Dissipative Dynamics: An Integrated Model Unifying Physics, Thermodynamics, and Emerging Complexity

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Abstract

The quantum wavefunction, as an empirical model of measurements and observations, tells us nothing by itself about an underlying reality. Conceptual models, based on additional assumptions, provide the framework for interpreting experimental results to deduce the underlying physical state and to explain measurement results. We argue that any interpretation of quantum measurements that assumes an objective physical reality fails to explain wavefunction collapse and nonlocal correlations.

We identify a deeply ingrained assumption that leads to this failure. Dissipative dynamics is a conceptual model that provides a more realistic conception of objective reality. Dissipative dynamics accommodates the empirical models of physics and thermodynamics and their experimental predictions as special cases, it reconciles nonlocality and relativity, and it embraces time's arrows of thermodynamics and emerging complexity.

1. Introduction

The block universe model regards the universe, its past, present and future, as a static block of four-dimensional spacetime. It describes the evolution of an isolated system as the deterministic playing out of a script, encoded in its initial state. The nature of an isolated system, however, cannot possibly be resolved by observation or measurement alone. The nature of a system, as it existed prior to observation behind a veil of isolation, is strictly a matter of interpretation of experimental results.

This paper identifies three key experimental facts that any interpretation needs to explain. It discusses and compares several common interpretations of physics and reveals a deep-seated assumption that underlies their shared failures to provide objective explanations for these experimental facts. Dissipative dynamics (Crecraft 2017) is a conceptual framework that integrates the existing theories of physics, thermodynamics, and evolution as special cases, fully consistent with experimental observations and physical laws. It provides an consistent and objective interpretation of physical systems that explains wavefunction collapse, nonlocality, and the arrows of time.

2. Key Experimental Facts

We identify three key experimental facts that an interpretation of physical reality needs to explain. These are 1) the indeterminism of quantum measurements, 2) the instantaneous correlation of quantum measurements, and 3) the thermodynamic arrow of time.

2.1 Indeterminism of Quantum Measurements

In quantum mechanics, individual measurements are intrinsically random. If an obliquely polarized photon interacts with a vertically polarized filter, measurements reveal either a vertically polarized photon passing through the filter, or a horizontally polarized photon absorbed by the filter. Quantum mechanics describes the photon prior to measurement as a superposition of these measurable component states. At observation, however, we invariably observe the collapse of the superposed quantum state to one polarized state or the other, but never both. We cannot determine which of the potentially observable states we will observe. We can only predict the statistical probability of an individual measurement. The indeterminism of quantum measurements is the first key experimental fact.

2.2 Instantaneous correlation

Numerous experiments verify the prediction of quantum mechanics that simultaneous measurements on a quantum state are strictly correlated. N. David Mermin (1989) describes a typical experiment in which a particle emits two electrons in opposite directions. An electron has a property of spin. Quantum spin is quantized, with two possible measurement values, which we can designate spin up and spin down. If the particles remain isolated and unperturbed, they remain entangled within a single quantum state. 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.

Two detectors, operated by Bob and Alice, are placed in the paths of the electrons at equal distances from their source. Repeated measurements show a random distribution of spin up and spin down states. The measurements, however, are instantaneously correlated, regardless of spatial separation. If Bob's and Alice's detectors are oriented parallel to each other, and if Bob measures an up spin on his entangled electron, then Alice measures a down spin with 100% certainty. This instantaneous correlation of measurements is the second key experimental fact.

2.3 The Thermodynamic Arrow of Time

Experimental observations of quantum and classical mechanical systems reveal clear asymmetries of time. A drop of ink in water will spontaneously disperse until it becomes uniformly dispersed, but we never see ink spontaneously unmix. An isolated particle is more likely to transition to a lower energy state than it is to spontaneously transition to a higher energy state. Thermodynamics codified this asymmetry of time with its Second Law. The Second Law of thermodynamics describes the arrow of time by the statistical tendency for entropy to increase. Increasing entropy describes both the dispersion of ink particles in water and the particle's asymmetrical transition to lower energy. The thermodynamic arrow of time is the third key experimental fact.

Indeterminism of measurement, instantaneous correlation of measurements, and time's asymmetry are all experimental facts that a consistent interpretation of physical reality needs to explain.

3. Models, Measurements, and States

Classical mechanics, thermodynamics, quantum mechanics, and relativity are all empirical models of nature. We develop an empirical model to describe a system's observable properties and their measurements. Laws describe how a system responds to environmental interactions, including measurements. Laws are of great practical importance, but they are not, by themselves, particularly interesting from a philosophical viewpoint. Laws make predictions, but they do not explain the mechanism or reason behind measurement results. We need a conceptual model to interpret how nature is organized and to explain why laws produce the results we see.

Before we can discuss and compare various conceptual models of physical reality, we need to adopt a common language to describe them. We use the terminology described below and summarized in Table 1.

Table 1. Hierarchies of Models and States

Models	Model Parameters	State	Description
Empirical e-model. (If the e-state is complete, the e-state equals the c-state at measurement)	Actual measurements	measured m-state	Imperfect measurement due to measurement errors or low resolution. Describes incomplete information.
	Perfect measurement	epistemic e-state	Representation based on perfect measurement. Describes all that we can know about a system.
Conceptual c-model.	Perfect measure-ment plus hidden variables, if any	conceptual c-state	c-model's representation of the o-state. If the c-state is complete, the c-state and o-state are equal.
Physical Reality	N/A	ontic o-state	A system's actual physical state.

The empirical model, or e-model, is based strictly on measurable properties. The e-model represents a system's measurable states. Actual measurements, however, are imperfect. If we apply imperfect measurement results to our e-model, it describes a measured state, or m-state. The m-state expresses all that we actually know about a system's state based on actual measurements. In the limit of perfect measurement, the m-state converges to an epistemic state, or e-state. The e-state expresses everything that we can possibly know about a system's state.

The conceptual model, or c-model, represents the physical system as it actually exists, whether or not we can completely measure it. A c-model might contain hidden variables, which are not measurable and therefore are not properties of the e-state. If we apply perfect measurements and assumed values for any hidden variables to the c-model, then we get the model's conceptual state, or c-state. The c-state is the c-model's conceptual representation of a system's actual underlying state.

The ontic state, or o-state, defines the system's actual physical state and all of its properties, known, unknown, and possibly unknowable. If the c-state is an exact description of the actual o-state, then we say that the c-state is complete. C-models typically assume the c-state is a complete representation of the o-state, and we will use 'o-state' to describe both the actual physical o-state and the c-model's conceptual representation, unless we need to express the incompleteness of a c-state.

We have one final important note. If the e-and c-state are both complete, then the e-state, c-state, and the o-state are identical and they are completely known at the point of perfect measurement. However, if the o-state changes randomly, the e-state remains unchanged, but it will cease to be complete. We can update the information by a new perfect measurement at a later time, but this defines a new e-state at a new moment in time. Whether or not the o-state is deterministic is a key conceptual model assumption.

4. Empirical Models of Physics

In this section, we briefly review the empirical models for Newtonian and Hamiltonian classical mechanics, thermodynamics, statistical mechanics, and quantum mechanics.

4.1 Newtonian Mechanics

In 1687, Isaac Newton proposed his three laws of motion. Together with his formulation of gravitational force, Newtonian mechanics allows us to predict the motions of celestial bodies to high precision. Newtonian mechanics defines perfect measurement and the e-state by the precise positions and momentums of a system's component bodies and of the forces acting on them.

Newtonian mechanics is about masses and forces, and friction is simply a force that irreversibly counters an object's motion. Newtonian mechanics accommodates frictional forces and the consequent loss of mechanical energy, as measured by its potential to do work. Nowhere in his laws of motion did Newton express or imply the conservation of work potential or energy. We can see this if we send two lumps of clay toward each other with equal but opposite momentums. The pair's combined momentum is conserved at impact (Newton's first law of motion), but their kinetic energy and work potential go from positive to zero. Newtonian mechanics is deterministic, but determinism implies neither reversibility nor the conservation of energy.

4.2 Thermodynamics

The First Law of thermodynamics later established the conservation of energy. The thermodynamic e-model, however, includes a body's internal energy, in addition to the mechanical energies associated with its motion and the external forces acting on it. Internal energy can include heat, the chemical potential of a battery, or the internal energy of a stretched spring. The thermodynamic e-model of the clay lumps conserves their total energy at impact by converting their kinetic energy to heat.

Thermodynamics was originally developed to analyze steam engine efficiency. Thermodynamics' "heat-engine" e-model subdivides thermal energy into thermal work potential[1], which can do work on the ambient surroundings, and ambient heat, which is heat at the ambient temperature and which has no potential for work. We can express the total energy, E_T, by:

$$E_T = W_T + Q. \qquad (1)$$

$$\begin{bmatrix}\text{Total}\\ \text{Energy}\end{bmatrix} = \begin{bmatrix}\text{Work}\\ \text{Potential}\end{bmatrix} + \begin{bmatrix}\text{Ambient}\\ \text{Heat}\end{bmatrix}$$

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[1] The thermal work potential W_q of heat q at temperature T, as measured by its potential work on a reference at T_a, is $W_q = (\frac{T-T_a}{T}) \times q$. In the textbook thermodynamic e-model, T_a=T, W_q = 0, and thermal energy is all ambient heat.

The work potential W_T is the total work that a system can do on its ambient reference utilizing kinetic energy, potential energy, and internal work potential. The ambient heat Q is the 'residual' thermal energy at the ambient temperature. It has zero potential to do work on the ambient reference. The First Law of thermodynamics says that any loss of work potential by dissipation is offset by an increase in ambient heat, while the total energy is conserved.

Ambient heat and thermodynamic entropy are closely related. Thermodynamics defines entropy as the ratio of ambient heat and a fixed ambient temperature[2]:

$$S = \frac{Q}{T_a} \quad \text{and} \quad Q = T_a S. \tag{2}$$

Equation 2 expresses the empirical definition of entropy, based on measurable quantities relative to an ambient reference. The Second Law of thermodynamics states that production of entropy and ambient heat are always positive, or zero at equilibrium.

4.3 Hamiltonian Mechanics

In 1834, a hundred and fifty years after Newton published his equations of motion and thirteen years before the First Law of thermodynamics, William Rowan Hamilton reformulated Newtonian mechanics (Hamilton, 1834). He left Newton's laws intact, but he changed the e-model description. Hamilton redefined the classical mechanical e-model as an energy function, expressing a system's total energy, equal to the sum of kinetic and potential energies of its elementary particles. A particle's kinetic energy is proportional to the square of its momentum, and its potential energy is specified by its position within a potential field, such as the height of a particle in a gravitational field. The Hamiltonian energy function is therefore defined over the coordinates of position and momentum of the system's elementary particles. The Hamiltonian e-model eliminated the forces in the Newtonian e-model and replaced them with potential fields.

Hamiltonian classical mechanics defines a system's e-state by the precise coordinates of position and momentum of its microscopic elementary particles. This effectively defines the system by perfect measurement at absolute zero, in the absence of thermal fluctuations. From equations (1) and (2), an absolute zero ambient temperature also means that there is no ambient heat, no dissipation, and the conservation of energy extends to classical mechanics.

The difference between the Hamiltonian and thermodynamic models is clearly illustrated by their respective descriptions of the colliding clay lumps. Hamiltonian mechanics describes the impact as the dispersal of the coherent kinetic energy of the initial clay lumps to the kinetic energies of the clay particles. Thermodynamics describes it as the dissipation of kinetic energy to ambient heat. Consequences of Hamilton's reformulation are the elimination of friction as a fundamental

[2] For an equilibrium system at the ambient temperature and for S and Q defined relative to the ambient reference, this is equivalent to the standard thermodynamic definition of entropy by $dS = \frac{dq}{T}$.

force, the conservation of work potential, and Hamilton's principle, commonly known as the least action principle. These changes greatly simplified complex calculations.

4.4 Statistical Mechanics

In the 1870s, after thermodynamics established its alternate e-model, Ludwig Boltzmann sought to reconcile the empirical models of thermodynamics and Hamiltonian mechanics. He defined an object's thermal energy as the sum of the kinetic energies of the object's elementary particles, and temperature as a measure of their average kinetic energy. He thereby redefined these key thermodynamic properties statistically, as bulk properties of an imperfectly measured m-state. He termed this m-state the macrostate. He assumed the Hamiltonian e-state completely defined a system's o-state, and he termed this the microstate. Boltzmann reinterpreted entropy as mechanical disorder, which he defined as the logarithm of the number of microstates (o-states) that are consistent with the macrostate (m-state).

Boltzmann had set out to extend classical mechanics to accommodate thermodynamics and the Second Law. In the end, however, he subsumed thermodynamics as a statistical approximation of Hamiltonian classical mechanics, and he firmly established physical reality as defined by perfect measurement at absolute zero, in the absence of thermal noise.

4.5 Quantum Mechanics

At the start of the 20^{th} Century, as physicists probed deeper into the details of matter and atoms, they discovered that individual measurements on quantum systems are statistical and unpredictable, even in the limit of perfect measurement. This forced fundamental changes in how a system's state was described and measured. First, the statistics of individual measurements led to redefining perfect measurement as multiple measurements on an ensemble of identically prepared systems, rather than as a single perfect measurement. Second, the coordinates of position and momentum are not independent properties, as they are in classical mechanics, and they cannot be simultaneously measured. Consequently, the quantum e-state is defined as a statistical function over the coordinates of either position or momentum.

Erwin Schrödinger introduced the wavefunction in 1926 as the quantum mechanical e-state to express the statistical measurement results on an ensemble of identically prepared systems. The wavefunction expresses all that can be measured and known about a quantum system. A superposed quantum state is represented as a superposition of eigenfunctions. Observation of a superposed quantum state, however, always reveals a single definite eigenstate. The transition from a superposed wavefunction to an individual eigenfunction at measurement is referred to as wavefunction collapse.

Schrödinger proposed his famous thought experiment to highlight a problem with ideas that were emerging in Copenhagen in the following years, in which the wavefunction e-model was considered to be a complete description of the actual quantum o-state. Completeness would imply that if a cat's fate were tied to the decay of a radioactive particle, and if the particle, cat and measurement apparatus were completely isolated from the environment, then the system would exist in a physically superposed state of live-cat+dead-cat, until that veil of isolation was pierced and the cat's fate was observed.

The quantum mechanical e-state leaves unresolved important questions. Does a superposed wavefunction completely describe the underlying o-state? Are the statistical measurements therefore random and intrinsically indeterminate? If not, does the o-state have hidden variables that determines the system's measurement results? Do statistical measurements reflect a distribution of distinct o-states, implying intrinsically random results from identical preparation procedures? These questions go to the heart of what quantum physics really says about physical reality. A conceptual model needs to reconcile the contradictions in these questions and to formulate a consistent interpretation of the o-state.

5. The Hamiltonian Conceptual Model

Hamilton modeled classical mechanics as elementary microscopic particles having precise coordinates of position and momentum. This goes well beyond an experimentally definable e-state, and it really describes a conceptual model of reality. We refer to this model as the Hamiltonian Conceptual Model. This section discusses the HCM's implications on physical reality and its explanations of the key experimental facts, as a reference interpretation for comparison with other interpretations.

The HCM for classical mechanics starts with three fundamental assumptions:

1. Perfect measurement is defined by precise measurements, in the absence of thermal noise at absolute zero.
2. The e-model and c-model are complete (there are no hidden variables).
3. The o-state, in isolation and unperturbed, is deterministic.

Two implications immediately follow:

4. The e-state, c-state, and o-state are identical and are completely defined by perfect measurement, as long as the system remains unperturbed by external interactions.
5. The o-state is non-dissipative (it conserves work potential).

When applied to quantum mechanics, the HCM defines perfect quantum measurement by the statistical results of measurements on an ensemble of identically prepared systems. Determinism and statistical measurement results mean that the individual systems share an identical and physically superposed o-state. To highlight this, we modify HCM implication 4 for classical mechanics to:

4Q. the wavefunction e-state, possibly superposed, is and remains a complete description of the quantum mechanical o-state as long as the system remains unperturbed.

We apply the Hamiltonian c-model to quantum mechanics and compare its implications to the key experimental facts.

5.1 Indeterminism of Quantum Measurement

In quantum mechanics, the indeterminism of measurement is expressed by the indeterminate collapse of a superposed wavefunction e-state. The collapse of the wavefunction upon measurement simply reflects new information, requiring a new wavefunction and a new e-state. However, implication 4Q implies that the underlying physical system exists in a superposed o-state until measurement or observation, when the system physically collapses to a definite eigenstate.

The HCM can reconcile the indeterminate collapse of the o-state with its intrinsic determinism only by attributing the indeterminate collapse to an external perturbation. This could be the measurement itself; or, if the measurement device is part of the system, it could be an observation. It is not clear, however, how or why observation of a superposed measurement device and its results, such as reading a paper printout after a measurement was completed in isolation, could cause physical collapse of its o-state.

The HCM does not formally explain indeterminate wavefunction collapse; it merely shifts the undefined source of indeterminism to the external surroundings. If we incorporate the surroundings into the system, the HCM pushes the source of indeterminism farther outward, but in a finite universe, at some point we run out of surroundings and external triggers to explain indeterminate collapse.

5.2 Nonlocality

To illustrate the HCM's difficulty with instantaneous correlation, we again consider Alice's and Bob's measurements of an entangled electron pair, using parallel detectors. Since each electron's measured spin state must be the opposite of the other's, there are the only two possible measurement results for the pair: {↑, ↓} and {↓, ↑}. Repeated measurements on identically prepared electron pairs are statistical, so the electron pair is described as a superposed wavefunction e-state. According to implication 4Q. There are no hidden variables, so the pair's actual o-state, while isolated and in flight, is a physical superposition of these two eigenstates. Neither electron has a specific spin until one of them interacts with a spin detector (or its detector interacts with an observer). This means that the measurement or observation of one electron instantly influences the measurement of the other in order to ensure that the pair has zero net spin. This instantaneous interaction across space illustrates nonlocality, which Einstein referred to as spooky action at a distance (Einstein at al., 1935). The HCM and quantum observations logically imply nonlocality, but it offers no explanation for reconciling nonlocality with relativity, which limits the propagation of influences to the speed of light.

5.3 The Asymmetry of Time

The HCM is both deterministic and non-dissipative. A consequence of determinism and conservation of work potential is microscopic reversibility. Microscopic reversibility means that, in principle, a system's o-state can run backward through time. This would happen if we reversed the motions of a system's elementary particles. If we reversed the motions of elementary particles in a glass of inky water, the particles would retrace their steps, and the ink would unmix. Similarly, if we reversed the particles' motions in the clumped clay lumps, the initial lumps would fling outward with their original speeds.

The HCM is microscopically reversible, but it also acknowledges the perception of time's asymmetry, based on increasing entropy. The HCM defines entropy as the number of microstates (o-states) available to a system that are compatible with its imperfectly measured macrostate (m-state). More possibilities mean a higher probability[3]. The HCM interprets the asymmetry of time as the progression from low probability to higher probability. According to physics, the only reason that we do not see ink unmix or clay lumps fling apart is that the disordered state is vastly more probable than the unmixed and ordered state. For a macroscopic system starting in a state of low entropy, the probability for observing entropy decline is virtually zero, and for all practical matters, entropy only increases.

The HCM defines entropy as a probability and the asymmetry of time as a statistical trend toward higher probability. In a deterministic world, however, probability simply reflects an individual's assessment based on incomplete information. In a deterministic world, entropy and the asymmetry of time are phenomenological properties, meaning that they apply only to our perception of reality and not to physical reality as it exists unobserved. So, while the HCM acknowledges time's asymmetry and while this is not incompatible with microscopic reversibility, entropy and time asymmetry have no foundational basis in the HCM's objective physical reality.

The Hamiltonian conceptual model fails to explain the indeterminate collapse of a superposed wavefunctions for the universe or for any isolated system. The instantaneous correlation of measurement seems to require superluminal interaction and this appears to violate relativity. The HCM can accommodate time asymmetry as a phenomenological property, but it is microscopically reversible, and it cannot explain time's asymmetry. The HCM for quantum mechanics falls short on all three experimental facts.

6. Quantum Interpretations

An informal poll of attendees at a 2011 conference, Quantum Mechanics and the Nature of Reality (Schlosshauer et al., 2013) shows after nearly a century of quantum mechanics, there is still a divergence of views and no consensus on what quantum mechanics says about the nature of reality. This section reviews a few of the most prominent interpretations.

6.1 Copenhagen Interpretation

The Copenhagen interpretation (**CI**) traces its origin to around 1927, primarily from the ideas of Niels Bohr and Werner Heisenberg in Copenhagen (Pykacz, 2015, Faye, 2014). The CI has historically been the traditional interpretation of QM. It formally describes the measurement process in terms of classical mechanics, thereby eliminating superposed measurement results. The CI additionally backs off from the HCM's assumption of intrinsic determinism. The wavefunction is taken as a complete description of a physical o-state only at a system's initial preparation and at its measurement. The CI is deliberately agnostic on whether the underlying o-state evolves deterministically while it is isolated and unobservable. The CI says it is meaningless to ask about a

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

system's o-state or its process of change if it cannot be measured. Mermin (1989) summarized the CI with characteristic pithiness with the edict: "Shut up and calculate!"

6.2 Many Worlds Interpretation

The Many Worlds (**MWI**) interpretation was proposed by Hugh Everett in his 1957 PhD thesis (Vaidman, 2016). The MWI was the second-most accepted interpretation in the 2011 survey, after the Copenhagen interpretation. The MWI fully embraces the HCM, as applied to the universe as a whole. The universe has no external observers and no external surroundings to trigger indeterminate change, so the wavefunction for the universe can never collapse. Rather, the universe splits into superposed branches in which all possibilities coexist in separate but superposed "worlds." As observers, we are also split and only experience one branch of the total universe. Our eigen-self's memory of events therefore appears to us as a sequence of indeterminate wavefunction collapses. From the objective perspective of the universe, however, there is no indeterminism. There is only an exponentially expanding multiplicity of branching eigen-worlds within a massively superposed universe, which is completely described by the wavefunction of the universe.

6.3 Hidden Variables Interpretations

Many physicists balk at having to accept the possibility of physically superposed cats and having to choose between the CI's unexplained process of wavefunction collapse or the MWI's metaphysical implications, in which anything that can happen, does happen in some branch of an ever-branching universe. Albert Einstein and colleagues suggested that hidden variables might provide a more rational explanation for wavefunction collapse and also reconcile nonlocality and relativity (Einstein et al., 1935). They argued that the instantaneous correlations of measurement of entangled particles could be explained by hidden variables inherited from their common origin. Wavefunction collapse is intrinsically indeterminate, but perhaps unmeasurable and unknowable hidden properties of the underlying o-state could determine the outcomes. Hidden variables can potentially provide a simple explanation for both the indeterminism of measurement and instantaneous correlations.

Einstein's hope for a local hidden variables theory was dashed, however, by a theorem by John Bell. Bell (1964) proved that any hidden-variables explanation for correlated measurements must violate the locality assumption, which asserts that an event cannot have nonlocal superluminal effects. Bell's theorem and quantum experiments prove that any objective interpretation of physical reality must be nonlocal (Mermin, 1981).

6.4 Information-Based Interpretations

A system's e-state is defined by perfect measurement. Classical mechanics and relativity provide transformations between any two perfect observers that preserve information about states. This means that the definitions of state in classical mechanics and relativity are independent of the particular observer and they are therefore objective. In quantum mechanics, however, a measurement by one observer can instantly affect the measurement by another observer, and there is no comparable equivalence between observers.

This has led to a host of interpretations in which quantum reality is specifically defined by an individual observer's description. As a group, these information-based interpretations garnered more support in the 2011 survey than any individual interpretation except for the Copenhagen interpretation. Prominent examples include QBism (Caves and Fuchs, 2002) and the consistent histories interpretation (Griffiths, 1984 and 2017).

Information-based interpretations assert that quantum mechanics describes our observations or descriptions of measurements or events, and nothing more. This eliminates the physical effects of observation on the collapse of a quantum state. This includes collapse of spatially extended entangled states, so it also eliminates nonlocality. The cost of information-based interpretations, however, is the denial of an objective reality independent of the observer or its framework.

The prevailing interpretations of physics seem to leave us with two bleak choices. We can have an objective physical reality if we accept nonlocality and time, deterministically playing out a script encoded at the universe's creation. Alternatively, we can reject these implications and reject the objective existence of physical reality. We reject both of these choices as a false choice.

7. Dissipative Dynamics of State

Physics defines physical reality by perfect measurement at absolute zero, where there is no heat or entropy. We refer to any such interpretation 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**) rejects this assumption. Dissipative dynamics is an integrated conceptual framework for interpreting classical mechanics, quantum mechanics, and relativity.

7.1 Postulates and Implications

Dissipative dynamics is 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 e-state and an equilibrium reference e-state at the ambient temperature.

Postulate 3: At perfect observation, there are no hidden variables. The c-state therefore equals the e-state.

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 cosmic microwave 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 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 at the ambient temperature completely describes the conceptual state.

Figure 1 illustrates DD's conceptual model of state.

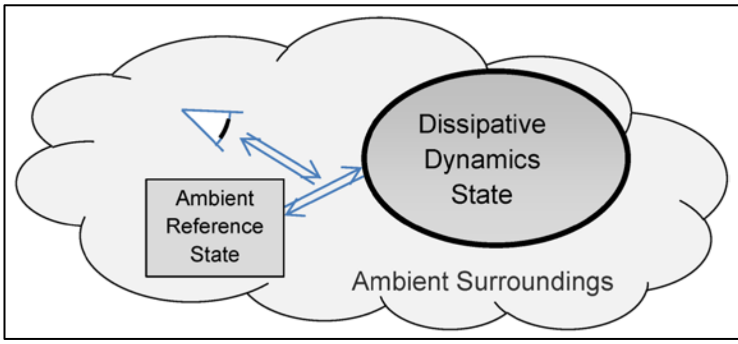

Figure 1. Dissipative Dynamics State

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 dissipative dynamics e-state and c-state.

Postulate 3 refers to the system's c-state rather than to its o-state. This is because, given our non-equilibrium and non-isothermal universe, the temperature of the surroundings depends on where we divide the system of interest from the surroundings. Dissipative dynamics recognizes that the c-model is just a simplification of objective reality. Physical reality, itself, does not depend on our delineation, however. The cosmic microwave background, which permeates the fabric of empty space and is part of the universe, defines the ultimate and objective ambient "surroundings."

When we include the ambient temperature as part of the reference state, we can no longer reversibly transform one arbitrary reference to another, as we could in classical or relativistic mechanics. In this sense, we abandon the idea of objective reality as conceived by non-dissipative conceptual models. However, rather than follow QBism and the consistent histories interpretation and abandon objective reality, dissipative dynamics alters the concept of objective reality by including the ambient surroundings as part of the system. The ambient reference is an essential and inseparable attribute of a system's o-state. The state is independent of the particular ambient observer, and it is objective within the framework of dissipative dynamics.

Dissipative dynamics is premised on simple and straightforward postulates, but it has major implications. Dissipative dynamics objectively defines ambient heat, exergy, and entropy. Exergy is the potential work on the 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.

Thermalization describes the statistical distribution of energy among a system's available energy levels[4]. Dissipative dynamics asserts that the ambient temperature determines a system's thermalization. This is in distinct contrast to the local equilibrium hypothesis of non-equilibrium thermodynamics, 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 and pressure. Dissipative dynamics, in contrast, defines a component's potential by its specific exergy[5], which is the work potential per unit of component as measured at the ambient temperature and pressure.

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 show that specific exergy, and not chemical potential, drives this chemical process.

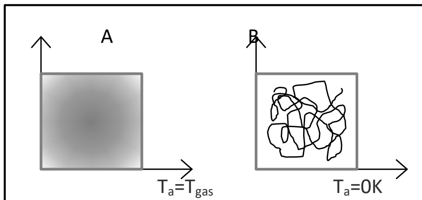

Figure 2. Configuration spaces for single-particle gas in 2D box.

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.

Figure 2 further illustrates the fundamental distinction between dissipative dynamics and non-dissipative interpretations of physical reality. 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 physically exist prior to measurement, and we contrast it to perfect equilibrium measurement at the ambient reference temperature. For the hypothetical dynamic illustrated in Figure 2A, phantom measurements would most likely reveal a particle in the darker, central region. However, the gas, as it exists in thermal equilibrium at its ambient temperature[6], is fully thermalized and there is no well-defined position or trajectory. The gas is fully and completely described by the probability function defined by the statistics of phantom measurements.

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

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

[5] 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.

[6] 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.

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 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 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. The latter 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.

7.2 Special-Case C-Models of State

Dissipative dynamics provides flexibility to define special-case conceptual models to represent quantum and classical mechanical systems, equilibrium and non-equilibrium thermodynamic systems, and as we will see later, even evolving systems. Table 2 summarizes these special-case c-models.

Table 2. Special-Case Dissipative Dynamics C-Models

Special Case DD C-Model	System Temperature	Ambient Temperature	Basis Temperature
Classical Mechanics	$T_{sys} = 0$	$T_a = 0$	$T_b = T_a = 0$
Equilibrium Thermodynamics and DD Quantum Mechanics	$T_{sys} > 0$	$T_a = T_{sys}$	$T_b = T_a$
Non-equilibrium Thermodynamics	$T_{sys} > 0$	$0 < T_a \leq$ minimum T_{sys}	$T_b = T_a$
Statistical Mechanics (DD) (non-DD)	$T_{sys} > 0$	$T_a = 0$	$T_b = T_a$ (microstate) $T_b = T_{sys}$ (macrostate)
Hamiltonian Quantum mechanics (Non-DD)	$T_{sys} > 0$	$T_a = T_{sys}$	$T_b = 0 < T_a$

Classical Mechanical C-model: Dissipative dynamics describes classical mechanics as an idealized special-case c-model where the system temperature, the ambient temperature of the surroundings and observer, and the basis temperature of perfect measurement are all equal to absolute zero. This allows for perfect and precise measurement of particles having precise coordinates of position and momentum and having no thermal fluctuations.

Thermodynamic C-models: Dissipative dynamics describes the equilibrium thermodynamic system as a special case c-state where the ambient temperature and the basis temperature of measurement are both equal to the system temperature. The equilibrium thermodynamic c-state expresses all that can be known by a perfect ambient observer. It is meaningless to ask where an individual gas particle is located. From the perspective of a perfect ambient observer, the equilibrium gas is homogeneous and structureless. This is not just an artifact of measurement imprecision. From postulate 3, the system has no hidden variables, and the thermodynamic state completely defines the system as it exists with respect to its ambient surroundings.

Real systems are not in thermal equilibrium with their ambient surroundings. Real systems can have varying and changing temperatures. A non-equilibrium system has system temperature(s) higher than its ambient temperature.

Statistical Mechanical C-model: Dissipative dynamics defines the statistical mechanical microstate the same as the classical mechanical o-state, except for a positive system temperature. Temperature is simply a measure of the average non-thermalized kinetic energy of the system's particles.

Statistical mechanics defines the macrostate with its basis temperature of measurement equal to the system temperature, the same as the equilibrium thermodynamic state. With its positive basis temperature of measurement and its ambient temperature at absolute zero, however, the macrostate constitutes an m-state and an imperfect description. The macrostate is not a dissipative dynamic c-state.

Quantum C-model: A quantum system's ground-state energy is always positive, and this is reflected by a positive temperature. For a system comprising a single particle, the system temperature is equal to the ambient temperature, given by $T_a=\frac{Q}{k_B}$, where k_B is the Boltzmann constant and Q is its thermalized energy. For perfect measurement at the ambient temperature, the dissipative dynamics quantum c-model is identical to the equilibrium thermodynamic c-model. The Hamiltonian quantum c-model, in contrast, defines perfect measurement at absolute zero, by the statistical distribution of phantom measurements. This violates Postulate 2 and the Hamiltonian quantum c-model is not a dissipative dynamics c-model.

7.3 Entropy and Thermodynamics' Arrows

Dissipative dynamics resolves the entropy of an isothermal system into two components, shown in Figure 3. The first component (horizontal line) relates an isothermal system to its basis reference at the system temperature. This is a generalized equilibrium thermodynamic entropy, defined by the system's ambient heat, relative to the reference state at the system temperature, divided by the ambient temperature.

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. For the special case where the ambient temperature equals the system temperature, the total entropy equals the equilibrium thermodynamic temperature. For the special case of absolute zero ambient temperature, it equals the Third-Law thermodynamic entropy, which also equals the Boltzmann entropy, defined by $k_B \ln(W)$, where W is the number of equally probable configurations. 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.

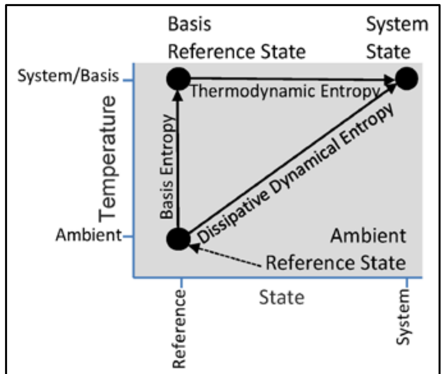

Figure 3. Two Components of Entropy. Dissipative dynamical entropy is resolved into the thermodynamic entropy, defined with respect to a basis reference at the system temperature, and the basis reference entropy, defined with respect to the ambient reference.

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 arrow of dissipation. The second path toward higher entropy results from a declining ambient temperature. A declining ambient temperature and the consequent refinement of configuration space increases the number of state-pixel configurations and the Boltzmann entropy. The resulting increase in basis entropy defines the arrow of refinement.

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.

8. 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 and objective 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), as interpreted within the framework of dissipative dynamics (Crecraft, 2017), provides a clear demonstration of retrocausality. Pusey and Leifer further argue that retrocausality can reconcile the instantaneous correlations of measurement with a local and objective 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. However, time asymmetry does not apply to intervals of metastability and time-symmetry.

Figure 4 illustrates how dissipative dynamics reconciles local reality and 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.

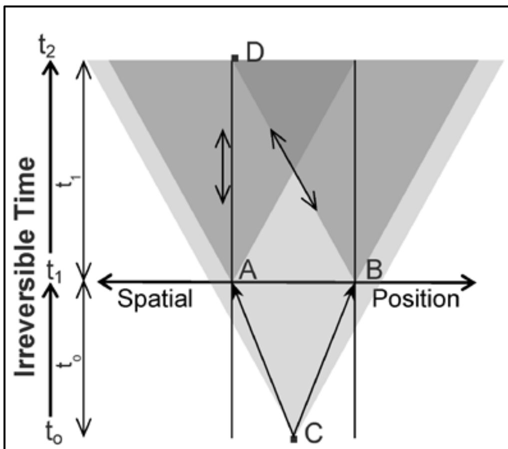

Figure 4. Not-so Spooky Action at a Distance

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.

From the conservation of electron spin, if Alice measures an up spin on her entangled electron, she instantly knows that Bob measures a down spin. The results are correlated, but 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, 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.

We could just as easily describe the experiment from Bob's perspective with equivalent results. Time-symmetry allows an information-preserving transformation between different observers and this restores objective reality to quantum mechanics. However, each irreversible transition actualizes a new quantum reality.

9. Evolving Complexity

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 formulating a principle of spontaneous organization and the emergence of complexity.

9.1 The Emergent C-State

Figure 1 previously presented the dissipative dynamics c-model for states. Figure 5 illustrates the DD model for the emergent c-state. Like the thermodynamic c-states, the emergent c-state assumes a stationary environment with a positive ambient temperature, but the surroundings for the emergent c-state is non-equilibrium and it includes stationary exergy sources. Over time, the system converges to a stationary process of dissipation, sustained by sources of energy and high-exergy components. This is the emergent c-state.

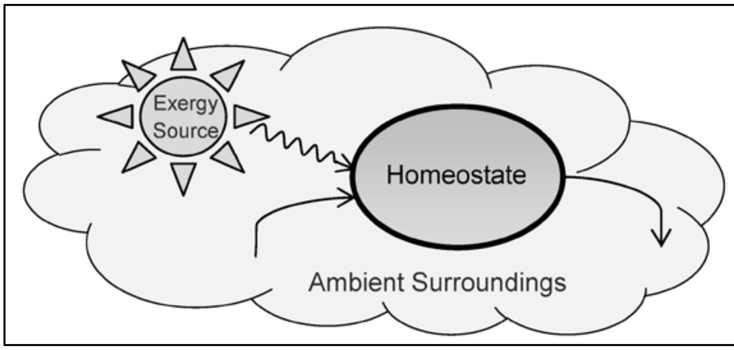

Figure 5. Homeostate Model

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.

The emergent c-state is stationary, but it is not microscopically static and it is not a true state, as its components are constantly reorganizing and dissipating exergy. Stationary does not necessarily mean steady state. At steady state, the component and energy fluxes are constant and state properties do not vary. The rates of component and energy flows and properties for emergent c-states, however, can and frequently do fluctuate. Stationary simply means that the time-averaged properties are constant. Crecraft (2017) refers to these stationary systems as homeostates.

A homeostate can be resolved into a network of dissipative nodes, links, and pods. 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. 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 says the dissipation of the whole equals the sum of dissipation by 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.

9.2 The Arrow of Emerging Complexity

The arrow of emerging complexity involves selection from multiple homeostates, which 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 to 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 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) defines a homeostate's utilization by the sum of internal dissipation and internal work. From Postulate 5, the internal dissipation simply equals the system's net exergy supply. Internal work is the work on system components needed to sustain its function. The Kelvin selection principle constitutes a principle of natural selection for the physical world. When resources are available, a system can increase its utilization simply by increasing its net exergy supply, for example, by expanding. When resources are fixed, a system can continue to increase its utilization by increasing its internal work by increasing internal efficiency and adding new pathways to recycle exergy. These trends define the arrow of emerging complexity.

10. Conclusions

Dissipative dynamics is a generalized conceptual framework for interpreting what experimental results reveal about the underlying physical reality. Dissipative dynamics accommodates classical mechanics, relativity, quantum mechanics, thermodynamics, and evolution as special cases. Hamiltonian classical and quantum mechanics, and relativity, are non-dissipative interpretations. Consequently, these mechanical theories do not recognize heat or entropy as objective properties of physical reality. Absolute zero, however, is an idealization that does not exist in reality.

The thermodynamics c-states take a step toward greater fidelity to reality by defining perfect measurement and objective reality at positive ambient temperatures. The equilibrium and non-equilibrium c-states still assume the ambient surroundings to be in equilibrium, and they are still an idealization and simplification of reality. The emergent c-state takes an additional step toward greater fidelity by accommodating non-equilibrium surroundings, containing stationary exergy sources. Exergy sources maintain and sustain fluxes of energy and components through emergent systems and sustain dissipative processes. The emergent c-state accommodates exergy utilization as an objective property of dissipative processes, and this defines a measure of complexity for homeostates. The Kelvin selection principle is a principle of natural selection for the physical world, guiding a dissipative system toward higher complexity as long as its environment allows.

This emergent c-model is still an approximation of reality, however. The emergent c-model and utilization are defined with a stationary environment and fixed ambient temperature. A more general c-model would account for changing ambient temperatures, such as the cooling cosmic microwave background, multiple ambient temperatures operating on different levels, and finite exergy sources. Nevertheless, The KSP and the emergent c-state provide an accurate description of evolution for systems within stationary non-equilibrium environments.

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