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 to interpret experimental results. A conceptual model allows us to deduce the underlying physical state and to explain measurement results. The Copenhagen Interpretation, Many Worlds Interpretation, the de Broglie-Bohm Pilot Wave Theory, Consistent Histories interpretation, and QBism all either fail to explain (or deny) paradoxes associated with wavefunction collapse and nonlocality, or they deny the existence of an objective reality.

We identify a deeply ingrained assumption, shared by these and other conceptual models, which leads to their shared failures. By revising this assumption, dissipative dynamics accommodates objective reality and the empirical models of classical, quantum, and relativistic mechanics, thermodynamics, and evolution as special cases. Dissipative dynamics eliminates the paradoxes of quantum mechanics and it embraces time's arrows of thermodynamics and emerging complexity.

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I. Introduction

The universe has evolved to its current exceptional state, where we are here to ponder why. Yet, despite the fantastic success of physics in describing the universe around us, from the subatomic building blocks of all matter to black holes, physics is at a loss to explain the extraordinary complexity and richness in our universe.

Physics generally describes the evolution of a system, isolated from external perturbations, as intrinsically deterministic. Determinism means that the history of the universe is the playing out of a script encoded in its initial state, and that free will is an illusion. Accordingly, our exceptional universe must have started in an exceptionally improbable initial state. Or, perhaps there is a multitude of universes, and ours is simply that extraordinarily rare outlier that allows us to exist and ponder it. The nature of a system as it exists in isolation unperturbed and unobserved, however, cannot possibly be resolved by observation or measurement alone. Observation and measurement pierce the veil of isolation. The nature of a system, as it exists undisturbed behind that veil, is strictly a matter of interpretation of experimental results.

This paper compares and analyzes some of the current interpretations of physics. It reveals a deep-seated assumption that underlies their shared failures to provide simple and objective explanations for key experimental facts. The paper clarifies and expands on the physical foundations for a conceptual framework introduced by Crecraft (2017). Dissipative dynamics is a conceptual model and interpretation that integrates the existing theories of physics, thermodynamics, and evolution as special cases within a single conceptual framework, fully consistent with experimental observations and physical laws. It provides a simple and objective interpretation of physical systems that explains wavefunction collapse, nonlocality, the thermodynamic arrow of time, and the arrow of emerging complexity.

II. Key Experimental Facts

Observations and measurements are the empirical facts on which we build our models and laws of physics. We conceive laws to predict experimental results and to be able to anticipate events within our environment. Laws predict, but they do not explain. If we want to understand why the underlying physical system produces the results that we see, we need a conceptual model to interpret experimental observations in terms of an underlying reality.

We identify four key experimental facts that we consider particularly important for an interpretation of physical reality to explain. These are 1) the indeterminism of quantum measurements, 2) the instantaneous correlation of quantum measurements, 3) the thermodynamic arrow of time and 4) the arrow of emerging complexity. Any consistent interpretation of physical reality should account for these key experimental facts.

Fact #1: Indeterminism of Quantum Measurements

In quantum mechanics, we cannot determine the outcome of a measurement, even if we know everything knowable about the system and we eliminate all errors of measurement. This is the indeterminism of quantum measurements. If an obliquely polarized photon interacts with a vertically polarized filter, it is impossible to predict whether or not it will pass through the filter. Measurements reveal either a vertically polarized photon passing through the filter, or a horizontally polarized photon absorbed by the filter. From the perspective of the polarizing filter, quantum mechanics describes the photon prior to measurement as a superposed sum of the measurable component states[*]. At observation, however, we invariably observe only a single state. This is the collapse of the quantum state. We cannot determine which of the potentially observable states we will observe. All that we can do is accurately predict the statistical probabilities of quantum measurements. The indeterminism of quantum measurements is the first key experimental fact.

Fact #2: Instantaneous correlation

Instantaneous correlation is the second key experimental fact. Instantaneous correlation refers to the correlations in measurements made on spatially separated parts of a quantum system. To illustrate, we consider a particle that emits two electrons in opposite directions. Because the electrons are still part of a single quantum state, we say they are entangled. Two detectors are placed equal distances in opposite directions from the electron-pair source. One detector is operated by Bob, in Houston, and the other, by Alice, on the moon. They are separated by 384,000 kilometers, or 1.3 light-seconds. After a pair of electrons is emitted at equal speeds toward the detectors, they reach their detectors. As soon as Alice detects her electron, she transmits her results to Bob, and he receives her results 1.3 seconds after he detects his own electron.

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. 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.

Experimental results of measurements on the entangled pairs are indeterminate. Repeated measurements on successive electron pairs by Alice or Bob show a random distribution of spin up and spin down states. The measurements, however, are strictly correlated. If Bob's and Alice's detectors are oriented parallel to each other, then if Bob measures an up spin on his entangled electron, he instantly knows that Alice measures a down spin. This is invariably confirmed 1.3 seconds later, when he receives her results. Even though Bob is spatially separated from Alice by 1.3 light-seconds, he knows that her signal traveled at the speed of light, and he concludes that they measured their electrons simultaneously and that the correlation in their measurements was instantaneous. These results have been experimentally verified numerous times and are established experimental fact.

Fact #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. We can observe a boulder rolling downhill to

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[*] By rotating the filter, we can describe the same photon as a superposition of two measurable states or as a single non-superposed and measurable state. However. it is generally not possible to dial away the superpositioning of a quantum state and assign it a definite value prior to measurement.

a more stable state, but we will never see a boulder spontaneously rolling uphill to a less stable state. Similarly, we are more likely to observe a high-energy quantum particle decay to a lower-energy and higher-stability state, than to find a low-energy particle spontaneously transition to a high-energy state. These observations illustrate two distinct manifestations of the thermodynamic arrow of time, both associated with increasing entropy. The dispersion of ink illustrates the increase in entropy, as defined by disorder and incomplete information on the detailed state. As the ink particles disperse, their distribution becomes more fine-grained and at some point, we inevitably lose track of their precise locations. The other examples illustrate the increase in entropy associated with the dissipation of free energy[*]. The thermodynamic arrow points in the direction of increasing entropy, increasing disorder and uncertainty, and decreasing free energy, all as expressed by the Second Law of thermodynamics.

In his *Autobiographical Notes*, Albert Einstein (1979) wrote of thermodynamics and the irreversible increase in entropy: "It is the only physical theory of universal content concerning which I am convinced that, within the framework of applicability of its basic concepts, it will never be overthrown." Entropy is a well-defined and measurable property. Its irreversible increase is a universally accepted asymmetry of time and the third key experimental fact.

Fact #4. The Arrow of Emerging Complexity

The evolution of the universe and of life on earth illustrates another of time's asymmetries, the arrow of emerging complexity[†]. There is no way to observe multiple universes, and opportunities to conduct experiments on biological evolution are very limited. Nevertheless, Stanley Miller and Harold Urey experimentally demonstrated the arrow of emergence on a much smaller scale (Miller, 1953). They took a mixture of gases, which they believed represented Earth's primordial atmosphere, and they stimulated it with electrical sparks to simulate lightning. When they analyzed the gas mixture afterwards, they found that the gas molecules had rearranged themselves into a variety of amino acids. Whereas the gas mixture started in a relatively stable equilibrium state, it ended up in an unstable higher-energy and lower-entropy state. The experiment is repeatable with similar results. The decline in entropy illustrates the empirical arrow of emerging complexity.

The arrow of emerging complexity does not violate the Second Law of thermodynamics. Whereas the Second Law says that the entropy of an isolated system can never decrease, the gas mixture is open to the input of electrical energy. The input of energy drives the gas molecules energetically uphill to assemble into low-entropy, high-energy amino acid molecules. If we isolate the gas from its energy source, the amino acids slowly break down into a more stable state, in accordance with the Second Law. If we consider the entire experiment in isolation, including a battery for its electrical discharges, we see that the system as a whole runs down in free energy and increases in entropy, led by the discharge of the battery, again in accordance with the Second Law.

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[*] Free energy is undissipated energy, which is freely available for work on a reference at the same temperature.
[†] Section IX provides a general definition of complexity. In this section, we use negative entropy as an example of complexity.

The arrow of emerging complexity and the thermodynamic arrow of increasing entropy are compatible with each other, but they illustrate distinct arrows of time and distinct experimental facts.

Indeterminism of measurement, instantaneous correlation of measurements, and time's asymmetries are all experimental facts that any comprehensive interpretation of physical reality needs to explain.

III. Models, Measurements, and States

Classical mechanics, thermodynamics, quantum mechanics, and relativity are all theories of nature. We can divide a theory of nature into its model of the system, and its laws. We develop a model to describe a system's physical properties and its measurement. Laws describe how a system responds to environmental interactions, including measurements. The laws of quantum mechanics and relativity, in particular, have been thoroughly vetted by experiment. The laws of thermodynamics have also been thoroughly vetted. These laws and their predictions are not questioned. 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. Models, in contrast, are our interpretation of how nature is organized and they help us understand why we see the results that we do.

A model does not make predictions. It merely provides a framework for interpreting experimental results. Does the indeterminism of a photon's interaction with an obliquely polarized filter, conducted in isolation, reflect intrinsic randomness, or is the collapse of the quantum state caused by an external perturbation when an observer breaks the veil of isolation to peek inside to check? Are there hidden and unknown properties that determine the photon's choice? These are questions of interpretation based on our model of physical reality, but the indeterminism of measurement results is an experimental fact.

Instantaneous correlation means that the measurement of one entangled particle is instantaneously correlated with measurements anywhere within the entangled system, regardless of spatial separation. Instantaneous correlation is an accepted fact of quantum measurements. Does the measurement of one instantaneously affect the measurement of the other, in apparent violation of relativity, which limits the propagation effects to the speed of light? The nature of this correlation, and whether it involves superluminal action, are questions of our interpretation and model of reality.

Does the thermodynamic arrow of time of time reflect the microscopic irreversibility of physical processes? Thermodynamics interprets entropy as an intrinsic property of state, and it defines the spontaneous increase of entropy as a law of nature. Is entropy a phenomenological property of our perception or knowledge? Statistical mechanics interprets entropy as a measure of our uncertainty of a system's precise state. Or, is the entropy an emergent property, arising from the collective behavior of particles? These are questions of interpretation, but the asymmetry of entropy's change, regardless of its physical interpretation, is an experimental fact.

Does the arrow of emerging complexity imply special initial conditions that deterministically play out according to script? Does the emergence of complexity arise spontaneously through a physical process of random change and natural selection, analogous to the evolution of life? The emergence of complexity is an experimental fact, but its origin is a matter of interpretation.

Indeterminism, instantaneous correlation, and time's asymmetries are all experimental facts, but the interpretations of physical reality and the explanations of measurement results continue to be debated, with no consensus on any single interpretation (Schlosshauer et al., 2013; Tammaro, 2014).

Before we can discuss and compare various interpretations of physical reality, it is essential that we adopt a terminology and common language to describe them. The failure to adopt a common language can lead to proponents of various interpretations talking past each other, with no common understanding. A lack of clear terminology has contributed to the current lack of a cohesive interpretation of physical reality.

We first need to distinguish between two distinct levels of models. The first is the empirical model, or e-model, of physical state. The e-model is based strictly on measurable properties. The second is the conceptual model, or c-model. The c-model represents the physical system as it actually exists, whether or not we can completely measure and know it. These are listed in Table 1.

The e-model represents a system's measurable states. Actual measurements are imperfect, due to measurement errors or to low resolution, both of which can result from thermal noise. If we apply imperfect measurements to our e-model, then we get 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 c-model is our representation of physical reality. A c-model might contain hidden variables, which are not measurable and 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 conceptual model's representation of a system's actual underlying state, which we refer to the ontic state, or o-state. The 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-state, unless we need to express the incompleteness of a c-state.

We have one final important note. If the c-model does not have hidden variables, then the e-state is a complete description of the c-state at measurement. If the c-state is also assumed to be a complete description of physical reality, then the e-state, c-state, and the o-state are identical and completely known at the point of perfect measurement. However, if the c-state/o-state changes randomly, then the e-state 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. Perfect measurement and its e-state are essentially static, meaning that the embedded information is fixed. Whether or not the o-state is deterministic and essentially static is a key c-model assumption.

Table 1. Hierarchies of Models and States

Models	Model Parameters	Modeled State	Modeled State Descriptions
Empirical e-model.	Actual measurements	measured m-state	Imperfect measurement due to measurement errors or low resolution. Describes incomplete information.
(If the e-state is complete, the e-state equals the c-state at measurement)	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 c-state is complete, c-state = o-state)
		ontic o-state	A system's actual physical state.

IV. The Hamiltonian Conceptual Model

We now explore a conceptual model that underlies classical mechanics, relativity, and, to varying degrees, many of the prevailing interpretations of quantum mechanics. We refer to this model as the Hamiltonian conceptual model, or HCM. The HCM is rooted in classical mechanics, and so we start with Newton's model of classical mechanics. As we will with all interpretations, we express the HCM using the terminology presented in Table 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. Newton's e-model describes a system by precise measurements for the positions and momentums of its component bodies, and for the forces acting on them. Classical mechanics assumes that both the e-state and the c-state are complete. The e-state, c-state, and o-state are therefore identical and they are all completely described by perfect measurement. We can refer to all of them as the system's actual o-state. Newton's laws of motion are deterministic. If forces and particles are precisely defined, the particles' measurable responses to the forces are precisely determined. Newtonian mechanics also assumes that the o-state is intrinsically deterministic, meaning that, as long as the system remains unperturbed, the present determines all future states.

Newtonian mechanics is about masses and forces, and friction is simply a force that counters an object's motion. The Newtonian mechanical model accommodates frictional forces and the consequent loss of mechanical energy, as measured by its potential to do work. Nowhere in Newton's laws of classical mechanics did he 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 to zero. Newtonian mechanics is deterministic, but determinism does not imply that nature is either reversible or that it conserves energy.

Thermodynamics

The First Law of thermodynamics later established the conservation of energy. The thermodynamic e-model, however, includes internal energy in addition to the mechanical energies arising from an object's motion or the external forces acting on it. Internal energy can include heat and internal work potential†. 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§, 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:

$$E_T = W_T + Q, \tag{1}$$
$$\begin{bmatrix}\text{Total}\\\text{Energy}\end{bmatrix} = \begin{bmatrix}\text{Work}\\\text{Potential}\end{bmatrix} + \begin{bmatrix}\text{Ambient}\\\text{Heat}\end{bmatrix}$$

where E_T and W_T include mechanical and internal energy components, and all terms are defined with respect to an ambient reference. The work potential W_T is the total work that a system can do on its ambient reference utilizing kinetic energy, potential energy, and thermal 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 originally defined entropy as the ratio of ambient heat and a fixed ambient temperature:

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

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

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* We assume zero or constant gravitational and other potential energies, and ignore them.

† Internal work potential can include the chemical potential of a battery or the internal energy of a compressed spring.

‡ This is not the textbook equilibrium thermodynamic e-model, which equates the ambient and system temperatures.

§ The thermal work potential W_q of heat 'q' at temperature T, as measured by the potential work on a reference at T_a, is $W_q = (\frac{T-T_a}{T}) \times q$. In the equilibrium thermodynamic e-model, T_a=T, W_q = 0, and thermal energy is all ambient heat.

** Equilibrium thermodynamics originally defined entropy by $dS = \frac{dq}{T}$, where 'd' designates an incremental value; this is easily shown to be equivalent to eq. (2) for an equilibrium system at a fixed ambient temperature.

Equilibrium thermodynamics and classical mechanics define two distinct e-models. They are each defined by perfect measurement. The thermodynamic e-model defines perfect measurement with respect to the ambient temperature of the surroundings and it includes thermal energy. The classical mechanical e-model, in contrast, defines perfect measurement by the precise measurements of positions and motions for the system's component parts, and it includes only the mechanical energies of its parts. They both assume that the e-state and c-state are complete, and they both assume that the o-state is deterministic.

Hamiltonian Mechanics

In 1834, a hundred and fifty years after Newton published his equations of motion and thirteen years before Hermann von Helmholtz published 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. Hamilton's energy function is therefore defined over the coordinates of position and momentum of the system's elementary particles. Hamilton's energy function e-model eliminated the forces in Newton's e-model and replaced them with potential fields.

In the HCM, an elementary particle has no internal parts and, consequently, it cannot have internal or thermal energy. The HCM e-model therefore does not accommodate dissipation or loss of energy. The difference between the Hamiltonian and thermodynamic models is clearly illustrated by their respective interpretations of colliding clay lumps. The HCM 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 internal thermal energy. Consequences of Hamilton's reformulation were the elimination of friction as a fundamental force and Hamilton's principle, commonly known as the least action principle. These changes greatly simplified complex calculations.

Statistical Mechanics

In the 1870s, after thermodynamics established its alternate description and e-model, Ludwig Boltzmann sought to reconcile thermodynamics with the Hamiltonian conceptual model. He described the thermal energy of an object as the sum of kinetic energies of the object's elementary particles, and temperature as a measure of their average kinetic energy. He thereby redefined the key thermodynamic properties statistically, as bulk properties of an imperfectly measured m-state. Boltzmann described the thermodynamic e-state as an HCM m-state, imperfectly measured with respect to a positive ambient temperature equal to the system temperature. Boltzmann took the thermodynamic state (and the HCM m-state) as the statistical mechanical macrostate and a statistical approximation of the actual state. He took the HCM o-state as the microstate and the complete description of the system's actual state.

Boltzmann went on to reinterpret entropy as mechanical disorder, defined by the number of microstates (o-states) that are consistent with the macrostate (m-state) description. Boltzmann described entropy as a measure of disorder, but it is also a measure of the incompleteness of the m-state. Claude Shannon (1948) later extended Boltzmann's entropy as a general measure of missing information.

The HCM sets the ambient temperature for perfect measurement to absolute zero. At absolute zero, thermal fluctuations are eliminated and there is no thermal noise to degrade perfect measurements. From equations (1) and (2), an absolute zero ambient temperature means that there is no ambient heat and no dissipation. At absolute zero, total energy and work potential are identical, and the first law of thermodynamics extends to classical mechanics to express the conservation of total energy and work potential. Boltzmann had set out to extend classical mechanics to accommodate thermodynamics and the Second Law. In the end, however, he rejected thermodynamics, as originally formulated in terms of heat, as a legitimate e-model. He purged heat as a thermodynamic property of state and from the definition of entropy and redefined thermodynamics in the mold of Hamiltonian mechanics. The HCM ended up subsuming thermodynamics as a statistical approximation of classical mechanics.

Summary

Hamiltonian classical mechanics, like Newtonian classical mechanics, is deterministic. Precise states and forces have precise results. Determinism does not rule out the possibility for the emergence of complexity, but it ascribes it to the playing out of a script encoded in a special initial state. Newtonian and Hamiltonian mechanics can both accommodate the arrow of emerging complexity, but they cannot explain it, except by invoking an extraordinarily improbable initial state or other unexplained metaphysical cause.

The Hamiltonian conceptual model implies more than just determinism. Unlike Newtonian mechanics, it also implies the conservation of work potential. A consequence of determinism and work potential conservation 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. In principle, 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. Another implication of microscopic reversibility is the Poincare recurrence theorem. This theorem states that, given infinite time, a system will repeatedly return arbitrarily close to its initial state. For a macroscopic m-state such as the glass of inky water or clay lumps, however, the probability for observing the reverse direction is virtually zero, and for all practical matters, time only runs forward.

These examples illustrate the asymmetry of entropy change. They also illustrate that, while the HCM can accommodate the asymmetry of entropy's changes as a phenomenological property of the m-state, its interpretation of the actual o-state is reversible. The HCM can only "explain" our observation of irreversible time by deferring to a highly improbable and low-entropy initial state, which it cannot explain. A reversible HCM cannot provide a physical explanation for why we observe time asymmetry. Explanation of any of time's asymmetries remains a deep and unresolved problem for the HCM and for any interpretation of physics that is deterministic, conserves work potential, and is therefore microscopically reversible. The Hamiltonian conceptual model marked a fundamental break from the Newtonian mechanical e-model, which did accommodate friction and the irreversible dissipation of work potential.

V. Quantum Mechanics

At the start of the 20^{th} Century, as physicists probed deeper into the details of matter and atoms, they discovered that measurements on quantum systems are often statistical and unpredictable, even in the limit of perfect measurement. It is only possible to predict the probabilities of measurements. These observations challenged the HCM's view of nature as intrinsically deterministic.

Following in the footsteps of the Hamiltonian model for classical mechanics, quantum mechanics describes the quantum o-state in terms of elementary particles, having kinetic and potential energies. These particles have mass and they respond to forces as described by Newton's laws of motion. The quantum mechanical e-model, however, differs radically from the classical mechanical e-model. There are two major differences between the Hamiltonian e-models for classical mechanics and quantum mechanics.

First, in contrast to classical mechanics, it is impossible in principle to measure simultaneously a quantum particle's precise coordinates of position and momentum. This is because the coordinates of position and momentum are not independent properties. Quantum mechanics therefore models measurement results and the e-state as a function over the coordinates of either position or momentum. Either set can perfectly model the e-state and measurement results. The second major difference is the intrinsically statistical nature of quantum measurements. The statistics of individual measurements led to redefining perfect measurement by multiple measurements on an ensemble of identically prepared systems, rather than by a single perfect measurement. Perfect measurement on an ensemble of identically prepared systems reveals everything that is knowable about the system's e-state. These differences resulted in a radical change in the description of physical states.

Erwin Schrödinger introduced the wavefunction in 1926 as the quantum mechanical e-model 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 system. It is a mathematical solution to the boundary constraints imposed on a system to elicit measurable properties.

The boundary constraints imposed on a system are specified by quantum mechanical operators. An operator describes the boundary conditions and a process of measurement for eliciting a quantum property or description of state. Each property of state has a corresponding operator. The Hamiltonian operator, for example, defines the boundary constraints and a process for measuring a system's energy. Operators can be chained together to create new operators to simultaneously measure multiple properties*.

There are generally multiple solutions consistent with an operator's constraints. Each solution is an eigenfunction of the operator. A key property of an eigenfunction is that it has a specific measurable value, and it defines a definite eigenstate. A fundamental property of the eigenstate is its contextuality. Contextuality means that a system's eigenstates depend not just on the system alone, but also on the operator, which expresses the experimental setup and boundary constraints that the measurement setup imposes.

A general system's wavefunction e-state is a weighted superposition of eigenfunctions, describing the statistical distribution of measurement results on an ensemble of identically prepared systems. The Born rule states that the probability of measuring a given eigenstate is equal to the square of the eigenfunction's weighting factor in the superposed wavefunction e-state.

The year before Schrödinger introduced his wavefunction, Werner Heisenberg formulated an alternate and equivalent description of quantum states in terms of matrices. Heisenberg's matrix formulation graphically represents the quantum state as a unit-length vector in a Hilbert vector space†. It is spanned by an orthogonal set of basis vectors (axes). Each normalized unit-length basis vector defines an eigenvector and represents a definite measurable state or state-property. Hilbert space is multidimensional, with one dimension and orthogonal axis for each potentially measurable eigenstate. An arbitrary superposed state is equivalently represented either by a superposed wavefunction or by a diagonal non-basis vector. Each represents a superposed e-state as a weighted sum of eigenstates and each specifies the statistical distribution of eigenstate measurement results.

To illustrate superpositioning, we can consider a radioactive particle. A radioactive particle is unstable to the spontaneous emission of energy and decay to a lower energy state. Measurements on an ensemble of identically prepared systems yield a statistical distribution of the decayed and energized states. These are the system's measurable eigenstates. Graphically, the particle is represented as a diagonal vector in a two-dimensional Hilbert space (Figure 1).

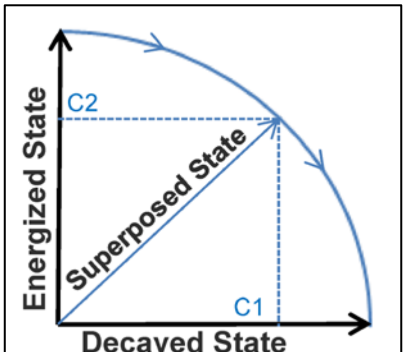

Figure 1. Hilbert Space Representation of an Unstable Particle

The diagonal vector represents a superposition of the basis-vector eigenstates, with weighting factors C_1 and C_2. Over time, the state vector rotates clockwise toward the stable decayed state.

*Only independent properties can be combined. Position and momentum are not independent. Their operators do not commute and they cannot be combined. Non-commuting properties cannot be measured simultaneously.

† Hilbert space is a complex vector space commonly of infinite dimensions. Scaling a vector by a complex number changes the vector length but leaves its direction in a complex vector space unchanged.

The probability of measuring the particle's decayed eigenstate increases over time. The change over time is graphically described by rotation of the state-vector toward the decayed-state eigenvector (Figure 1). Similarly, the time-dependent wavefunction describes an increasing weighting factor for the decayed state over time. Except at initial preparation and at infinite time, the probabilities of measurement are intrinsically random, even with perfect measurement and complete information on the e-state.

The transition from a superposed wavefunction to an eigenfunction at measurement defines wavefunction collapse. The wavefunction e-model, however, is merely an empirical model of measurement results. Its collapse is simply a consequence of new measurement, new information, and a new e-state. The wavefunction e-model predicts the statistics of measurements perfectly, but it is moot on the question of whether or not the system's actual o-state can exist as a physically superposed eigenstate prior to measurement and therefore collapses.

The quantum mechanical e-model leaves unresolved important questions. Does a superposed e-state, defined by statistical measurements on an ensemble of identically prepared systems, completely describe an ensemble of identical physically superposed o-states? Are the statistical measurements therefore random and intrinsically indeterminate? If not, do the o-states have hidden variables that distinguish one eigenstate from another and do they determine each system's measurement results? Do statistical measurements reflect a distribution of distinct eigenstate o-states and intrinsically random results from identical preparation procedures? These questions go to the heart of what quantum physics really says about physical reality. Assessing the nature of o-states depends on the conceptual model and its assumptions.

.VI. The HCM of Quantum Systems

If we strip away any interpretation of quantum mechanical reality, we are left with an empirical theory. The empirical theory of quantum mechanics comprises the wavefunction as the e-model, describing the perfect measurement of a system, and its laws, which predict measurable results. Quantum mechanics has been highly successful at predicting experimental results. As a strictly empirical theory, however, it says nothing about the underlying reality. Since the first quantum measurements, physicists have struggled to understand what they tell us about that reality. A full theory of quantum mechanics would include the quantum mechanical empirical theory and a conceptual model that describes the physical reality behind the experimental results.

This section extends the HCM interpretation to quantum mechanics. It discusses the HCM's implications on quantum reality and its explanations of the key experimental facts. The purpose of this section is not to propose or justify a particular interpretation. It is rather to apply the HCM to quantum mechanics to provide a reference interpretation for later comparisons with other interpretations of quantum mechanics.

We saw that the HCM for classical mechanics is based on the following assumptions:

1. Perfect measurement is defined at absolute zero, in the absence of thermal fluctuations.
2. A system is resolvable into elementary particles having kinetic and potential energies only. An elementary particle is defined as having no internal parts and therefore no (changes in) internal energy.
3. The o-state is intrinsically deterministic and non-dissipative.
4. The e-state and c-state are complete.

An immediate implication of these assumptions is:

5. 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.

These are the assumptions and implication underlying the Hamiltonian conceptual model for classical mechanical systems.

In quantum mechanics, perfect measurement is defined for an ensemble of identically prepared systems. Determinism means that identical preparation procedures produce identical results. It follows that an ensemble of identically prepared systems is therefore an ensemble of identical systems. Statistical measurements on the ensemble and completeness of the e-state imply that the individual systems share an identical and physically superposed o-state. To highlight this difference, we modify HCM implication 5 for classical mechanics to:

5Q. 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 take the Hamiltonian c-model for quantum mechanics and apply it to the key experimental facts.

Indeterminism of 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, creating a new wavefunction and a new e-state. However, the completeness of a superposed wavefunction e-state (implication 5Q) implies that the physical system exists in a physically superposed o-state until measurement or observation, when the system is invariably found in a definite eigenstate. Implication 5Q implies indeterminate physical collapse of the quantum state.

The HCM can reconcile the indeterminate collapse of the o-state with its intrinsic determinism (assumption 3) only by attributing the indeterminate collapse to an external and unknown 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 is isolation, could cause physical collapse of its o-state.

Erwin Schrödinger proposed a thought experiment in 1935 that highlights this problem. He considered a radioactive particle. For added drama, he included a detection apparatus that dropped a cyanide tablet into acid if it detected a decay event. He put all of this into an airtight and completely isolated box, along with a cat. After the initial preparation and prior to measurement, the wavefunction describes the particle and the cat as an entangled superposed e-state of decayed/ energized and dead/alive. If we peek inside, we see either a dead cat or a live cat. The HCM implies that the physical o-state exists as a physical superposition until observation or some other environmental perturbation pierces the veil of isolation and triggers indeterminate collapse. The intrinsic determinism of the HCM does not allow collapse as long as the system is isolated. The HCM also offers no explanation for how mere observation of the cat triggers actualization of its fate one way or the other.

The HCM does not formally explain indeterminate wavefunction collapse; it merely shifts the undefined source of indeterminism to the external and unknown surroundings. If we incorporate the surroundings into the system, the HCM pushes the source of indeterminism farther outward, but at some point, we run out of surroundings and any source for indeterminate collapse. The HCM implies that as long as the system remains isolated from external perturbations and observation, it can exist as a superposed o-state. This implies that the universe as a whole can only evolve deterministically and that the entire history of the universe must have been encoded in its initial state.

Instantaneous Correlation

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 {↓, ↑}, where the first arrow shows the spin direction measured by Bob on Earth, and the second is the result measured by Alice on the moon. Repeated measurements on identically prepared electron pairs are statistical, so the electron pair is described as a superposed wavefunction e-state. According to implication 5Q, the pair's actual o-state, while isolated and in flight, is a physical superposition of the two eigenstates. There are no hidden variables. Therefore, neither electron has a specific spin (or hidden trigger for 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. The HCM can offer no explanation for this instantaneous cause-and-effect or how it can be reconciled with relativity, which limits the propagation of influences to the speed of light.

Asymmetries of Time

Assumption 3 of the HCM says that an isolated system conserves work potential and is intrinsically deterministic. This implies microscopic reversibility. The collapse of the wavefunction e-state, however, is asymmetrical in time and the HCM cannot explain this. The HCM of quantum mechanics can accommodate asymmetries of time, but microscopic reversibility precludes any explanation for any asymmetry of time, except by invoking a highly improbable initial state.

To summarize, 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 cause and effect and to violate the theory of special relativity. The HCM can accommodate time asymmetry as a phenomenological property, but it is microscopically reversible, and it fails to explain any of time's asymmetries. The HCM for quantum mechanics falls short on all four experimental facts.

VII. Quantum Interpretations

Numerous interpretations and conceptual models of quantum mechanics have been proposed to explain quantum mechanical results, while avoiding at least some of the conceptual difficulties implied by the HCM: the physical superposition and unexplained collapse of the o-state, instantaneous correlation at a distance, and the failure to account for any of time's asymmetries. An informal poll of attendees at a 2011 conference, Quantum Mechanics and the Nature of Reality (Schlosshauer et al., 2013) shows after nearly one hundred years of quantum mechanics, there is still a divergence of views and no consensus on what quantum mechanics says about the nature of nature. In the sections below, we will discuss and analyze a few of the more prominent interpretations.

Copenhagen Interpretation

The Copenhagen interpretation (**CI**) traces its origin to around 1927, primarily from the ideas of Niels Bohr and Werner Heisenberg (Pykacz, 2015). The term Copenhagen interpretation, however, did not formally appear until Werner Heisenberg first coined it in the 1950s, by pulling together the sometimes-conflicting interpretations that were emerging in the mid-1920s in Copenhagen (Faye, 2014). As a result, the Copenhagen interpretation is not well defined. Nevertheless, it has historically been the mainstream interpretation of quantum mechanics. Since the late 20th Century, its popularity has steadily declined, but it still garnered the most support in the 2011 poll, with 42%

Schrödinger wrote of the prevailing doctrine developing in Copenhagen during the 1930s: "We are told that no distinction is to be made between the state of a natural object and what [we can] know about it.[*]" This statement clearly expresses the idea that a superposed wavefunction e-state completely describes the physically superposed o-state. This is the HCM's implication 5Q from Section VI.

[*] Schrodinger, 1935, cited by Goldstein, 2017 p2

To avoid the problem of whether Schrödinger's cat can physically exist in a superposed state of live/dead, the CI formally separates the measurement process from the quantum mechanical description. The CI describes the measurement process in terms of classical mechanics, 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 the system's o-state or process of change if it cannot be measured. N. David Mermin (1989) summarized the CI with characteristic pithiness with the edict: "Shut up and calculate!"

Many Worlds Interpretation

Whereas the CI's embrace of the HCM is tentative, at best, the Many Worlds interpretation (**MWI**) fully embraces the HCM, as applied to the universe as a whole. The MWI was the third-most accepted interpretation in the 2011 survey*. Vaidman (2016) presents a recent review of the interpretation.

As with the HCM interpretation of quantum mechanics, the MWI takes the wavefunction e-state to be a complete description of a physically superposed o-state and it assumes that the o-state is intrinsically deterministic. The wavefunction for the universe or any isolated system therefore never collapses and its future is determined by its initial state.

The MWI asserts that measurement, or any other event which we perceive to trigger collapse of the wavefunction e-state, does not indeterminately select one o-state or another. In Schrödinger's cat experiment, the particle does not select whether or not it decays and whether or not the cat dies. Rather, the MWI asserts that both the dead cat and the live cat coexist within a physically superposed o-state of the universe. As observers, we are also split and become a superposition of eigen-observers. Each of our eigen-observer selves only experiences one branch of the total universe and creates a memory of only one of the possible choices. Each eigen-observer's memory of events therefore appears as a sequence of indeterminate selections and wavefunction collapses. From the objective perspective of the universe, however, there is no indeterminate selection or wavefunction collapse. 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.

The MWI pushes the conceptual interpretation of the HCM to its logical conclusion. All possibilities are superposed within a single wavefunction for the universe, which never collapses. The MWI is internally consistent and consistent with experimental facts. Its innovation over the HCM is to introduce many branching "worlds" to avoid the problem of indeterminate wavefunction

*The second most popular interpretation was information-based interpretations. Although there is currently much interest in the connection between information and physics information-based theories are not well developed and not discussed here.

collapse. Nevertheless, many physicists and philosophers of science reject its philosophical implications.

Hidden Variables Interpretation

We have seen that the HCM's assumptions of completeness and intrinsic determinism logically imply physically superposed states. The collapse of an entangled and superposed quantum system at measurement then implies instantaneous and superluminal action across the entire system. Albert Einstein mockingly referred to this as spooky action at a distance. In a paper titled *Can Quantum Mechanical Description of Physical Reality Be Considered Complete?*, Einstein and colleagues (1935) questioned the completeness of the wavefunction in describing the correlated measurements on an entangled system. They argued that the instantaneous correlations of measurement could be explained by hidden variables inherited from their common origin. Hidden variables could avoid the problem of indeterminate wavefunction collapse by asserting that hidden variables determine all outcomes, including measurements. Wavefunction collapse is intrinsically determinate, but unmeasurable and unknowable hidden properties of the underlying o-state, means that it is impossible to determine. Hidden variables can potentially provide a simple explanation for both the indeterminism of measurement and instantaneous correlations.

In the mid-1920s, Louis de Broglie, postulated that a physical system consists of particles having precise and well-defined positions in space. These would be hidden variables, since the wavefunction e-state generally does not ascribe definite positions to particles. The leading physicists did not receive de Broglie's ideas well, however, and he abandoned it for the ideas emerging in Copenhagen at the time. David Bohm, rediscovered his ideas in 1952, and the theory is now known as the de Broglie–Bohm pilot wave theory (**PWT**). This is the prevailing hidden-variables interpretation. Goldstein (2017) presents a substantive and accessible review of the theory.

The PWT readily explains the perplexing results shown by the electron diffraction experiment, which confirmed the wave-like characteristics of particles, proposed by de Broglie in his 1924 PhD thesis. In this experiment, an electron is initialized as a definite particle and emitted toward a detector screen. The detector screen detects it as a definite particle at a discrete point. However, if a pair of slits separates the electron source and the detection screen, the accumulated impacts of multiple identically prepared electrons record bands of high intensity and low intensity over time. These correspond to a wave interference pattern.

The PWT asserts that the ensemble of identically prepared electrons are identical only in their observable properties, as described by their shared and superposed wavefunction e-state. Their actual o-states, however, are distinct in their hidden variables and there is no superpositioning of o-states. The PWT describes the wavefunction as a wave passing through both slits, with the two wavefunction segments then interfering with each other. The interference forms bands of high and low wavefunction intensity, similar to the diffraction patterns seen with light waves. The electrons' preparation procedure is blind to their precise hidden-variable trajectories, which are statistically distributed among the individual electrons of the ensemble. Electrons maintain their identity as a particle with well-defined but hidden trajectories. The electrons are guided by the pilot wavefunction and the Born rule, so the probability of a particle being at a specific location is proportional to the square of the wavefunction intensity. This results in the characteristic diffraction pattern of bright and dark bands that develop after many individual impacts.

The PWT expresses a "common sense" view of quantum mechanics, which Albert Einstein had sought, to explain both the particle-wave duality and instantaneous correlation. Einstein's hope for a hidden variables theory was dashed, however, by a theorem by John Bell. Bell (1964) proved that any hidden-variables explanation of correlated measurements must violate the locality assumption, which asserts that an event cannot have nonlocal superluminal effects. As reasonable as the assumption of locality may appear to be, Bell's theorem and numerous experiments to test his theorem have proved that hidden variables cannot provide a local explanation for instantaneous correlations. Mermin (1981) provides a delightfully simple explanation of Bell's theorem and its implications.

Bell's theorem was regarded by many as a blanket proof against all hidden variables theory. The results of the 2011 survey showed that De Broglie-Bohm's PWT garnered zero votes, suggesting that this belief persists. However, as Bell himself was very aware, the PWT does not violate Bell's theorem. The PWT is explicitly nonlocal, by defining the motions of particles as a function of the instantaneous positions of all particles within the system. This means that any change in the system at one point instantly affects the entire system. The PWT is thereby fully compatible with Bell's theorem, which only shows that a hidden variables theory must be nonlocal.

Nonlocality also does not allow superluminal signaling, so there is no direct experimental proof to counter nonlocality. Bell was an advocate of the strongly nonlocal de Broglie-Bohm's PWT, and he suggested that it is special relativity that needs modification in order to reconcile it with nonlocality. In an interview with the philosopher Renée Weber, not long before he died, John Bell said (Goldstein, 2017):

> one of my missions in life is to get people to see that if they want to talk about the problems of quantum mechanics—the real problems of quantum mechanics—they must be talking about Lorentz invariance [Relativity].

The Lorentz transformation relates an event or sequence of events, such as measurements, from one inertial reference to another inertial reference for the theory of special relativity. It precludes any cause-effect relationship, and therefore any instantaneous action, between events outside of each other's light cones of influence.

Reconciling nonlocality with Special Relativity is a serious challenge facing hidden variables theories in general. Nevertheless, the PWT goes farther in explaining the experimental facts than the CI or the MWI, neither of which offered any explanation for instantaneous correlations.

Consistent Histories

The Consistent Histories interpretation (**CHI**) was introduced by Robert Griffiths (1984). Murray Gell-Mann and James Hartle (1990) proposed a closely related interpretation, which they designated decoherent histories. Griffiths (2017) recently provided an overview of both interpretations. The CHI introduces several innovations, which its advocates claim eliminate all of the conceptually difficult implications of the interpretations previously discussed.

First innovation: The CHI's first innovation is to redefine perfect measurement for a quantum system as a single perfect measurement. This changes the quantum mechanical e-state from an often superposed wavefunction, describing measurements on an ensemble of systems, to a definite eigenfunction. The CHI further assumes that the eigenfunction e-state is a complete description of the o-state. It thereby eliminates physically superposed o-states. The CHI regards a superposed wavefunction to be a statistical description and an imperfect m-state, describing the uncertainty of an o-state's actual eigenstate.

Second innovation: The second innovation of CHI is the single framework rule. A framework in CHI typically defines the potentially measurable states*. These are graphically represented by Hilbert space eigenvectors. The framework then partitions the eigenvectors into m-states, which describe actually measurable states, reflecting the limitations of an actual measurement device. If an m-state partition includes a single basis vector, it describes a pure state and perfect measurement; if it includes multiple basis vectors, it describes a mixed state and imperfect measurement. A framework partitions the entire Hilbert space into a set of all potentially measurable m-states. If all m-state partitions are orthogonal to each other, then the framework is consistent. A consistent framework ensures that all measurement results are mutually exclusive and non-statistical.

In general, there are many ways to define and partition the vector space's eigenvectors into m-states, corresponding to different measurement devices and frameworks for describing a system. The single framework rule requires using a single framework for describing a system. The CHI further asserts that any consistent framework is valid and we are free to select any framework on the basis of its "utility" to address the questions at hand. In particular, we are free to refine a framework, increasing the number of eigenvector eigenstates available to a system, or coarse-grain a framework, reducing the number of available eigenstates Refinement and coarse graining change the dimensionality of the system's Hilbert space.

The single framework rule prohibits us from combining incompatible measurements into a single description of state. Thus, it forbids us from describing Schrödinger's cat based on the framework of the experiment's preparation, when the particle and cat exist as a well-defined and discrete o-state, and at the same time describing it based on the framework for its subsequent measurement, when the o-state can exist as one of multiple possibilities. These are incompatible† frameworks and they cannot be combined into a single description of state. The single framework rule eliminates incompatible descriptions of a system's state and consequent paradoxes.

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* A framework is not necessarily compatible with a measurement device. In this case, o-states and m-states are still defined by the basis eigenvectors and partitions for the chosen framework, but if these are not measurable, we need to speak of pure states instead of measurable states.

† Incompatible frameworks have non-commuting properties, meaning they cannot be independently and simultaneously measured.

Third innovation: CHI's third innovation is to describe a quantum system in terms of its state history at multiple discrete points of time. The CHI takes the tensor product of Hilbert spaces for a quantum system at discrete points of time to create a single composite histories Hilbert space*. This innovation simply involves a mathematical operation, and it introduces no new assumptions or interpretation. A state history is a basis vector of the composite histories Hilbert space. Mathematically, it is equivalent to the state vector in a conventional quantum mechanical Hilbert space.

The histories framework partitions the composite histories Hilbert space, which spans all possible histories, into a set of measurable histories. The single framework rule requires using a single histories framework to describe a history, but it does not require the same framework at all points in a history. A single histories framework can have different component frameworks to describe measurable states at different points in the system's history.

Implications: The CHI e-state is definite and complete. The CHI thereby rejects physically superposed o-states, but it introduces intrinsic indeterminism. This allows identical eigenstate o-states to diverge randomly to distinct eigenstates.

We can illustrate the intrinsic indeterminism of the CHI with the measurement of the obliquely polarized photon, described in Section II. The CHI describes the entire process, from the photon's initial preparation to its measurement, as a history with respect to a single histories framework. The single framework rule does not allow simultaneous descriptions of the process from different histories frameworks, but it does allow description of the photon from different frameworks at different points in its history.

At preparation, the CHI describes the photon with respect to the preparation's framework, as an obliquely polarized photon and definite eigenstate. At a subsequent point prior to measurement, the CHI describes the photon with respect to the vertically polarized filter's framework. It describes the photon from this vertical framework as an incomplete mixed m-state, and as an o-state consisting of either a vertically polarized photon or a horizontally polarized photon. Between these two points in its history, the o-state transitions randomly from a single eigenstate to one of its two possible o-states. There is no superpositioning of o-states, but there is indeterminism and a random selection of possibilities instead.

The physical indeterminism of o-states addresses one of the most perplexing questions facing physics: it provides an explanation for one of time's asymmetries. Indeterminism associated with refinement of the CHI framework involves the creation of new potential o-states and the random selection and actualization of these potentialities. Refinement and the creation of new potentialities describe a direction of rising entropy, from an initially known and complete e-state to an uncertain and incomplete m-state. This increase in entropy defines the arrow of refinement. It

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* The dimension of a tensor product of vector spaces is the product of the dimensions of the individual spaces. If any of the vector spaces are infinite (infinitely many possible states), then the tensor product space is also infinite dimensional.

corresponds to the thermodynamic arrow associated with increasing uncertainty and disorder, described in Section II.

Finally, whereas the previous interpretations either ignored instantaneous correlation or involved "spooky action," the CHI's single framework rule strips away any spookiness and provides a straightforward explanation. Griffith (2017) describes the entangled electron spin experiment with a simple analogy:

> Charlie in Chicago places a red slip of paper in an opaque envelope and a green slip in a second identical envelope, and after shuffling them chooses one at random and mails it to Alice in Atlanta and the other to Bob in Boston. Upon opening her envelope and finding a red slip, Alice can at once conclude from her knowledge of the protocol that Bob's envelope contains a green slip of paper. There is no need to invoke some superluminal influence to explain this.

The choice of measurement settings specifies the CHI's framework and the system's measurable eigenfunction e-states. From the completeness of the e-state (i.e. no hidden variables), it also defines the system's allowable o-states. This clearly illustrates the contextuality of quantum mechanics. The single framework rule limits the measurable results and physical o-states for Bob's and Alice's electrons to spin up and spin down parallel to the detector's orientation. If Bob measures a spin up, he instantly knows from the conservation of spin that Alice must measure a spin down*. The single framework rule means we can describe this experiment with respect to Bob's or Alice's choice of measurement orientation, but not both. The experiment's apparent spookiness arises as soon as we allow Bob and Alice to choose orientations independently and we try to mix these two incompatible frameworks into a single description, but this is forbidden by the single framework rule.

Are Any of These Interpretations Good?

Table 2 summarizes the conceptual models reviewed above. We ask: Are any of these interpretations good? We evaluate a model's goodness in part by its ability to explain the facts of measurement that we identified in Section II—indeterminism of measurement, the instantaneous correlation of measurements, and the asymmetries of time—in terms of underlying physical processes. A good conceptual model must also avoid unreasonable or contradictory implications. We apply these criteria to the interpretations discussed above to answer whether any of them make a good conceptual model of quantum mechanics.

* If Alice's measurement is parallel to Bob's, she will measure the opposite spin with 100% certainty. If she chooses a different orientation, her results will be statistical, but the statistics of multiple measurements will define the electron's spin before measurements as being opposite to Bob's. See Mermin, 1993.

Table 2. Summary of Conceptual Model Interpretations of Quantum Mechanics.

	e-model	e-state complete?	c-model deterministic?	Experimental facts explained	Conceptual model implications
CI	Wavefunction	Yes	Non-Committal	Offers descriptions only. No explanations	Not carried through
MWI (HCM)	Wavefunction	Yes	Yes	Indeterminism of measurement	Determinism, reversibility, and massively superposed universe
PWT	Wavefunction	No	Yes	Indeterminism of measurement; instant correlation	Determinism, reversibility, hidden variables; definite o-states; superluminal action
CHI	Eigenfunction	Yes	Contingent on framework	Indeterminism of measurement; Instant correlation Arrow of refinement	Contextuality and non-Unicity; definite o-states; single framework rule

The CI is a half-baked attempt to interpret quantum reality. The CI represents the wavefunction as an empirical model, expressing all that can be measured and known about a system, and accurately predicting the statistical outcomes of measurements. It also asserts that perfect measurement and the wavefunction e-state is a complete description of the actual o-state at the moment of perfect preparation or measurement, and that it can be physically superposed. However, the CI does not address the system's o-state between preparation and measurements, while it is isolated and unobserved, and it offers no physical explanations for any of the key experimental facts. The CI barely qualifies as a conceptual model, and certainly not as a good conceptual model.

The MWI and PWT both explain the first experiment fact, indeterminism of measurement. The MWI asserts that indeterminism of measurement is apparent, due to splitting of observers into separate branches. The PWT says measurement results are deterministically caused by hidden variables, but they are unknowable and this precludes us from determining measurement results. The PWT, but not the MWI, offers an explanation for the second experimental fact, the instantaneous correlation of measurements. Neither the MWI nor the PWT offers any explanation for the third and fourth experiment facts, time's asymmetries. The MWI and PWT both fall short on explaining the experimental facts.

The MWI and PWT also fall short in the reasonableness of their implications. The MWI implies a massively superposed and branching universe with no wavefunction collapse. While there is no way to prove that we, as observers, and our measurement devices do not split along diverging branches of a branching universe, we reject this implication as unreasonable. The PWT implies nonlocal action at a distance. The PWT does not violate Bell's theorem, and nonlocality does not experimentally violate relativity. Nevertheless, without an explanation for how action at a distance and special relativity are reconciled, we cannot consider this implication as reasonable.

If we reject the MWI and the PWT, this leaves us with the Consistent Histories interpretation. The CHI eliminates physical superposition and it allows for indeterminism of the o-state. Indeterminism provides a straightforward explanation for the first experimental fact, indeterminism of measurement, and for one expression of the thermodynamic arrow of time, the arrow of refinement. The CHI also provides a common-sense explanation for the second fact, instant correlations, which is fully compatible with special relativity.

The CHI achieves these simple common-sense explanations by the single framework rule. Griffiths (2017) describes the single framework rule simply as a syntactical rule, necessary to assign meaningful probabilities to a system's measurements. The CHI imposes the single framework rule to eliminate logical conflicts, in much the same way that the CI prohibits discussion of states and processes between points of preparation and measurements in order to avoid the problem of superposed cats. Griffiths (2017) describes the CHI as "Copenhagen interpretation done right."

The CHI's common-sense explanations of experimental facts come at a great cost, however. The single framework rule is the heart of the consistent histories interpretation, and this is its major source of controversy (Bassi and Ghirardi, 1999; Griffiths, 2000). Changing the selected framework changes the system's actual o-states. For example, the actual but generally unknown direction of polarization of a photon before measurement depends on the orientation of a polarizing filter used to describe it. And, Bob's choice of framework instantly determines the o-states physically available to Alice's electron.

These examples violate unicity. Griffiths (2017) describes unicity as the idea that "at any point in time there is one and only one state of the universe." Mermin (2013) expresses the controversy over non-unicity by comparing it with special relativity:

> I am disconcerted by the reluctance of some consistent historians to acknowledge the utterly radical nature of what they are proposing. The relativity of time was a pretty big pill to swallow, but the relativity of reality itself is to the relativity of time as an elephant is to a gnat.

Griffiths (2017) countered:

> Abandoning unicity is certainly a radical proposal, comparable in the history of science to the radical step our intellectual ancestors took when they replaced the centuries old notion of an immovable earth with the modern concept of a spinning planet in motion around the sun.[However,] it is what must be abandoned if the histories interpretation of quantum theory is on the right track.

What Griffiths argues needs to be abandoned is the idea that there exists an objective reality, independent of an agent's selected framework. Erwin Schrödinger, in a 1931 letter to Arnold Sommerfeld, presaged this idea when he stated (Fuchs et al., 2013):

> Quantum mechanics forbids statements about what really exists – statements about the object. Its statements deal only with the object-subject relation. Although this holds, after all, for any description of nature, it evidently holds in a much more radical and far reaching sense in quantum mechanics.

Schrödinger refers to Newtonian and relativistic mechanics when he says that the system-reference relationship holds for any description. However, in these cases, any inertial reference is equivalent to any other through a reversible transformation. These theories describe a reality that exists, independent of transformations or the particular reference chosen. When we try to apply this idea to quantum mechanics to describe a reality that is independent of whether we use Bob's or Alice's perspective, we run headlong into the issue of nonlocality. This was the CHI's motivation for establishing the single framework rule. The single framework rule immediately sweeps away the problem of nonlocality. QBism (Caves et al, 2002; Fuchs et al., 2013) is a more recent and stripped down version of CHI. It similarly eliminates paradoxes, by replacing the single framework rule with a corresponding rule that defines quantum reality relative to an individual agent's experience of quantum events.

The CHI and QBism introduce good ideas, but defining reality by an agent's experience or relative to her selected framework amounts to a rejection of objective reality. Can we achieve Bell's mission of reconciling nonlocality with special relativity, without simply sweeping it under the rug by abandoning objective reality? As we show in the next sections, yes we can.

VIII. Dissipative Dynamics of State

The interpretations of quantum mechanics that we have discussed up to this point leave us two choices. We can abandon the idea of an objective physical reality, independent of an agent's choice of framework or his experience of it; or, we can be left with intrinsic determinism, nonlocality, and no way to explain time's asymmetries. We seek a third way.

These interpretations all define perfect measurement at absolute zero, in the absence of thermal fluctuations. This one assumption eliminates thermal randomness and it equates total energy and work potential, thereby eliminating dissipation. The assumption of absolute zero ambient temperature underlies all of the interpretations previously discussed, and it underlies their shared failings. We refer to all of these as non-dissipative interpretations.

Crecraft (2017) proposed a new model of systems, which he called dissipative dynamics (**DD**). He argued that DD unifies the theories of classical and quantum mechanics, relativity, thermodynamics, and evolution into a single conceptual framework. Dissipative dynamics breaks from the previous non-dissipative models in that it explicitly defines perfect measurement and physical reality with respect to an ambient reference state at a positive temperature. We will see that DD shares key elements with the CHI without abandoning objective reality. It reconciles the contextuality of quantum mechanics with special relativity, eliminating the problem of nonlocality, and it accounts for all of time's asymmetries.

The Postulates of State

We start with the first three postulates of dissipative dynamics, the DD postulates of state:

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

Postulate 2: The c-state for a system in thermal equilibrium with its ambient surroundings is completely specified by properties measurable a perfect ambient observer.

Postulate 3: A general system's c-state is completely specified by perfect measurement, which is defined by a reversible process of transformation between the system's initial c-state and an equilibrium reference c-state at the ambient temperature.

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 is a statement about DD's conceptual representation of physical reality, the DD c-model and its c-state. Postulate 2 states that the c-state for any system in thermal equilibrium with its ambient surroundings is completely specified by what can be measured by a perfect observer and measurement device at the ambient temperature. This postulate formalizes the observer as an external agent in the ambient surroundings. The ambient temperature is a property of a system's actual ambient surroundings, but it is also the temperature of perfect measurement and observation.

Postulate 3 defines the c-state and perfect measurement as a reversible process of transformation between a system's initial state and an ambient reference state. Starting with the ambient reference c-state, which by Postulate 2 is perfectly measurable and knowable, reversing the measurement process completely restores the system's initial c-state as it existed prior to measurement.

Like the CHI, dissipative dynamics defines perfect measurement on an individual system. Consequently, there can be no superposed e-states. Since the c-state is completely specified by perfect measurement, there are no hidden variables, and the c-state is identical to the e-state at the moment of measurement.

We refer to the system's c-state rather than to its o-state, as we did before. This is because, for our non-equilibrium and non-isothermal universe, the ambient temperature for a system's conceptual model depends on where we delineate the system from its surroundings. Perfect measurement, the e-state, and the c-state's description of reality all depend on the ambient temperature and therefore on where we divide the system from its surroundings. Dissipative dynamics does not claim that physical reality itself depends on our delineation, however, and it does not deny objective reality. Dissipative dynamics recognizes that when we describe limited parts of the universe, the c-model is merely a representation and a simplification of objective reality. In particular, we generally ascribe a single fixed ambient temperature to the system's local surroundings, and we assume that this is a sufficiently complete representation of the system as it exists within that local environment. The ultimate and objective ambient "surroundings" is the cosmic microwave background, which permeates the fabric of empty space and is part of the universe.

The postulates of dissipative dynamics mean that we can only define a system's c-state with respect to an ambient reference. Einstein's theory of special relativity already tells us that physical reality, including even the sequence of events in time, is defined relative to an external inertial reference. Dissipative dynamics also defines the DD c-state relative to an external reference, but it includes a non-zero ambient temperature. When we include the ambient temperature, we can no longer reversibly transform one 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 CHI and QBism and abandon objective reality, dissipative dynamics alters the concept of objective reality by integrating the system with its actual (or in practice, with its simplified local) ambient surroundings. The ambient reference and temperature are an essential and inseparable attribute of a system's o-state and its c-model representation. A change in the ambient temperature changes the division of energy between ambient heat and work potential, and this cannot be reversibly transformed away without violating the Second Law of thermodynamics.

Special-Case C-Models

Dissipative dynamics provides flexibility to define realistic conceptual representations of various types of systems, including quantum and classical mechanical systems, equilibrium and non-equilibrium thermodynamic systems, and as we will see later, even evolving systems. These are distinguished by differing special-case surroundings, which define the system's allowable c-states. In this section, we describe special case c-models for various types of systems within the DD framework. Table 3 summarizes these special-case c-models.

Table 3. Special-Case Dissipative Dynamics C-Models

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

Classical Mechanical C-model: Classical mechanics does not recognize heat as thermal energy and it does not consider temperature as a property of state. 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 at the hypothetical limit at absolute zero. This allows for perfect and precise measurement of particles having precise coordinates of position and momentum and having no thermal fluctuations. This is the Hamiltonian idealization of classical mechanics.

Equilibrium Thermodynamic C-model: To illustrate the dissipative dynamic representation of an equilibrium thermodynamic state, we consider the DD c-model for a gas in equilibrium with its ambient surroundings at the system temperature. Perfect measurement by an ambient observer can record temperature, pressure, volume, and mass. These properties define the equilibrium thermodynamic state. 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 equilibrium 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 2, the system has no hidden variables, and the thermodynamic state completely defines the system as it exists with respect to its ambient surroundings.

Statistical Mechanical C-model: Dissipative dynamics allows us to describe the equilibrium thermodynamic gas statistically as a classical mechanical state in the hypothetical limit of absolute zero ambient temperature. Classical statistical mechanics actually describes two states. It defines the microstate by perfect measurement at a basis temperature equal to the ambient temperature at absolute zero. This defines the system as a classical mechanical state, where the positive system temperature is simply a measure of the average kinetic energy of the system's particles. The statistical mechanical microstate is the special case c-state of classical mechanical.

Statistical mechanics defines the macrostate by measurement of the same system at a basis temperature equal to the system temperature. This describes a thermodynamic state. With an absolute zero ambient temperature, however, the macrostate constitutes an imperfect measurement and incomplete description of the actual microstate. The macrostate is a DD m-state. It is not an e-state or c-state of dissipative mechanics.

The difference between the thermodynamic and statistical mechanical c-states highlights an important point. Both c-states have the same temperature, and therefore the same absolute energy*. The equilibrium thermodynamic c-model sets the ambient temperature to the system temperature. The system's energy is fully-thermalized ambient heat. Being thermalized means that energy is equilibrated and is randomly distributed among available energy levels†. Statistical mechanics, in contrast, sets the ambient temperature to absolute zero. In this case, there is no thermalization and no ambient heat. Statistical mechanics describes the gas as particles having kinetic and potential energies only, exactly as described by classical mechanics. Dissipative dynamics describes very different c-states and physical realities for the same gas, depending on the temperature of the ambient surroundings.

Non-Equilibrium C-model: Real systems are not in thermal equilibrium. There have been extensive efforts to extend equilibrium thermodynamics to describe non-equilibrium systems. Despite these efforts, there is no single comprehensive theory of non-equilibrium thermodynamics. A ubiquitous assumption among the various non-equilibrium formulations is the local equilibrium hypothesis. Local equilibrium says that a non-isothermal system is locally thermalized at the local temperature. Dissipative dynamics takes a totally different approach. The postulates of dissipative

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*Temperature is a measure of absolute energy, defined relative to absolute zero. For a quantum particle, this relationship is given by $E=k_BT$ where k_B is Boltzmann's constant. In thermodynamics, for a mole of ideal gas (containing 6.02×10^{23} particles), it is given by $E=RT$, where R is the universal gas constant, equal to $k_B\times$mole.

† The Boltzmann distribution function describes the distribution of energies as a probability function of temperature.

dynamics assert that the non-equilibrium c-state is thermalized at its single ambient temperature, and that this provides a complete description of a system as it exists within its ambient surroundings.

Dissipative dynamics allows us to define a system's work potential, or exergy, as a property of state for a non-equilibrium system. Exergy is defined by the work potential on the ambient reference state. Free energy, in contrast, is defined by work potential at the local temperature. Exergy, but not free energy, can describe a non-equilibrium system as a single integrated system with respect to a single ambient reference state. Exergy, but not free energy, is a property of state for dissipative dynamics. Ambient heat is the thermal energy at the ambient temperature, and it is also a DD property of state. Ambient heat has no capacity for work on the ambient surroundings, and it exists as a third form of energy, distinct from the potential and kinetic energies of the HCM and other non-dissipative interpretations.

Quantum C-model: A quantum system's ground-state energy is always positive. For a system comprising a single particle, the temperature is given by $T=\frac{E}{k_B}$, where k_B is the Boltzmann constant. Dissipative dynamics assumes that the quantum system's energy is thoroughly thermalized (E=Q) and it defines both a positive system temperature and an equal ambient temperature. Perfect measurement requires that the basis temperature is also equal to the system temperature. This is the special-case equilibrium thermodynamic c-model (Table 3) and it is also the special case DD c-model for quantum systems. Thermodynamics and quantum mechanics share the same conceptual framework; they differ only in the laws that govern respective systems' behaviors. Differences should be expected, based on their vastly different scales and finites ranges of applicability of their laws.

We illustrate the equilibrium thermodynamic c-model for a quantum system containing a hydrogen atom in equilibrium with its ambient surroundings at 800 kelvins. The hydrogen atom exchanges photons with its ambient surroundings. When the hydrogen atom's sole electron drops to a lower-energy orbital, it emits a photon. An electron can also absorb a photon and jump to a higher-energy orbital. At equilibrium, photons are constantly exchanged with the ambient surroundings, but there is no net transfer of energy. The system is in thermodynamic equilibrium with its ambient surroundings. In dissipative dynamics, the system is completely defined by the thermodynamic c-state with respect to its ambient temperature. Its energy and state are well defined and definite, as perfectly measured at the ambient basis temperature. Dissipative dynamics completely describes the hydrogen atom, and quantum systems generally, as a DD equilibrium thermodynamic c-state. The ambient and system temperatures are equal, and perfect measurement is at the system's ambient temperature.

Non-dissipative interpretations of quantum mechanics (the non-DD quantum model in Table 3), in contrast, recognize a positive energy and temperature but they assume a basis temperature of perfect measurement equal to absolute zero. For a basis temperature near absolute zero, multiple energy measurements on the hydrogen atom reveal a statistical mix of values, randomly distributed about its equilibrium energy value. Statistical measurements are simply an artifact of measuring a system having a positive ambient temperature with respect to a basis temperature at (or very close to) absolute zero. Non-dissipative interpretations of quantum mechanics attempt to interpret the statistical measurement results for an essentially thermodynamic quantum system within a conceptual foundation of mechanics. This is the source for assuming physical superpositioning and for quantum paradoxes. The actual thermodynamic character of the quantum state is the motivation for quantum interpretations based on information or entropy. These ranked the second most popular in the 2011 survey of quantum interpretations (Schlosshauer et al., 2013).

Thermodynamics' Arrows

Dissipative dynamics recognizes two distinct arrows of thermodynamics, each associated with increasing entropy: the arrow of dissipation and the arrow of refinement. Dissipative dynamics readily accommodates both. We first clarify Dissipative dynamics' concept of entropy.

Entropy: Dissipative dynamics defines a system's entropy with respect to an ambient reference state. Figure 2 shows the resolution of the dissipative dynamical entropy into two distinct components. The thermodynamic entropy is the entropy as originally defined by equilibrium thermodynamics. It defines entropy relative to a reference in thermal equilibrium with the system (see also equation 2). The basis entropy is defined relative to the ambient reference by integrating $\frac{dq}{T}$ from the ambient to the basis temperature.

We can extend this scheme to non-isothermal systems by partitioning a system and its basis reference into isothermal zones, and summing the thermodynamic and basis entropy components over all the zones. The entropy of a non-isothermal and non-equilibrium system is well defined with respect to the ambient reference.

Crecraft (2017) showed that, in the limit of absolute zero ambient temperature, the dissipative dynamical entropy is equal to the Boltzmann and Third Law entropies, defined with respect to absolute zero. The dissipative dynamical entropy is therefore a generalization of these entropies. Going forward, entropy, without qualification, will refer to the dissipative dynamical entropy.

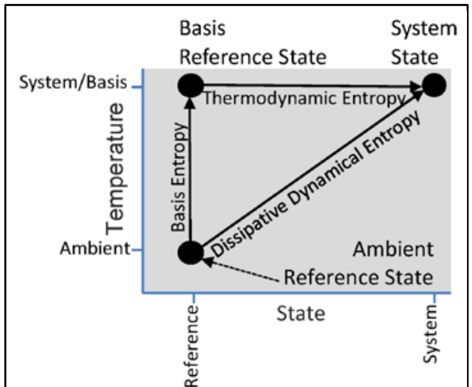

Figure 2. Two Components of Entropy.

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.

Arrow of Dissipation: As shown in Figure 2, entropy is defined relative to the ambient temperature. As described in equation 2, entropy is closely related to ambient heat. We can see from equation 2 that, for a positive ambient temperature, the irreversible production of entropy is associated with the irreversible dissipation of exergy to ambient heat. This defines the thermodynamic arrow of dissipation. Dissipative dynamics defines the arrow of dissipation for any non-equilibrium system having a fixed positive ambient temperature.

The universe has a positive ambient temperature and it has an arrow of dissipation. This arrow of dissipation points toward an eventual state of heat death for the universe when all energy is thermalized and unavailable for anything other than random fluctuations. William Thompson (1862), also known as Lord Kelvin, first expressed this idea, when he wrote:

> although mechanical energy is indestructible, there is a universal tendency to its dissipation… The result would inevitably be a state of universal rest and death…in which all the energy ends up as a homogeneous distribution of thermal energy, so that no more work can be extracted from any source.

Arrow of Refinement: Figure 2 shows that entropy is defined relative to an ambient reference. It follows that as the ambient temperature falls, the basis entropy and dissipative dynamical entropy both increase. The thermodynamic arrow of refinement expresses the increase in entropy with a falling ambient temperature.

The arrow of refinement in dissipative dynamics refers to the refinement of configuration space. Configuration space allows us to represent a system's spatial configuration geometrically as a single point. The configuration space for a classical mechanical system with a single particle spans three dimensions, one for each of the particle's coordinates of position. We can represent the configuration for a system of N particles by a single point in a 3N-dimensional configurational space[*]. The 3N axes of configuration space for classical mechanics are continuous, and a point in this configuration space specifies the spatial coordinates of the N particles with infinite precision.

To see how refinement of configuration space relates to the increase in entropy with a falling ambient temperature, we start with the configuration space for a classical mechanical system. If we maintain the system's basis temperature of measurement at absolute zero but raise its ambient temperature, individual measurements, conducted at absolute zero, are still precise, but the system and its configuration space become increasingly "pixelated." Thermalization at a positive ambient temperature blurs the system's spatial configurations from discrete points to finite-pixel probability distributions. If we increase the ambient temperature to equal the system temperature, the probability distribution pixel expands to the point that it spans the entire configuration space. For a classical mechanical system, the single-pixel probability function is the thermodynamic state, as measured at absolute zero. For example, the classical mechanical description of an ambient gas describes the gas particles statistically, as just being somewhere within its configuration space. This defines a complete description of the gas at its ambient temperature and it defines a single pixel spanning all of its configuration space. For a quantum system, this probability-function pixel is the eigenfunction, which completely describes the system's state and its configuration as a single pixel in its 3N-dimensional configuration space.

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[*]Hamiltonian classical mechanics treats elementary particles as points with no orientations. A Newtonian system with N rigid bodies would require a 6N-dimensional configuration space to describe each body's position and orientation in space. Configurational space specifies a system's configuration, but not its complete state. It does not specify the particles' motions.

From postulates 2 and 3, a falling ambient temperature reduces the thermalization of a system's c-state and this increases the resolution of the system and its configuration space. Increasing the resolution and the number of possible configurations mean that the system's actual configuration is increasingly uncertain. This describes the increase in the system's entropy with falling ambient temperature. The spontaneous increase in entropy drives falling ambient temperatures and the arrow of refinement.

The indeterminate decay of a radioisotope provides a specific example of the creation of new potentialities with a drop in the ambient temperature. During a radioisotope's synthesis inside a supernova or merging neutron stars, it existed in or near equilibrium with its very hot ambient surroundings as a definite radioisotope c-state. Its potentially measurable c-states under laboratory conditions at much lower ambient temperature include its many possible decay-state configurations, only one of which is eventually actualized. A drop in ambient temperature led to higher resolution of its configuration space and to the creation of new potentialities. This illustrates the arrow of refinement and the second arrow of thermodynamics' second law.

The radioisotope's high exergy illustrates a second effect of the arrow of refinement; a falling ambient temperature allows continuous reclamation of exergy from previously hotter ambient heat. This effect accounts for the high exergy of the radioisotope, and it provides a brake on thermodynamics' first arrow of dissipation.

Instant Correlation

In the thermodynamic limit, the dissipation of exergy is continuous. This describes, for example, the irreversible dispersion of a chemical or thermal gradient. In quantum mechanics, in contrast, dissipation is discontinuous. Discontinuous dissipation occurs during the spontaneous decay of a radioisotope or the irreversible transition of an electron to an equilibrium ground state. Dissipation in these cases marks the discharge of a quantum of energy and its loss to the ambient surroundings. For quantum mechanical systems, the thermodynamic arrow of dissipation is discontinuous, with periods of metastability, separated by discontinuous and irreversible transitions.

During periods of metastability, a system is not truly at equilibrium, but like equilibrium, there is no dissipation and no production of entropy[*]. At true equilibrium, the forward and backward directions of any process occur at precisely the same rate. This defines equilibrium. Dissipative dynamics asserts that the lack of entropy production during intervals of metastability likewise implies time symmetry[†]. This leads to the segmentation of time into reversible intervals of time symmetry, separated by irreversible discontinuities. Each interval of reversible time represents a single discontinuous instant of irreversible time.

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[*] Throughout this discussion, we assume a constant ambient temperature and isolation from external perturbations other than ambient heat exchange.

[†] This is postulate 4 of dissipative dynamics, discussed in the next section.

Pusey and Leifer (2017) argue that any time-symmetric* system must also be retrocausal. With time symmetry, there is no distinction between past and future, and effect can precede cause as easily as cause precedes effect. They acknowledge that the universe is not time-symmetric, and that time symmetry can only apply to special cases. Within the framework of dissipative dynamics, time symmetry applies to equilibrium and to the intervals of metastability between irreversible transitions.

Pusey and Leifer argue that retrocausality can explain nonlocality without conflicting with relativity. Figure 3 illustrates this idea using the entangled electron experiment. At point C, midway

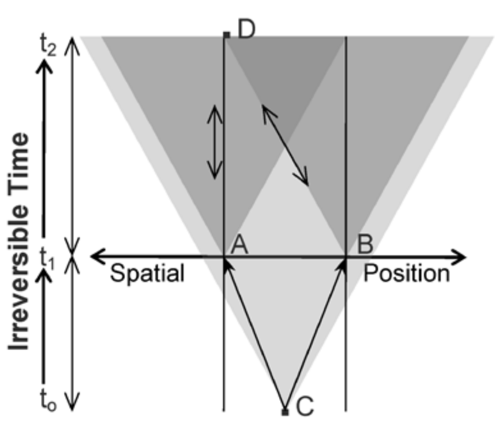

Figure 3. Not-so Spooky Action at a Distance

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 linked through a chain of forward and retrocausality.

between Alice (position A) and Bob (position B), a pair of entangled electrons is emitted in opposite directions toward Alice and Bob. This is a spontaneous event, marking the beginning of an interval of metastability at time t_o. The electrons travel toward Bob and Alice at less than the speed of light without environmental perturbation. At time t_1, they simultaneously and irreversibly interact with Alice's and Bob's detectors. This marks an irreversible transition from one interval of metastability and time-symmetry to a new interval of metastability. Measurements are irreversible and imperfect. Each measurement indeterminately selects and actualizes a spin direction either parallel or anti-parallel to the detector. Each measurement marks a spontaneous cause, and the start of a new light cone of potential effects. The measurements are made in spatially separated light cones, so there is no way that one measurement can directly influence the other at the instant of their measurement.

Bob's receipt of Alice's measurement result at time t_2 marks the point D, at which he intersects Alice's light cone. Between times t_1 and t_2, there is no dissipation and the system evolves within an interval of time-symmetry. If Bob receives Alice's result and maintains time symmetry throughout, their individual measurement results are time-symmetrically linked through a chain of forward and retrocausality. This ensures their consistent histories. The correlation of events within an interval of time-symmetry is instantaneous only in the "instant" of irreversible time that spans that interval of time-symmetry.

* They distinguish between the "usual notion" of time symmetry, which we refer to as reversibility in this paper, and a "stronger notion" of time symmetry, which is the notion used in this paper.

Is Dissipative Dynamics a Good Model of State?

The dissipative dynamics c-model is flexible. Depending on the boundary constraints imposed by the system's environment, it can encompass the theories of relativity, quantum mechanics, or thermodynamics as special cases. These theories have all been thoroughly vetted, and their vetting immediately extends to their dissipative dynamic interpretations. The special-case dissipative dynamics models are fully vetted experimentally.

The general DD conceptual model, furthermore, fully explains the first three key experimental facts. It accommodates and explains indeterminism of measurement, it reconciles relativity with the contextuality of quantum mechanics, and it explains both arrows of thermodynamics. DD's implications are also reasonable. It avoids instantaneous action at a distance; it recognizes objective reality (but rejects Hamiltonian reality defined with respect to absolute zero); and it accommodates intrinsic indeterminism. Dissipative dynamics unifies classical, quantum, relativistic mechanics and thermodynamics within as special cases within an integrated conceptual framework. By these criteria, dissipative dynamics is an excellent model of state. But as we will see in the next section, there is more. Dissipative dynamics also embraces evolving systems. It explains the key experimental Fact #4 for the emergence and evolution of complexity.

IX. Evolving Complexity

So far, we have only addressed states. The second law of thermodynamics describes the relative stability of states of higher entropy over states of lower entropy. The arrow of emerging complexity, in contrast, addresses the stability of processes. We need to shift our attention to the description of processes. We start by introducing postulates 4 and 5 for dissipative processes:

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

Postulate 5: The rate of entropy production of the whole equals the sum of entropy productions of the parts.

Postulate 4 reformulates the second law of thermodynamics in terms of entropy production. Postulate 4 establishes entropy production as the driver for irreversible process. It drives both thermodynamic arrows of dissipation and of refinement. The production of entropy also provides a system-specific measure for the passage of irreversible time, whether continuous, for a thermodynamic or biological system, or discontinuous, for a mechanical system. Postulate 5 expresses a "conservation" of entropy production. It states that, in terms of entropy production, the whole equals the sum of its parts. Postulates 4 and 5 do not address the relative stabilities of irreversible processes or the arrow of emerging complexity. We introduce them only to formally establish irreversible dissipative processes and a basic property of dissipative process.

The Emergent C-State

The emergent c-state is another idealization and simplification of reality. It represents a step forward from the previous c-states in generalizing the dissipative dynamics c-state to make it more broadly applicable for representing real systems, as they exist in real environments. Like the non-equilibrium c-state, the emergent c-state assumes a stationary environment with a fixed ambient temperature, but the surroundings for the emergent c-state is non-equilibrium and includes exergy sources. These stationary sources sustain flows of mass and exergy through the system. Over time, the system converges to a stationary process of dissipation, sustained by stationary exergy sources and an ambient sink for waste and heat discharge. This is the emergent c-state.

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. And, 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 rates are balanced and the time-averaged properties are constant. Crecraft (2017) refers to these stationary systems as homeostates.

The gas-filled chamber in the Miller-Urey experiment illustrates an emergent c-state. The gas is open to input of high-exergy electrical sparks and output of heat. The homeostate emerges when the system converges to a stationary process, at which point the average rate of synthesis of complex molecules from simple molecules equals the average rate of breakdown of the complex molecules to simpler ones. (It is unlikely that the actual experiment ever reached this point.)

The emergent c-state describes a system that is open to fluxes of mass and exergy from its surroundings. 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. Lars Onsager (1931) showed that a near-equilibrium system with steady-state boundary constraints converges to a unique steady-state dissipative process at the minimum point in the system's entropy production rate well[*]. The minimum entropy-production point is the system's steady-state solution to its boundary constraints in the near-equilibrium linear regime. The near-equilibrium homeostate emerges when the system reaches steady state.

Far from equilibrium, linearity breaks down. At a critical temperature gradient, for example, heat flow through a liquid increases dramatically as the heat flow transitions to 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 possible homeostates for a given boundary constraint. This creates another opportunity for indeterminate selection. However, whereas the arrow of refinement offers a selection of states, the arrow of emerging complexity offers a selection of homeostates.

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[*] We can express the rate of entropy production as a function of system variables. The entropy production well is the graphical representation of entropy production rates over a hyperplane spanning the system's pertinent variables.

The Kelvin Selection Principle

The arrow of emerging complexity does not arise simply from random selection. In Darwin's theory of evolution, evolution requires more than random variations. It requires a goal-oriented principle of selection. Dissipative dynamics' arrow of emerging complexity similarly requires a goal-oriented selection principle. Lord Kelvin suggested such a principle in the same 1862 article in which he described the heat death of the universe.

After Kelvin described the idea of heat death, he 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 to a future time— "and hence into heat" —and instead to utilize exergy for palpable work. If a source of exergy defers dissipation by doing palpable work on some other non-equilibrium system, then that system could likewise defer its dissipation and do work on other systems. The recursive deferral of dissipation for work to sustain other dissipative systems would lead to an expanding network of connected systems and increasing organization. This idea expresses the arrow of emerging complexity.

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

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

Crecraft (2017) defines utilization for a network of dissipative nodes as the sum of exergy inputs to dissipative nodes within the network. Dissipative nodes are the emergent c-state's elementary dissipative units, for which we can only measure and know the inputs and outputs of energy and material components. Nodes represent transitions of energy and material components; they have no storage capacity. Exergy inputs can come from external sources and from other nodes within the system. Exergy inputs include direct exergy inputs and the exergy of material component inputs.

Postulate 5 and the conservation of energy mean that the total dissipation by the dissipative nodes is equal to the network's net exergy supply. Any principle of evolution based on dissipation or entropy production rates is really about expanding net exergy supply or reducing the ambient temperature. By deferring dissipation and recycling exergy among networked systems, however, the nodes' total utilization is not bound by the network's net exergy supply rate. In terms of utilization, the whole can exceed the sum of its parts, with no upper bound in the limit of perfect efficiency. 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. The Kelvin section principle

(**KSP**) selects homeostates of increasingly higher utilization and higher complexity, even when the net exergy supply is fixed.

The KSP can provide us insight into the emergence of complexity in the Miller-Urey experiment. We can represent the system as a network of dissipative nodes, linked by exchanges of low-exergy gas particle reactants, of high-exergy amino acid products, and of exergy. Exergy is released to the network by the external sparks and by the action of exergonic[*] nodes on high-exergy inputs. The KSP guides the system to recycle exergy and components between endergonic and exergonic nodes, and to minimize the nodes' internal dissipative demands, leading to higher-exergy outputs and higher utilization. Although the kinetic details are complex, random kinetic explorations and selections by the KSP guide the system toward higher utilization. Endergonic nodes take low-exergy reactants and utilize exergy from the network to output high-exergy amino acids. Exergonic nodes break amino acids down to their low-exergy components and release exergy back to the network. The external supply of exergy provides the nodes' internal dissipative demands and sustains the entire process.

The KSP is a principle of natural selection for the physical world. It guides the evolution of emergent c-states toward higher complexity by the progressive selections of homeostates of higher exergy utilization. As the system evolves, it expands with the addition of new nodes and new energy pathways. The KSP selects new homeostates of higher utilization and complexity from the adjacent possible. Complexity evolves organically, from the simple to the complex. Crecraft (2017) provides examples and models of evolving complexity in fluid dynamic and chemical systems, in ecological succession, and in social systems involving cooperation and competition. He shows that when external sources of exergy are available, the KSP drives expansion to capture those sources and increase net exergy supply. When sources are constrained, the KSP drives internal organization, recycling of resources and higher efficiency. The KSP underlies the drive for self-organization and the arrow of emerging complexity.

The KSP is only an interim principle. The emergent c-model and utilization are both defined with a stationary ambient temperature, and the c-model is still a simplification of reality. More general c-models would account for changing ambient temperatures, or even multiple overlapping and spatially variable ambient temperatures. A more general principle of selection would be needed to apply to these more general and realistic c-model representations of the real world. Nevertheless, The KSP and the emergent c-state provide an accurate description of evolution for systems within stationary non-equilibrium environments.

[*] An exergonic node takes a high-exergy component and transforms it to a lower-exergy state. It outputs any exergy remaining after its internal dissipation requirements. An endergonic node utilizes exergy from an external source or exergonic node to do work of taking a low-exergy component input and transforming it to a higher-exergy state.

X. The Emergent Universe

The present-day universe exists with respect to the existing ambient cosmic microwave background. During the instants following the Big Bang, this background was intensely hot and we would expect that the universe was initially thermalized and near equilibrium at these extremely hot ambient surroundings*. Entropy in dissipative dynamics is defined with respect to the ambient reference, so a near-equilibrium universe is also a low-entropy state. Low entropy, however, does not mean low probability. Near-equilibrium, in fact, means high probability. An initial equilibrium zero-entropy state would have spanned the universe's single-pixel configuration space. A single pixel means that it would have been selected and actualized with 100% probability.

A spontaneous increase in entropy would lead to the expansion of the universe, the falling cosmic microwave background temperature, and the refinement of the universe's configuration space. The current ambient temperature of the cosmic microwave background temperature is 2.7 kelvins. This temperature has declined from the very high temperatures at the Big Bang, and it will continue to decline as the universe continues to expand. Expansion, ambient cooling, and refinement of the universe's configuration space, driven by the increase in entropy, have led to the creation and actualization of new potentialities.

Actualization, guided by the KSP or a generalization of the KSP†, led to a condensation of the universe's initial hot ambient energy into high-exergy particles. These particles later coalesced into hydrogen atoms to become the fuel for the stars. A star progressively transforms high exergy atoms into lower exergy atoms. Partial deferral of dissipation of this process by the output of high-exergy photons provides an exergy source for the star's planets and interplanetary dust clouds.

Michaelian (2017) and references therein detail the kinetic and thermodynamic processes by which photon-stimulated micro-dissipative structuring has produced complex organic molecules in dust clouds throughout the galaxy and on the early earth's surface. The solar exergy source continues to sustain exergy gradients and give rise to dissipative processes and homeostates within the Earth at all scales, from chemical and biological activity to the global climate and chemical cycles. The selective pressure of the KSP to defer dissipation has led to the organization of isolated dissipators into networked webs of energy flows and to the evolution of homeostates of ever-increasing complexity and organization. This has led, in at least one case, to intelligent life, which continues to seek new exergy sources and to create and expand organizations.

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* The ambient "surroundings" for the universe is the cosmic background radiation within the universe. Dissipative dynamics therefore describes the universe with respect to an ambient reference within, not external to, the universe.

† The KSP is defined for a fixed ambient temperature. We need a generalization of the KSP for a more realistic explanation of the evolution of an expanding and cooling universe.

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