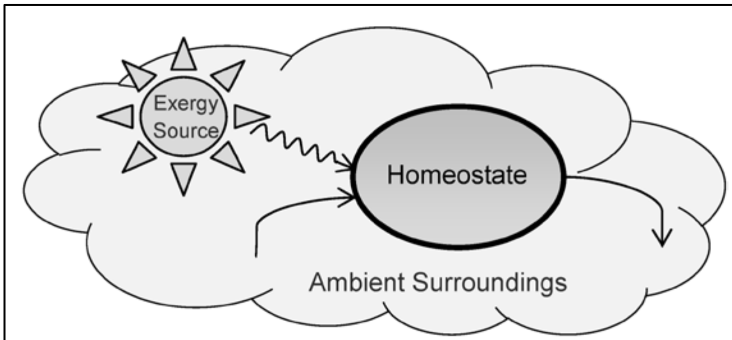

Figure 5. Homeostate Model

The exergy source might supply energy directly to the system (e.g. sunlight), or it might supply components with high specific exergy (e.g. food) that are subsequently discharged as low-exergy waste.

Ambient resources are also freely available to the system for processing and discharge.

A homeostate can be resolved into a network of dissipative nodes, links, and pods. Figure 6 shows the dissipative network for the Brusselator reaction (Nicolis and Prigogine, 1977). The Brusselator is a theoretical model for an autocatalytic reaction exhibiting oscillations. Links are the pathways for energy and components to flow from sources, through the system, and to the ambient surroundings. Nodes represent the irreversible transitions of energy and material components from one state to another. Pods provide the capacity for temporary storage and release of energy and components for fluctuating (but stationary) homeostates. Elementary nodes, links and pods are defined with respect to the ambient surroundings and they have no internal details. Perfect measurements can only reveal component concentrations and energy levels within links and pods and the flows of exergy and components into and out of the nodes.

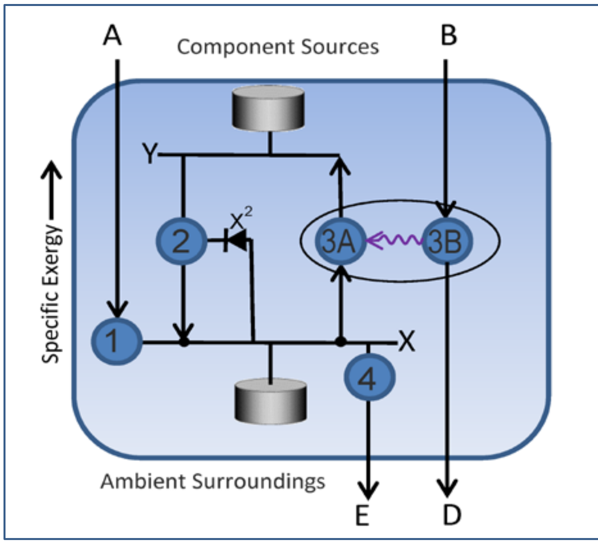

Figure 6. The Brusselator Network Model

The Brusselator comprises four reaction steps:

R1: External source state A→ state X

R2: Y+2X→3X

R3: External source B + X→Y+ discharge D

R4: X→ discharge E

R3 is resolvable into two coupled transitions: X→Y and B→D.

The reaction step for node 2 is autocatalytic, indicating that the reaction rate depends on the concentration of X squared.

The Brusselator has a periodic solution with periodic accumulations and discharges of X and Y. This requires links to have storage volumes, shown by the appended pods. For more details, see Crecraft (2017).

All entropy production within the dissipative system is assigned to nodes; links and pods are assumed to be dissipation-free. Postulate 5 expresses the "conservation" of entropy production:

> Postulate 5: The sum of entropy production for a system equals the sum of entropy production by its parts.

For the special case of constant ambient temperature, Postulate 5 states that the entropy production of the whole equals the sum of entropy production of the parts. For a stationary homeostate, Postulate 5 and the conservation of energy mean that the system's total dissipation is equal to its net rate of exergy supply. Exergy supply can be direct, such as by sunlight (e.g. Figure 5), or indirect, by the throughput and dissipation of high-exergy component sources.

For near-equilibrium systems, fluxes are proportional to gradients. Fourier's Law, Fick's Law, and Ohm's Law express the linearity of fluxes and gradients for heat conduction, chemical diffusion, and electrical flow, respectively. Linearity defines the near-equilibrium regime. Lars Onsager (1931) showed that a near-equilibrium system with steady-state boundary constraints converges to a unique steady-state dissipative process at a point of minimum entropy production. The minimum entropy production point is the system's unique steady-state solution to its boundary constraints in the linear near-equilibrium regime.

Far from equilibrium, linearity breaks down. At a critical temperature gradient, for example, heat flow through a liquid dramatically increases as the system spontaneously reorganizes itself from conduction to convection. Chemical autocatalysis drives highly non-linear reaction rates. Non-linearity defines the far-from-equilibrium regime. In the far-from-equilibrium regime, non-linearity can allow multiple dissipative solutions and multiple homeostates to exist for a system with fixed environmental constraints.

7. The Arrow of Emerging Complexity

The arrow of emerging complexity involves selection from multiple homeostates, which can arise from the nonlinearity of dissipative processes far from equilibrium. The arrow of emerging complexity requires more than simple random selection, however. Like Darwin's theory of evolution, it requires selection.

Lord Kelvin suggested a principle of selection for dissipative systems in an article he wrote in 1862 (Thomson, 1862). He started by describing heat death as the inevitable end-result of dissipation within a finite universe, at which point all directed activity would cease. He then proceeded to express a much deeper and overlooked idea. Backing off on the inevitability of heat death, he continued that the universe is in a state of "endless progress…involving the transformation of potential energy into palpable motion and hence into heat." Palpable motion is motion we can touch, and which we can therefore utilize for some purpose—exergy, in our terminology. He stated that a source of exergy tends to defer dissipation— "and hence into heat" — and it instead utilizes exergy for palpable work. If a source of exergy defers dissipation by doing palpable work on some other dissipative system, then that system could likewise defer dissipation and do work on other systems. The recursive deferral of dissipation for work to sustain other dissipative systems leads to an expanding network of dissipative nodes of increasing interconnectedness and organization. This idea precisely expresses the arrow of emerging complexity.

When Lord Kelvin stated this idea in 1862, classical mechanics was well entrenched in physical thought. Kelvin's idea was incompatible with the classical mechanics, and it never gained a foothold and was largely ignored. His idea is fully compatible with dissipative dynamics, however, and we formalize his insight with Postulate 6:

> **Postulate 6 (Kelvin Selection Principle)**: Of the multiple homeostates that may be available to a dissipative system, the homeostate with the highest utilization is the most stable and is the most likely to be selected.

Crecraft (2017, 2018) defines a homeostate's utilization as the sum of internal dissipation and internal work. From Postulate 5, the internal dissipation is simply equal to the system's net exergy supply. Internal work is the work needed to sustain the system's function. It includes work by nodes on system components and the periodic work of pumping exergy or components up potential gradients into pods. The dissipative network for the Brusselator, shown in Figure 6, illustrates both of these.

Node 3B in Figure 6 is an exergonic node. This is a node in which a component is input with high specific exergy (state B), and discharged with lower specific exergy (state D). Part of the exergy is necessarily dissipated by the node, but part of it is transferred to node 3A (illustrated by the wavy exergy link). Node 3A is an endergonic node, which utilizes an input of exergy to transition component with low specific exergy (state X) to a state of higher specific exergy (state Y). The work of transforming component from state X to state Y is internal work by an endergonic node on its component.

For a sufficiently high value of A, the Brusselator has an oscillating mode in which the concentrations of X and Y cycle periodically. Any perturbation from the steady-state solution sends the system on a trajectory that converges to the stationary cycling solution. The steady state and cycling homeostates have virtually identical average rates of exergy supply. They also have virtually identical average rates of internal work by node 3A. For the oscillating mode, however, components periodically accumulate in and are released from the X and Y pods. Increasing the concentrations of components require work on the pods, and this marks an additional component of internal work.

The work of cycling constitutes an additional component of work on the pods, which the steady-state mode lacks. The Kelvin Selection Principle (**KSP**) therefore predicts that the oscillating mode is spontaneously selected over the steady-state mode. We can generalize this conclusion and assert that an oscillating homeostate is more stable than a steady-state homeostate, all other factors being equal. Figures 7 and 8 extend this analysis to a network of linked oscillators. As detailed in the captions, the analysis shows that a network of linked oscillators increases its exergy utilization when all oscillators synchronize. The KSP therefore predicts that coupled oscillators have a tendency to spontaneously synchronize. In his book, *Sync: The Emerging Science of Spontaneous Order*, Steven Strogatz (2003) argues that complex systems have an intrinsic drive toward oscillations and synchronization. Empirical observations and dynamical analysis of dissipative systems commonly show this to be the case. The KSP, however, provides a general principle that explains oscillation and synchronization in terms of a general principle, independent of a system's specific dynamics.

Researchers have long sought a general principle to explain the evolution of complexity in dissipative systems. Alfred Lotka proposed that natural selection maximizes the total exergy flux through a system and that "this law of selection becomes also the law of evolution" (Lotka, 1922). More recently, the Maximum Entropy Production Principle (Kleidon and Lorenz, 2005) asserts that systems seek to maximize the rate of entropy production. These and related proposals are equivalent to maximizing net exergy supply. When resources are abundant, a system can and does increase its utilization by increasing its rate of exergy supply. When exergy supply is limited, however, competition for exergy becomes a zero-sum game; one system's increase in exergy supply occurs at the expense of others' loss. A system cannot increase its net exergy supply or rate of entropy production when its resources are fixed. This does not mean that evolution ceases, however.

Crecraft (2017) illustrated the distinction between net exergy supply and exergy utilization with whirlpools. A whirlpool and radial flow directly toward the drain are two homeostates and dissipative processes for draining water. A whirlpool is commonly selected over radial flow. The centrifugal force of a whirlpool's circulation lowers the water level and pressure over the drain. This actually reduces the rate of water discharge and exergy throughput. The whirlpool therefore provides a counterexample to any principle based on maximizing energy flow and dissipation or maximizing entropy production. The whirlpool has a higher exergy utilization, however. By accelerating the circulation of water as it approaches the drain, the whirlpool has a higher rate of exergy utilization compared to radial flow. The KSP therefore predicts the stability of whirlpools over radial flow. Unlike exergy supply, exergy utilization is not limited by available exergy sources. By deferring dissipation and recycling exergy among nodes, a system with fixed exergy supply can increase its internal work and exergy utilization, with no upper bound in the limit of perfect efficiency.

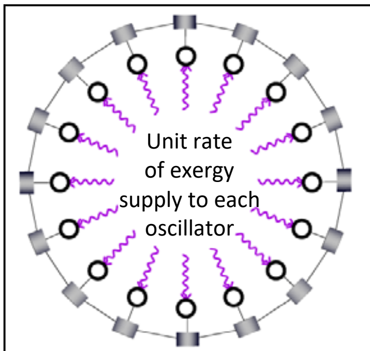

Figure 7. Coupled Oscillators.

The figure shows sixteen oscillators linked in a circle. All oscillators have identical unit-rate inputs of exergy, which pump component into pods. When concentrations reach a critical value, the component is released, and the cycle resumes.

Coupling between adjacent pods allows component to leak from one pod to another. The leak rate equals the difference in concentrations, multiplied by a coupling coefficient.

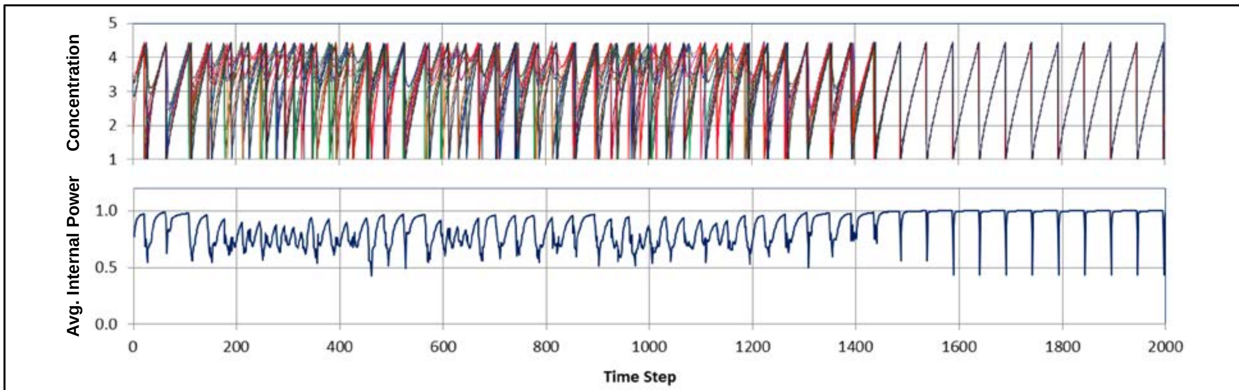

Figure 8. Synchronization of Coupled Oscillators

Top—Pod Concentrations: Oscillators are randomly assigned periods between 49.5 and 50.5 time units. They start at random points in their cycles. After about 1500 time steps, the oscillators synchronize.

Bottom—Average Internal Power: Each oscillator has a unit rate of exergy input, used to pump component into its pod. When oscillators are not synchronized, some exergy is lost to diffusive leakage between adjacent oscillators. When all oscillators are synchronized, concentrations are equal and there is no diffusive loss. Internal power to each oscillator then equals the unit-rate exergy inputs, except at the single time step of discharge per cycle. The average internal power is maximized by synchronization. See Crecraft (2017) for additional details.

8. Conclusions

Dissipative dynamics accommodates classical and quantum mechanics, relativity and thermodynamics as special cases of a generalized conceptual model. It also accommodates a physical model for irreversible process, and it introduces the Kelvin Selection Principle as a principle of natural selection for non-equilibrium systems. The KSP guides the evolution of dissipative systems toward higher complexity by the progressive selections of homeostates of higher exergy utilization. Utilization is a well-defined and measurable property of dissipative process within the framework of dissipative dynamics, and it defines a general measure of complexity.

When a system has easily available sources of exergy, the KSP drives the system's expansion to capture those sources and increase its net exergy supply. This captures earlier proposals for a physical principle of evolution based on maximizing energy flows or entropy production. When sources are constrained, the KSP drives internal organization, recycling of resources, and higher efficiency. This defines the arrow of emerging complexity. A dissipative system can continue to increase its complexity and evolve, even when its exergy supply is fixed, by promoting cooperation and coordination among its agent-nodes. At the same time, the KSP drives the agent-nodes to compete among themselves to increase their individual exergy supplies. The evolution of complexity proceeds as a balanced interplay between competition and managed cooperation. Over a prolonged period of environmental stability, such as the 50 million years over which the Amazon rainforest ecosystem has evolved, a system can develop extremely complex webs of interactions for recycling components and exergy.

The KSP is only an interim principle. The homeostate model and utilization are both defined for a fixed ambient temperature, and the model is a simplification of reality. A more general model would account for changing and spatially variable ambient temperatures. A more general model would also consider overlapping ambient temperatures working at different levels. For example, the biosphere comprises global cycles dissipating solar energy to interplanetary space; ecosystems dissipating energy to the night sky or oceans; and biochemical processes dissipating energy within their host organisms. It is also expected that the KSP can be extended to systems driven by generalized notions of exergy, such as economic systems. A more general principle of selection is needed to apply to these more general and realistic models of the real world. Nevertheless, The KSP and the homeostate provide a useful model for the evolution for physical systems within a stationary environment and with a fixed ambient temperature.

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