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A Contextual Foundation for Mechanics, Thermodynamics, and Evolution

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Abstract: The prevailing interpretations of physics are based on deeply entrenched assumptions, rooted in classical mechanics. Logical implications include: the denial of entropy and irreversible change as fundamental physical properties; the inability to explain random quantum measurements or nonlocality without unjustifiable assumptions and untestable metaphysical implications; and the inability to explain or even define the evolution of complexity. The dissipative conceptual model (DCM) is based on empirically justified assumptions. It acknowledges the contextual relationship between a physical system and its positive-temperature ambient background, and it extends HCM descriptions by defining entropy and exergy as objective contextual properties of state. The irreversible production of entropy establishes the thermodynamic arrow of time and a system's process of dissipation as fundamental. The DCM defines a system's measurable rate of internal work as an objective measure of stability of dissipative process. A dissipative system can follow either of two different paths leading to higher stability: 1) increase its exergy supply or 2) improve its function utilizing its existing exergy supply. The evolution of life proceeded both by competition for resources and by cooperation to evolve and sustain higher functional complexity.

Keywords: Physical Foundations; Quantum mechanics; Nonlocality; Time; Entropy; Thermodynamics; Origin of Life

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1. Introduction

Physics has had a foundational crisis since the early Twentieth Century, when classical mechanics ceded its supremacy to quantum mechanics and relativity as fundamental descriptions of physics. Four conceptual problems that highlight this crisis are: 1) the problem of time, 2) the problem of contextuality of physical reality, 3) the problem of measurement, and 4) the problem of nonlocality.

1.1 The Problems of Time

Perhaps the most fundamental conceptual issue facing physics concerns the nature of time [1-4]. Relativity describes time as a dimension of spacetime, and like the three dimensions of space, time has no preferred direction. Change within spacetime is reversible and deterministic. Reversibility means that there is no fundamental arrow of time, and determinism means that the future is determined by the present. The future, as well as the past, is set in stone.

Determinism is a logical consequence of classical mechanics. Classical mechanics defines the **microstate**, which expresses everything that is measurable and empirically knowable about a system, by perfect measurement in the absence of thermal noise. Perfect measurement reveals (in principle) the precise positions and motions of a system's parts and the forces acting on them. Application of the equations of motion to a precisely defined microstate leads to fully deterministic change across all time, past and future.

Determinism does not by itself imply reversibility. Newton's laws of mechanics do not include conservation of energy. Newtonian mechanics did not recognize heat as energy, and it accommodates the dissipation of mechanical energy by frictional forces as an irreversible loss of mechanical energy, which is not conserved.

Reversibility is a consequence of what I refer to as the Hamiltonian conceptual model (**HCM**). The HCM goes beyond the empirical laws of Newtonian mechanics by resolving a system into elementary particles, which have no internal parts. With no internal parts to vibrate or interact, a particle's internal energy is limited to its rest-mass energy. A particle's energy equals the sum of its kinetic energy, potential energy, and rest-mass energy. These are quantified by their potential for work, so the conservation of energy means the conservation of work potential.

The conservation of work potential, along with determinism, imply that we could, in principle, reverse the motions of a system's particles and reverse its evolution without external work. This is the definition of reversibility. Classical mechanics assumes that the microstate is a complete specification of the system's actual underlying **physical state**. The determinism and reversibility of the HCM microstate therefore extends to the physical state, as it exists in isolation and unperturbed. The HCM extends the determinism and reversibility to isolated physical states in quantum mechanics and relativity, as well.

A system's changes may be reversible, but reversibility does not by itself imply equal probabilities for directions of change. Physics acknowledges the empirical arrow of time, as recorded by the increase in entropy. Boltzmann defined entropy by a system's disorder, which he related to the number of accessible microstates consistent with its thermodynamic **macrostate** description. The macrostate is defined by the coarse graining of detailed measurements, such as due to thermal noise. He described the increase in entropy as the statistical tendency for large numbers of initially ordered particles to disperse and become increasingly disordered. The particles' motions and increasing entropy could, however, be reversed in principle. The HCM therefore regards entropy and its increase as emergent properties of a macrostate and its imperfect description, and not as fundamental properties of physics. This is the idea raised by Maxwell's Demon [5], which could reverse the increase in entropy without violating any fundamental laws of physics.

In his book, *The End of Certainty* [6] (see also [7]), Ilya Prigogine sought to extend classical and quantum mechanics to accommodate irreversibility and the thermodynamic arrow of time as fundamental. He asserted that statistical descriptions for both classical and quantum systems are necessitated by two key factors: instabilities and "persistent interactions." He detailed the mechanical instabilities related to Poincare resonances, and he attributed persistent interactions to sustained environmental fluctuations. Prigogine argued that these two factors mark the end of certainty and establish irreversibility and randomness as fundamental properties. Environmental fluctuations may be unknowable, but within the HCM, they are deterministic. Prigogine's conclusion may be correct, but he failed to substantiate his assumption for the fundamental randomness of environmental fluctuations.

The thermodynamic arrow of time is not the only empirical arrow of time. The universe has evolved from a nearly homogeneous state following the Big Bang to its current state of extraordinary diversity and complexity. In our own corner of the universe, prebiotic chemicals evolved into self-replicating life forms as early as 0.1 billion years after formation of the Earth's oceans [8]. Diverse ecosystems have subsequently spread throughout the oceans and across the globe. Much more recently, humans have evolved culture, technology, and a global economy. These trends exemplify the empirical arrow of evolving complexity.

If the universe is strictly deterministic, then the existing complexity of the universe must have been encoded in the initial state of the universe. The origin of such a finely tuned initial state and the consequent complexity of our universe, however, defy physical explanation. There is not even a clearly defined physical measure for a system's complexity. The failure to account for the universe's state of extraordinary complexity has motivated interest in the idea of a multiverse and the anthropic principle, in which our universe is a rare statistical outlier that has allowed us to exist and ponder its origin [9].

With the HCM's reversibility and determinism of the physical state, there is no fundamental arrow of time, and there is no irreversible dissipation or evolution of complexity. There just is. The HCM views reality as a static block in 4D spacetime spanning the past, present and future. This is the block model of the universe, and it provides the conceptual foundation for Eternalism [2,10,11], in which all time, past and future, exist and are equally real. The emergence of empirical arrows of time from the fundamental reversibility of physical laws is the unresolved conceptual problem of time.

1.2 The Problem of Contextuality

The microstate and physical state in classical mechanics and relativity are independent of an observer's inertial reference frame, aside from an information-preserving Galilean or Lorentz transformation. This means that the physical state for classical mechanics and relativity can be defined independent of the physical reference frame and is therefore **non-contextual**.

With the discovery of quantum phenomena in the early twentieth century, it became clear that the laws of classical mechanics break down for very small particles, and a new theory was needed. Individual quantum measurements are described as eigenfunctions of a quantum operator corresponding to an observable property. An eigenfunction describes an eigenstate's definite measurable properties. Individual energy measurements, for example, are definite and are described by eigenfunctions of the Hamiltonian operator.

The Kochen-Specker theorem [12] proved that individual quantum measurement results are contextually dependent on the measurement framework. Individual measurements on an ensemble of identically prepared polarized photons, for example, contextually depend on the orientation of the detector's polarization.

The HCM restores non-contextuality by defining the pre-measurement microstate as a superposed wavefunction, comprising a statistical superposition of individual measurement results:

$$\Psi = \sum c_i \psi_i . \tag{1}$$

The ψ_i are measurable eigenstates, Ψ is the superposed wavefunction, and the c_i's are complex weighting factors based on quantum-state tomography [13]. This uses statistical measurement results on an ensemble of identically prepared systems and the Born rule to reconstruct the system's microstate as it existed prior to measurement, in isolation and independent of the measurement framework. Following classical mechanics, the HCM takes the microstate as a complete specification of the physical state. The physical quantum state is therefore also taken to be independent of the measurement framework and therefore non-contextual. The costs of non-contextuality, however, are the problems of time, measurement, and non-locality.

Not all interpretations of quantum mechanics adhere to the HCM assumptions. The Consistent Histories Interpretation [14], for example, asserts that physical states are defined by eigenstates, which are contextually defined by the system's measurement framework. In Quantum Bayesianism [15], the state is contextually defined and updated by an observer's information. Contextual interpretations are motivated by efforts to resolve the outstanding conceptual problems of quantum mechanics, but they typically come at the cost of abandoning the objectivity of physical reality.

1.3 The Problem of Measurement

Observation of measurement results for an ensemble of identically prepared radioactive particles, subsequent to their preparation, reveals a statistical mix of decayed and undecayed microstates. If the superposed wavefunction is just an empirical approximation of the system's actual microstate, then the collapse of a superposed wavefunction to a mixture of definite microstates simply reflects a change in the system's description, based on new information acquired at observation.

However, the HCM regards the wavefunction as a complete specification of the underlying physical state. The determinism and completeness of the wavefunction description implies that as long as a system remains isolated from external perturbations or observation, there can be no randomness. This, in turn, implies that the random collapse of a pure wavefunction to a statistical mix of eigenstates can only occur after the system's isolation is violated, such as when we observe a system or its measurement results.

Erwin Schrödinger tried to highlight the absurdity of equating a superposed wavefunction with a system's physical state. He considered a perfectly isolated system comprising a radioisotope and its measurement apparatus. For added drama, Schrödinger used a cat for the measurement device. If the particle decays, the cat dies. At observation, we either find a dead cat, indicating that the particle decayed, or we find it alive, indicating no decay. Equating the physical state with a superposed wavefunction, as asserted by the then-emerging Copenhagen Interpretation, implies that the radioisotope and cat exist as a physically superposed state of undecayed-decayed and live-dead as long as they remain isolated and unobserved. Schrödinger rejected the Copenhagen Interpretation of physical reality and the superposition of physical states, and he proposed his experiment to illustrate the absurdity of its implications. The Copenhagen Interpretation nevertheless remains the mainstream interpretation of quantum mechanics.

Hugh Everett proposed an alternative HCM interpretation that avoids the absurdity of superposed cats. In essence, his Many Worlds Interpretation [16] says that everything that can happen does happen in separate branches of an exponentially branching universe. Even we, as observers, are split. Each of our split selves observes our own particular branch and sees only a single outcome. We perceive random wavefunction collapse, but from the objective perspective of the universe as a whole, there is no random selection, and the universe evolves deterministically. The Many Worlds Interpretation trades the absurdity of superposed cats for an exponentially branching universe instead.

Both of these interpretations are consistent with observations, and despite their untestable and counterintuitive metaphysical implications, they ranked well in a survey at a foundations of quantum mechanics conference [17]. The measurement problem and the role of the observer on triggering the apparent randomness of observed results nevertheless remain unresolved and highly contested conceptual problems of quantum mechanics [18].

1.4 The Problem of Nonlocality

Closely related to the measurement problem is the unresolved issue of the violation of locality by quantum mechanics [19]. Locality asserts that effects cannot propagate superluminally from a cause. Numerous Bell-type experiments, however, demonstrate the physical reality of nonlocality [20,21]. Experiments show that measurements on spatially separated but entangled particle pairs are correlated, even if measurements are spatially separated and simultaneous. Nonlocality cannot be used to transmit signals superluminally, and there is no empirical conflict with relativity. However, there is no consensus explanation for how quantum nonlocality and relativity can coexist, and this poses a significant and unresolved conceptual problem [19,22].

1.5 We Need a Better Conceptual Model

The nature of a system’s physical state, while it is isolated and unobserved, cannot be resolved experimentally. It is strictly a matter of the assumptions on which experimental results are interpreted. The HCM interpretation is consistent with observations, but its implications are problematic. Its implications include eternalism, the measurement problem, non-locality, and an exquisite fine tuning of the universe’s initial state needed to simultaneously reconcile fundamental reversibility with time’s two empirical arrows of increasing entropy and increasing complexity.

Any viable interpretation of quantum mechanics necessarily makes predictions consistent with observations. This begs the question of what difference any particular interpretation really makes? There has been a strong sentiment among some physicists to dismiss the philosophy of science. Richard Feynman is credited with saying: “The philosophy of science is as useful to scientists as ornithology is to birds.” Efforts to understand the meaning of quantum mechanics are countered with the edict: “Shut up and calculate!” [23].

We take a different position. Seeking an objective interpretation of physical reality is more than an idle intellectual exercise, and it has real-world consequences. The universe is not a static block in spacetime, unchanging for eternity. Recognizing the objective reality of irreversible dissipative processes and explaining their behavior in terms of fundamental physical principles is essential if we want to understand how nature works. To advance physics beyond its current focus on states, we need a conceptual model that embraces irreversible dissipative processes and the spontaneous self-organization of dissipative systems. This requires nothing less than a major shift in our interpretation of physical reality.

2. The Dissipative Conceptual Model of State

The dissipative conceptual model (**DCM**) is an alternative to the HCM's interpretation of physical reality. Like any conceptual model, the DCM is an axiomatic system based on simple postulates, which it assumes to be true. A conceptual model of physical reality must be consistent with observations and it must accept basic empirical laws of Nature as axioms. A model seeks to explain empirical observations in terms of its assumptions and interpretation of reality.

None of the prevailing interpretations of quantum reality explains time's arrows, the measurement problem or nonlocality, while also maintaining an objective physical reality. This is a direct consequence of the Hamiltonian conceptual model's assumptions, rooted in classical mechanics. The DCM takes a very different approach. Whereas the HCM is based on the idealizations of mechanics and interprets thermodynamics and its Second Law as a statistical approximation of mechanics, the DCM accepts the empirically documented and universal principles of thermodynamics as fundamental physical truths.

2.1 The Postulates of State

The DCM's interpretation of physical state is based on the following postulates and definitions:

Postulate 1: No system has surroundings at absolute zero temperature and no system can be perfectly insulated from its surroundings at a positive ambient temperature.

Definition 1: A system's ground state is defined by thermodynamic equilibrium with the system's ambient surroundings.

Definition 2: Perfect measurement is a reversible transformation from a system's initial state to its ground state.

Postulate 2: There are no unobservable "hidden" variables. Perfect reversible measurement therefore provides complete information on the system's physical state.

Postulate 3 (1st Law of Thermodynamics): The total energy for a system plus its surroundings is conserved. A system's energy is conserved in the limit of perfect isolation.

Postulate 4 (Generalized 2nd Law of Thermodynamics): Any irreversible transition between states is associated with the production of entropy.

The postulates and definitions above as accepted as true. They are the logical foundation for the DCM and its implications.

Postulate 1 says that absolute zero temperature can be approached, but it is an unattainable idealization. No system is perfectly isolated from its surroundings and all systems have a potential to interact with their surroundings at a positive ambient temperature. The universe, by definition, has no surroundings, but its ambient cosmic background temperature at 2.7 kelvin permeates the vacuum of space, and this defines its ambient temperature.

Definitions 1 and 2 define perfect measurement by a reversible (and information preserving) transformation between a system and its ground-state reference (Figure 1). Perfect measurement involves an ambient agent or device to reversibly record the system's changes during measurement. By recording the transformation process and then reversing it, a perfect ambient observer can reverse the process and restore the system to its initial state. The same change in state can occur without an ambient observer, but with no mechanism for reversing the measurement, the system's state cannot be restored, and the process is irreversible. In the limit of perfect reversible measurement and its reversal, the system's initial state is left undisturbed.

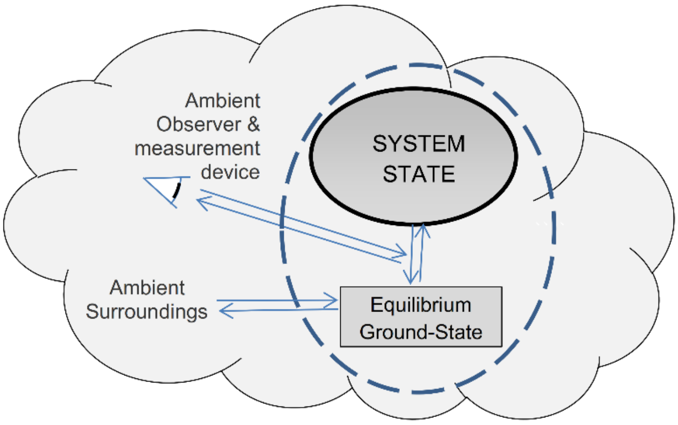

Figure 1. Dissipative Conceptual Model of State. The DCM defines a system's state relative to its equilibrium ground state and within the context of its ambient surroundings. Perfect measurement is a reversible transformation from the system's state to its ground-state reference in equilibrium with its ambient surroundings. Perfect reversible measurement involves an ambient observer or measurement device to record the process of physical change in state. Reversing the process restores the initial pre-measurement state.

The possibility of perfect reversible measurement is necessary for the definition of a microstate, but reversible measurement is not always possible. The Quantum Zeno effect shows that a continuously measured (and measurable) state does not change irreversibly [24]. The contrapositive of this is equally true: an irreversibly changing system is not continuously measurable. A system can be continuously measurable and reversible *between* irreversible transitions, and it exists as a state. But during transition a system is not continuously and reversibly measurable, and it therefore does not exist as a DCM state. It is in transition between states.

Postulate 1 and the definition of perfect measurement allow us to partition a system's total energy into energy components, given by:

$$E = Q_{gs} + E_{sys} = Q_{gs} + X + Q. \tag{2}$$

Ground-state energy, Q_{gs}, is the positive energy of the ambient ground state reference relative to absolute zero. Any excess energy is the system energy, E_{sys}. The DCM further partitions system energy into exergy (X) and ambient heat (Q). Exergy is defined by the potential work that can be done on the ambient surroundings. Ambient heat is heat at the ambient temperature, and it has zero potential for work on the ambient surroundings. The total energy and ground-state energy are defined relative to absolute zero, but the system energy, ambient heat, and exergy are contextually defined relative to the ambient ground state, which sets their zero values.

Exergy includes all potential and kinetic energy, and thermal exergy, X_q, given by

$$dX_q \equiv \frac{(T - T_a)}{T} dq, \tag{3a}$$

where dq is an increment of the system's thermal energy. Thermal energy is equilibrated at temperature T and has no measurable potential for work at T. The system temperature T is generally (but not necessarily) equal to or greater than the ambient temperature T_a. Ambient heat is given by

$$dQ \equiv (T_a/T)dq. \tag{3b}$$

The DCM generalizes the thermodynamic definition of entropy. The Third Law of thermodynamics defines a system's entropy by:

$$S_{TD} \equiv \int_0^{T_{sys}} \frac{dq}{T}. \tag{4}$$

The Third Law entropy is equal to the statistical mechanical entropy. The DCM redefines entropy as a contextual property of state with respect to the ambient temperature by:

$$S_{DCM} \equiv \int_{T_a}^{T_{sys}} \frac{dq}{T} = \frac{Q}{T_a}. \tag{5}$$

The last term follows from integrating (3b) from T_a to T_{sys}. As the ambient temperature approaches absolute zero, the S_{DCM} approaches S_{TD}. The DCM extends the definition of entropy to real systems, for which T_a can never equal absolute zero.

The DCM entropy is a function of three independent variables: system temperature, ambient temperature, and a reaction progress variable, zeta (ζ), which indexes exchanges of heat with the ambient surroundings. By integrating partial differentials with respect to each of these variables and grouping, the DCM resolves entropy into two components, the ambient entropy, S_{amb}, and entropy of refinement, S_{ref}. These are defined in (6) and illustrated in Figure 2:

$$\begin{aligned} S_{DCM} \quad &= \quad (S_{amb}) \qquad + \qquad (S_{ref}) \\ &= \left(\int_0^1 \left(\frac{\partial S}{\partial \zeta}\right) d\zeta \;+\; \int_{T_a}^{T_{sys}} \left(\frac{\partial S}{\partial T_{sys}}\right) dT_{sys}\right) + \left(\int_{T_a}^{T_{a,new}} \left(\frac{\partial S}{\partial T_a}\right) dT_a\right) \\ &= \left(\int_0^1 \left(\frac{\partial q}{\partial \zeta}\right) d\zeta \;+\; \int_{T_a}^{T_{sys}} C_v(T)\frac{dT}{T}\right) - \left(\int_{T_a}^{T_{a,new}} C_v(T)\frac{dT}{T}\right). \end{aligned} \tag{6}$$

$C_v(T)$ is the temperature-dependent volumetric heat capacity, $\left(\frac{\partial q}{\partial T}\right)_{v,\zeta}$. The negative sign for S_{ref} is because heat q is relative to the ambient state, and as the ambient temperature declines, the system's heat q increases.

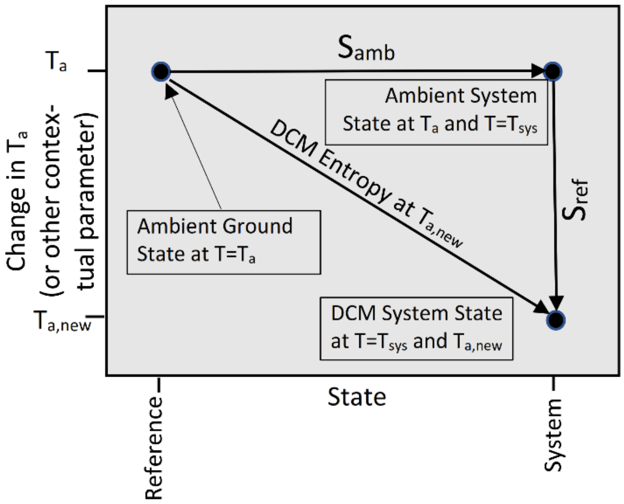

Figure 2. The Two Components of Entropy. The DCM resolves a system's entropy into the ambient entropy (S_{amb}) and the entropy of refinement (S_{ref}). S_{amb} describes the entropy due to changes in T_{sys} and ζ at fixed T_a. S_{ref} describes the entropy due to a change in ambient temperature or other contextual property of the ambient surroundings, prior to any adjustment to the system's new context.

The ambient entropy (S_{amb}, horizontal vector in Figure 2) reflects change from the ambient ground state (defining zero entropy) to the ambient system state at fixed ambient temperature. Equation (6) resolves the ambient entropy into an isothermal reaction and exchange of heat as the system progresses from ζ=0 to ζ=1 at temperature T_a, and the increase in heat as the system's temperature progresses from T_a to T_{sys}. The entropy of thermal refinement (S_{ref}, vertical vector in Figure 2) is a consequence of a change in the ambient reference, but before the system readjusts to the change.

The DCM recognizes exergy as a generalization of free energy, defined by $F=E_{total}-TS_{TD}$. Free energy and exergy gradients both describe the thermodynamic driving force for change. For an isothermal system at its ambient temperature, gradients in free energy and exergy are identical. However, whereas free energy is defined as a thermodynamic property for isothermal systems only, exergy is defined within the DCM as a physical property of state, and it is defined for non-isothermal systems as well.

Postulate 2 is a statement about the DCM's conceptual model of physical reality. Postulate 2 defines physical reality by perfect measurement from a system's actual ambient surroundings. Perfect ambient measurements of a gas particles' positions, for example, can only yield a probability distribution. The probability distribution is therefore a complete specification of particles' positions for the gas as it exists in the context of its ambient surroundings. Probabilities refer to the potential for particles to actualize more highly refined positions following a decline in ambient temperature, but prior to its actual transition to a new contextual state.

A state has no hidden properties, so properties beyond what are measurable from the ambient surroundings do not exist. The microstate is a complete description of the physical ontological state, as it exists in context of its actual ambient surroundings. "State," without qualification, will refer to both the microstate and the physical state.

Postulate 3 is a restatement of thermodynamics' First Law, expressing the conservation of energy for a system and its surroundings. Conservation of total energy and equation (2) imply that, in the limit of perfect isolation,

$$\Delta E = \Delta Q + \Delta X + \Delta Q_{gs} = 0, \tag{7}$$

where the deltas refer to changes over time.

If the ambient surroundings are fixed, the ambient ground-state energy is likewise fixed, and equation (7) expresses the conservation of energy during irreversible dissipation of exergy to ambient heat. Equation (7) also expresses conservation of energy during changes in the ambient surroundings. A change in the ambient surroundings changes the ground-state energy and redistributes the system energy, but in the limit of perfect isolation, a system's total energy does not change.

Postulate 4 is a generalization of thermodynamics' Second Law. Whereas the Second Law is a statistical description of transition to states of higher entropy and lower free energy, Postulate 4 describes the irreversible process of entropy production. It states that any irreversible transition produces entropy and increases the total entropy of the system and its surroundings.

The DCM recognizes two distinct paths for entropy production. The first path of entropy production is the path of dissipation:

$$\Delta S_{amb} = -\Delta X/T_a, \tag{8}$$

where ΔS_{amb} is the production of entropy due to dissipation of exergy, $-\Delta X$, at a fixed ambient temperature. The second path of increasing entropy is by refinement associated with a change in ambient surroundings. Differentiating entropy (6) with respect to $T_{a,new}$ at fixed T_a and T_{sys} shows that the increase in the entropy of thermal refinement from a decline in ambient temperature is given by:

$$\mathrm{d}S_{ref} \equiv \left(\frac{\delta S}{\delta T_{a,new}}\right)\mathrm{d}T_{a,new} = -\mathrm{C_v}\mathrm{d}ln(T_{a,new}). \tag{9}$$

Dissipation at a fixed ambient temperature (8) and refinement, commonly associated with a declining ambient temperature (9), describe two distinct paths leading to the irreversible production of entropy and the thermodynamic arrow of time.

The DCM's postulates are firmly based on empirical observations and the definition of perfect measurement. Postulate 1 asserts that the system interacts with its actual surroundings at a positive ambient temperature. Postulate 2 establishes exergy, ambient heat and entropy as measurable contextual properties of state, defined with respect to the system's actual surroundings. Postulates 3 and 4 establish the empirical First and Second laws of thermodynamics as fundamental physical laws. The DCM is consistent with empirical observations, and it extends the definition of state to systems as they exist in the context of positive temperature ambient surroundings. The HCM, in contrast, bases its conceptual interpretation on a physically unattainable idealization of absolute zero noise-free surroundings and perfectly precise measurements.

2.2 The Dissipative Classical State

To illustrate the dissipative classical state, we consider an ideal classical gas prepared at equilibrium with ambient surroundings at 500K. Measurement of the gas's temperature, pressure, and volume determines its total energy and defines its thermodynamic macrostate (Table 1, top row left column). The thermodynamic macrostate and total energy do not depend on the ambient temperature, and they are non-contextual. The gas's DCM microstate, in contrast, is contextually defined by the thermodynamic macrostate plus the system's contextually defined DCM entropy and energy components, listed in the bottom five rows of Table 1.

Table 1. DCM Macrostates and Contextual Microstate Properties

Energy Component	n-Particle Ideal Gas	Hydrogen Atom at Temperature T	Contextual?(1)
Macrostate Description	Temperature, Pressure, Volume, Mass (n particles)	$\Psi(T) = \sum_i c_i(T)\psi_i \;\text{ where }\; \sum_i \lvert c_i(T)\rvert^2 = 1$	No
Energy (total)	$E=nk_BT$	$\langle \mathrm{E(T)} \rangle = \sum_\mathrm{i} \mathrm{E_i} \times \lvert c_\mathrm{i}(\mathrm{T})\rvert^2$	No
Q_{gs} (ground-state energy)	$Q_{gs}=nk_BT_a$	$Q_{gs} = \langle \mathrm{E(T_a)} \rangle = \sum_i E_i \times \lvert c_i(\mathrm{T}_a)\rvert^2$	Yes
E_{sys} (system energy)	$E_{sys}=nk_B(T-T_a)$	$\langle \mathrm{E_{sys}(T)} \rangle = \langle \mathrm{E(T)} \rangle - \mathrm{Q}_{gs} = \sum_i E_i(\lvert c_i(T)\rvert^2 - \lvert c_i(T_a)\rvert^2)$	Yes
$Q = T_a(S_{ref} + S_{amb})$ (ambient heat)	$Q=T_a\left(\int_{T_a}^{T_{sys}} C_v \frac{dT}{T} + 0^{(2)}\right)$	$\langle \mathrm{Q(T)} \rangle = T_a\left(\int_{T_a}^{T}\left(\frac{\partial\langle \mathrm{E_{sys}(T)}\rangle}{\partial T}\right)\frac{dT}{T} + 0^{(2)}\right)$	Yes
X (exergy)	$X=E_{sys}-Q$	$\langle X(T) \rangle = \langle E_{sys}(T) \rangle - \langle Q(\mathrm{T}) \rangle$	Yes
$S_{DCM} = Q/T_a$ (entropy)	$S_{DCM} = \frac{Q}{T_a} = \int_{T_a}^{T_{sys}} C_v \frac{dT}{T}$	$\langle S_{DCM}(\mathrm{T}) \rangle = \frac{\langle \mathrm{Q(T)} \rangle}{T_a} = \int_{T_a}^{T}\left(\frac{\partial\langle \mathrm{E_{sys}(T)}\rangle}{\partial T}\right)\frac{dT}{T}$	Yes

k_B = Boltzmann constant. C_v=volumetric heat capacity. ⟨Angle brackets⟩ indicate the time-averaged properties. E_i is the total energy of the quantum mechanical eigenstate ψ_i.

(1) Contextuality only considers ambient temperature, not relative velocity, which would affect kinetic energy.

(2) Cooling to the ambient temperature brings the system to its ambient ground state, so S_{amb}=0.

Simply reducing the system's ambient temperature immediately changes the gas's contextual properties, as shown in Table 1. If we insulate the gas and lower its ambient temperature from 500K to 300K, its system energy and exergy increase. The gas's state is metastable; it has a potential to approach its new ambient ground state at 300K, but the process is suspended by the insulation.

Perfect reversible measurement of the metastable gas from the new ambient temperature involves extracting and reserving energy (e.g. by employing a reversible heat engine and thermal reservoir) until the gas reaches 300K. The process exchanges entropy between the gas and its ambient surroundings, but it is reversible, and no entropy is produced. Reversing the measurement process uses the reserved energy to pump ambient heat back, restoring the gas's 500K state as it contextually exists at the 300K ambient temperature.

2.3 The Dissipative Quantum State

To illustrate the quantum dissipative state, we switch from describing a gas of essentially inert particles to describing the particles' internal states as they interact with ambient (black body) photons. We consider an ensemble of hydrogen atoms prepared in equilibrium with ambient photons at 6000K. The ensemble is below the temperature range for ionization of hydrogen (7,000-10,000K), but high enough that multiple energy levels are occupied, so the atom's energy state is described as a superposed wavefunction.

Quantum mechanics describes the hydrogen's energy state, Ψ, based on statistical measurements of transitions between the atoms' discrete energy levels. A spectrometer sufficiently close to absolute zero[1] could in principle measure the emitted photons with high precision and determine the statistical distribution of energy transitions.

Measurements would reveal a statistical distribution of discrete and measurable eigenstates, ψ_i, as expressed by the ensemble's superposed wavefunction (Table 1, top row, right). Individual eigenstate energies are quantized and are independent of temperature but their complex weighting coefficients, c_i, do depend on the ensemble's temperature of equilibration. The total energy consequently depends on the system temperature, but it is independent of the ambient temperature and it is therefore non-contextual.

The bottom five rows of Table 1 define contextual time-averaged quantum properties with respect to the ambient surroundings. Postulates 1 and 2 and the definition of perfect measurement logically establishes these contextual properties as objective properties of state. They supplement the HCM's non-contextual properties and extend the HCM's description of state to real systems with surroundings at a positive ambient temperature.

The HCM interprets a superposed wavefunction as a microstate and a complete description of the physical state. In contrast, the DCM generally interprets the wavefunction as a macrostate and an incomplete description of the system's instantaneous physical state, as it randomly fluctuates amongst its allowable microstates. The macrostate's average energy is $\langle E(T)\rangle = \sum_i |c_i(T)|^2 E_i$, where the $|c_i(T)|^2$ are the probabilities that a hydrogen atom exists in the measurable eigenstate ψ_i at any given instant (independent of actual measurement), and E_i is its energy. The DCM microstate at any instant is completely defined by the wavefunction macrostate together with the instantaneous values for the time-averaged property values listed and defined in Table 1.

A superposed wavefunction is generally an incomplete macrostate description of the physical state. However, for an ambient temperature of 6000K, the hydrogen atom at 6000K is in its ambient ground state, all contextual properties equal zero, and fluctuations in the ground state are not measurable. A ground-state's superposed wavefunction is therefore a complete description of the system as it exists in equilibrium with the ambient surroundings. The HCM and DCM interpretations converge for equilibrium quantum systems.

2.4 The Quantization and Refinement of Space

A system's configuration specifies the positions of the system's constituent particles. In classical mechanics, a point in 3N dimensional configuration space specifies the coordinates of position for a system's N particles in 3D space, and it defines the system's instantaneous configuration. The point and its motions over time specify the system's classical mechanical state. In quantum mechanics, the time-dependent wavefunction and quantum state is also defined over configuration space and time.

In the HCM interpretations of classical and quantum mechanics, perfect measurement in the absence of thermal noise allows measurement of position coordinates to arbitrarily high precision. This implies continuous space. In the DCM, in contrast, the resolution of space is finite and a function of the positive ambient temperature. As the ambient temperature and thermal noise of measurement approach zero, the resolution of space and measurement increases. Space is continuous only in the idealized and unattainable limit of absolute zero and zero thermal noise. For real systems at a positive ambient temperature, space is not infinitely resolvable, and it is quantized.

To illustrate the quantization of configuration space for a simple quantum system, we consider the wavefunctions for a particle confined to a one-dimensional infinite potential well. The physical system is illustrated in Figure 3A.

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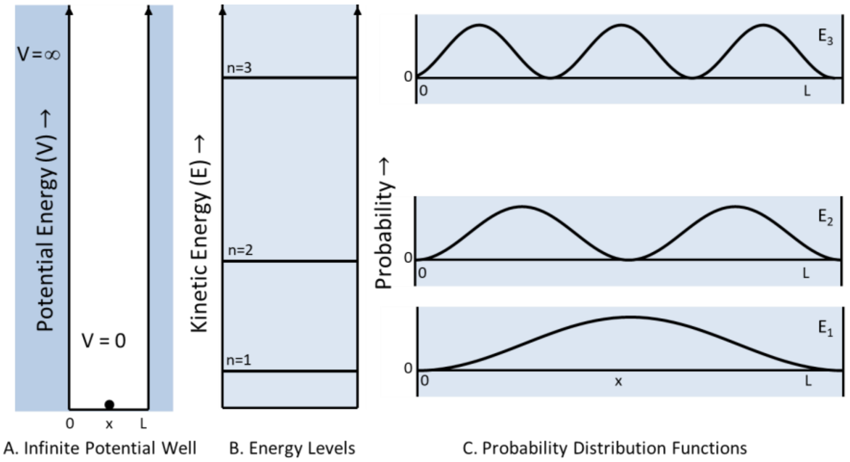
[1] A hydrogen atom at 300K is essentially in its ground-state energy, so 300K is sufficiently close for high (but finite) precision.



A. Infinite Potential Well B. Energy Levels C. Probability Distribution Functions

Figure 3. Quantum Particle in a 1D Potential Well.

The quantized energy levels are illustrated in Figure 3B for the particle's first three energy levels. The energies for the particle's eigenfunctions are given by [25]:

$$E_n=(n^2h^2)/(8mL^2), \tag{10}$$

where n is the quantum number, h is Planck's constant, m is the particle's mass, and L is the length of the one-dimensional configuration space over which the wavefunction is defined. The probability distribution functions (**PDF**s) for the particle's position are illustrated in Figure 3C. The probability of finding the particle outside the well is zero, and the area under each PDF is one, meaning there is a 100% probability that the particle is somewhere within the interval L.

Each energy level can be assigned a temperature by:

$$T_n = E_n/k_B, \tag{11}$$

where k_B is Boltzmann's constant. If the particle's temperature and ambient temperature are equal, then the particle's energy is entirely ground state and the corresponding PDF expresses everything that can be known about the particle's position. This represents the equilibrium ground state. The PDF constitutes a single pixel spanning the particle's configuration space and it defines the particle's microstate.

We next consider the case in which the ambient temperature is less than the particle's temperature. We consider a particle at temperature T_3 and ambient temperature equal to T_1. The particle's total energy is E_3. The particle's energy is unaffected by the change in ambient temperature, but its ground-state energy equals E_1, its system energy equals E_3-E_1, and its configuration space and its PDF are changed. The particle exists as a metastable particle with positive system energy and exergy.

To see the ambient temperature's effect on configuration space we can perform (in principle) the following steps:

1. Reversibly reduce the particle's energy from E_3 to its ground-state energy, E_1, reserving the change in the particle's energy. The particle's configurations space is then the single PDF for E_1.
2. Apply the reserved energy to insert barriers at L/3 and 2L/3. This constrains the particle to an interval of L/3 and from equation 10, this restores the particle's energy back to E_3. The PDF is again illustrated by the PDF for E_3, but it now comprises three discrete humps.

Lowering the ambient temperature from T_3 to T_1 resolves configuration space from one pixel spanning the entire configuration space to three pixels, each spanning an interval of length L/3. After enacting the two steps above, the PDF, with its three discrete humps, no longer provides a complete description of the particle. It constitutes a macrostate and an incomplete description of the particle's actual but unknown location. Each hump and pixel describes everything than can be known about the particle's possible location, and it defines a possible microstate for the system.

Figure 3 illustrates the refinement associated with a decline in temperature, but refinement was originally associated with non-thermal changes. The concept of quantum refinement was introduced by Robert Griffiths in his Consistent Histories Interpretation [14]. Refinement results from a change in measurement framework when a single projector (potential measurement) is replaced with multiple consistent measurement possibilities. When measuring a polarized photon, for example, if the polarized analyzer's orientation is parallel to the photon's source, measurement is determined and definite. If the analyzer is rotated 45°, the photon might pass through the detector's filter, or it might be absorbed. The change in the measurement framework refines the photon's configuration space (which includes an additional dimension to account for the polarized photon's quantum spin) from one pixel to two pixels, corresponding to its potential measurements. As a system's ambient context changes, refinement typically involves a succession of changes, as graphically expressed in Figure 4.

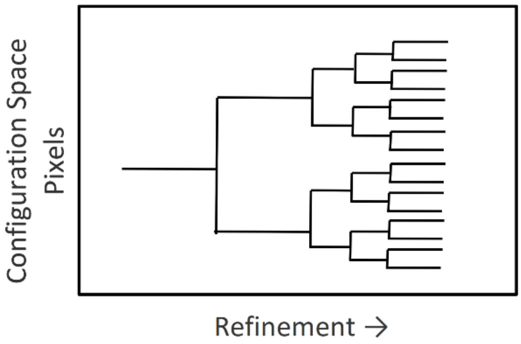


Figure 4. Refinement of Configuration Space. Refinement is the increasing pixelization of configuration space resulting from lowering the ambient temperature or other contextual change in the ambient surroundings.

The DCM leads to the quantization of space, but its quantization of space is contextual, without an invariant minimum length. It therefore does not conflict with length contraction in relativity, which is incompatible with the existence of an invariant minimum length of space.

2.5 Entropy, Wavefunction Collapse, and Measurement

The HCM entropy for a quantum system is the von Neumann entropy [26], which can be expressed by:

$$S_{vN} = -\sum_i \eta_i \log(\eta_i). \tag{12}$$

The HCM interprets the η_i as the statistical probabilities of measurable eigenstates following the collapse of a pure (zero-entropy) superposed quantum state to a statistical mixture of eigenstates. If the probability η_i of the eigenstate *i* is known to equal one and the remaining probabilities are zero, there is no uncertainty, and the system exists as a pure state with zero entropy. Uncertainty and entropy are maximized when all possible eigenstates have equal probabilities.

The von Neumann entropy is mathematically equivalent to the Gibbs entropy, with the η_i replaced by p_i, denoting the probabilities of classical statistical mechanical microstates, and to the Shannon information entropy, with the η_i replaced by P_i, denoting the probabilities of events. These entropies are all subjective measures of an observer's uncertainty. Entropy, in the HCM, is about the incompleteness of an observer's knowledge. It is not a fundamental property of state within the HCM's conceptual framework.

The DCM has a simple contextual interpretation for the von Neumann entropy. Configuration space for the particle in Figure 3, with energy E_3 and ambient temperature T_1 is resolved into three pixels. After the ambient temperature is reduced to T_1 but before the system adjusts to its new ambient surroundings, each of the three pixels represents a potential microstate. Which potentiality is eventually actualized is random and objectively unknowable. If each potential microstate has equal probability of being actualized, then $\eta_1 = \eta_2 = \eta_3 = ⅓$, and from (12), $S_{vN} = \log(3)$. The positive entropy expresses the objective randomness, after the decline in ambient temperature but before the system adjusts to this decline, of which potential microstate will be actualized.

Steps 1 and 2 above represent a process of random actualization of the particle to one of its potentialities. After actualization, but before any measurement, the actual microstate is unknown, but it is definite and measurable, so its DCM entropy is zero. The spontaneous and random actualization of a potentiality is analogous to wavefunction collapse, but it is a natural process as a system responds and readjusts, following a change in its ambient surroundings.

The intrinsic randomness of quantum transitions is key to Schrödinger's cat thought experiment and resolution to the measurement problem. The experiment's radioisotope exists as a metastable state with respect to ambient surroundings much cooler than the surroundings during its creation. The particle can momentarily exist in spontaneous transition *between* measurable states, but during irreversible transition, it is not reversibly measurable, and it does not exist as a DCM state. The cat's fate is entangled with the particle's fate by virtue of the deterministic chain linking them. At no time does the particle or its entangled cat exist as part of a physically superposed state. There is only the irreversible and random transition of the particle to a new state of higher stability. The measurement problem thereby vanishes.

3. The Dissipative Conceptual Model of Time

3.1 The Two Components of System Time

The DCM recognizes two fundamental and distinct components of time. Thermodynamic time describes the irreversible production of entropy. Mechanical time describes the reversible and deterministic change of a system during intervals between transitions, while it exists as a state.

Thermodynamic time records a system's irreversible production of entropy due either to the dissipation of exergy or to refinement. The dissipation of exergy for a first-order kinetic system[2] is given by:

$$X(t_q)=e^{-\lambda t_q}X_o, \tag{13}$$

where X_o is the initial exergy, λ is a dissipation rate constant, and t_q is the real-valued thermodynamic component of system time. Equation (13) describes, for example, the dissipation of exergy during radioactive decay. At time zero, the system's exergy equals its initial exergy, X_o, and as time advances toward infinity, the system approaches zero exergy at equilibrium. Thermodynamic time depends contextually on the ambient surroundings, and it is therefore incompatible with, and ignored by, the HCM and conventional interpretations. Thermodynamic time is an objective contextual property of state and a logical consequence of the DCM postulates of state.

Mechanical time in relativity is defined by a coordinate on the time axis in 4D spacetime. Mechanical time is conventionally defined as a real-valued coordinate, but this is merely a matter of convention. The DCM adopts a different convention, by replacing the notation for real-valued time t with the mathematically equal $-i(it_m)$, where i is the square root of negative one and it_m is the imaginary coordinate of mechanical time. The DCM changes mechanical time to an imaginary parameter, but it leaves all equations of mechanics unchanged. For example, the DCM expresses the time-dependent quantum wavefunction for an isolated (fixed energy) and metastable (non-reactive) quantum system, by:

$$\psi(x,it_m)=e^{\frac{-it_mE}{\hbar}}\psi_o(x). \tag{14}$$

Except for the change in the function's argument for time, equation (14) is identical to the conventional expression for the system's time-dependent wavefunction. Equations (13) and (14) are notably similar.

System Time: Equation (13) describes the continuous dissipation for a many-particle thermodynamic system. In the quantum limit, dissipation by an unstable positive-exergy particle is discontinuous. Periods with no dissipation mark intervals during which the particle exists as a well-

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[2] One in which the system's rate of exergy dissipation is proportional to its exergy at fixed ambient temperature

defined and reversibly measurable metastable state. Its time evolution is indexed by a reversible time coordinate. At some point, however, the particle irreversibly transitions to a more stable state. An irreversible transition marks an interval of entropy production and an irreversible advance in thermodynamic time. A metastable quantum particle therefore requires both mechanical time and thermodynamic time to describe its behavior.

The DCM recognizes system time as a complex property of state, comprising both real-valued thermodynamic time and imaginary mechanical time. System time is represented by a point on the complex system-time plane (Figure 5A). A change over imaginary mechanical time (vertical axis) conserves exergy and describes the reversible and deterministic changes between irreversible transitions or measurements, within a single instant of thermodynamic time. A change over real thermodynamic time (horizontal axis) describes an irreversible transition to a more stable state and the production of entropy.

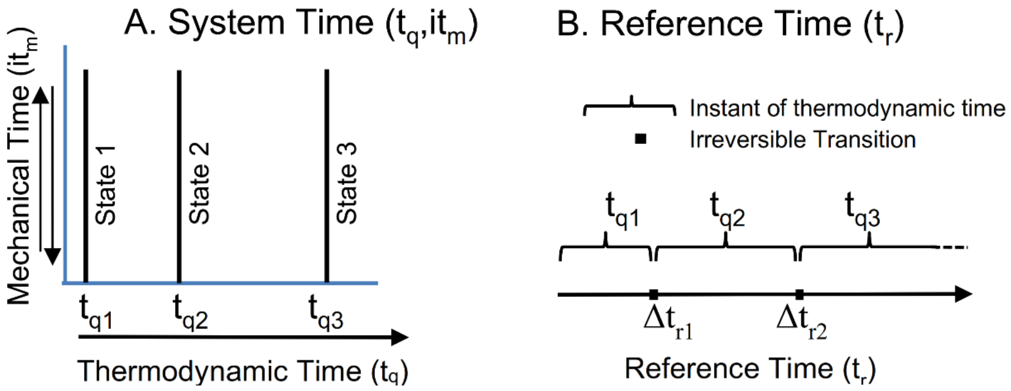

Figure 5. Complex System Time and Reference Time. Figure 5A shows the complex system-time plane, spanned by real-valued thermodynamic time (horizontal axis) and imaginary mechanical time (vertical axis). Figure 5B shows the irreversible advance in an observers' reference time during changes in system-time. Δt_{r1} and Δt_{r2} are advances in reference time during irreversible transitions. The intervals between transitions mark the advance of reference time during reversible changes in mechanical time.

3.2 Reference Time

System time, whether it proceeds reversibly or irreversibly, is empirically measured by the advance of reference time, t_r, as recorded by an observer's reference clock (Figure 5B). Counting oscillations and recording memories is an inherently irreversible process [27]. The DCM provides a decoupling between system time and reference time. Reference time marks the continuous and irreversible "flow" of time, and it provides the empirical time scale across which a system's events are recorded.

3.3 Space, Time, and Nonlocality

We can now consider how quantum nonlocality coexists with relativity. We first consider simultaneous measurements of entangled photons at points A and B by Alice and Bob (Figure 6), using parallel vertically polarized filters. The entangled electron pair has zero spin and no net polarization. Experiments show that if Bob measures a vertically polarized photon, then Alice measures a horizontally polarized photon, even when the measurements are physically separated and simultaneous. Individual measurement results are random, but they are strictly and instantaneously correlated.

The shaded light cones show the allowable domain for causal effects emanating from events at A and B within the empirical constraints of relativity and locality. The instantaneous correlation of physically separated measurements at points A and B, outside of each other's light cone, graphically illustrates the nonlocality of the photon pair's correlated measurements. Einstein famously referred to nonlocal correlations as "spooky" action at a distance.

Einstein, Podolsky, and Rosen [22] suggested a simple interpretation of the correlated results, without invoking nonlocal superluminal interactions. They suggested that measurement of one photon simply reveals a preexisting but "hidden" property of the entangled state. Hidden properties could be locally inherited from the photon pair's common origin, and they could determine the measurement outcomes, which only appear random. In this case, discovering this property simply reveals the locally determined outcome of the other photon's measurement.

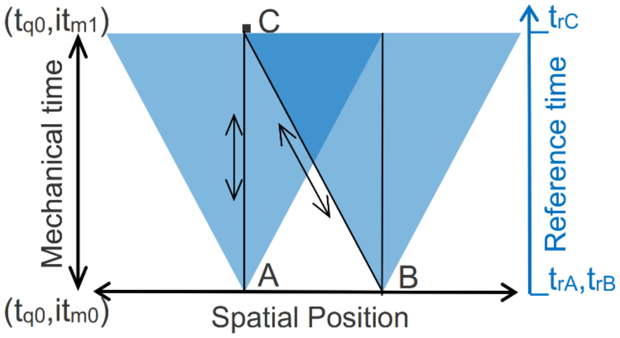

Figure 6. Instantaneous Correlation of Spatially Separated Measurements. The figure spans space (projected onto the horizontal axis) and mechanical time (left vertical axis) at a single instant of thermodynamic system time at t_{q0}. Alice and Bob simultaneously record their measurement results for the photons at points A and B.
Superimposed on the diagram are two light cones, bounded by spherical light pulses from points A and B advancing across reference time (right vertical axis). Alice records her results at reference time t_{rA} and at subsequent reference time t_{rC} (point C), she receives the results Bob recorded at point B.

However, in 1964, John Bell devised a test for hidden variables, based on the statistics of measurements using non-parallel analyzers [19]. Numerous experiments have demonstrated that the statistics of multiple measurements violate Bell's test [28]. The results prove that measurement results cannot result from preexisting hidden properties, unless those hidden properties are themselves nonlocal. The results prove that quantum nonlocality and relativity coexist within any objective interpretation of reality.

The DCM explains the coexistence of quantum nonlocality and relativity by recognizing system time as comprising both thermodynamic time and mechanical time. When the entangled photon pair is initially produced, it has zero spin and no net polarization. According to the DCM, measurement at either A or B actualizes the photons' transition to photons with random, but definite and anticorrelated polarizations. If the polarizers at A and B are parallel, then the measurement at one ensures that measurement at the other is anticorrelated.

At point B, Bob reversibly records his definite measurement result and transmits it to Alice via a signal photon polarized with the orientation that he measured. Alice reversibly records her photon's measurement result, and based on her results, she knows the orientation of Bob's entangled photon and his signal photon. The light cone and Bob's signal photon both reach Alice at point C. Knowing the signal photon's orientation, Alice reversibly measures it and confirms the correlation of their results.

Alice's observation of her measurement at A, Bob's observation and transmission of his measurement at B, and Alice's measurement of Bob's signal photon at C are all reversibly conducted over mechanical time. Reversibility means no entropy production. With no change in entropy, mechanical time is not just reversible; it is also time symmetrical. With time symmetry, asserting that an initial event causes a future event and asserting that a future event causes the initial event are equally valid. This expresses the idea of retrocausality [29,30], and it exists over time-symmetrical mechanical time. The time-symmetry of recording and transmitting the measurement results creates a deterministic chain of causality and retrocausality within a single instant of thermodynamic time, represented in Figure 6 by A↔C↔B. The photons at A and B are entangled by virtue of the deterministic link connecting them. No hidden variables or spooky action is required to explain the deterministic and nonlocal correlation of measurements at A and B.

We next consider measurements using obliquely oriented polarizers. If Bob's analyzer is rotated 45 degrees, the system's contextual framework changes. Bob's and Alice's measurement results are no longer strictly correlated. Alice can no longer know Bob's result based on her own results, and she cannot reversibly measure his signal photon. The time-symmetry link of causality and retrocausality connecting their measurement results is broken and the photons at A and B are no longer entangled. The observed statistics of measurements reflect local measurements on photons with definite anticorrelated but random polarizations. The photons' statistical measurement results are consistent with Bell's theorem. Again, no hidden variables or spooky action is required to explain the observed results.

The righthand axis of Figure 6 shows the record of Alice's measurement events at points A and C, as measured by her reference clock. Even when the events at A, B and C are correlated within an instant of thermodynamic time, the reference clock continues to mark the irreversible passage of reference time. Alice experiences the irreversible passage of time between recording her measurement at time t_{rA} and her recording of Bob's measurement at t_{rC}. The irreversible flow of an observer's reference time and the empirical constraints of relativity preclude superluminal exchange of information between observers across their reference time. The DCM successfully explains the mechanical details of nonlocality and it explains how relativity and quantum nonlocality compatibly coexist without spooky action or hidden variables.

4. The Dissipative Conceptual Model of Process

Up to this point, we have focused on states and their transitions. The statistical mechanical interpretation of thermodynamics describes the relative stabilities of states and the statistical potential for a metastable state to transition to a state of higher entropy. It does not, however, address entropy production or irreversible process in terms of fundamental physical properties. In this section, we shift from the physical description of states to the description of non-equilibrium systems and their process of dissipating useful energy to waste heat.

The DCM provides a logically consistent framework that goes beyond HCM's statistical mechanical interpretation of thermodynamics. Postulate 4 generalizes the Second Law to describe the irreversible process of entropy production and exergy dissipation. The DCM establishes a physical foundation for nonequilibrium dissipative processes and their self-organization into increasingly complex dissipative structures.

4.1 The Dissipative Homeostate

Figure 7 extends the dissipative dynamics model for states (Figure 1) to a stationary dissipative system. The dissipative model assumes a stationary environment, but it is nonequilibrium. The system's ambient surroundings includes one or more sources of exergy or high-exergy material components. A system with stationary exergy sources and environment for wastes will converge over time to a stationary process of dissipation. The system is stationary, but it is not microscopically static, and it is not an actual state, as its components are in constant flux and dissipating exergy. We refer to a stationary dissipative system as a homeostate. A homeostate is a generalization of David Duetsch's constructor [31,32], formulated within the DCM framework.

For a near-equilibrium system, energy flow is proportional to gradients. Fourier's Law, Fick's Law and Ohm's Law express the linearity of fluxes and gradients in potential for heat conduction, chemical diffusion, and electrical flow, respectively. Linearity defines the near-equilibrium regime. A near-equilibrium system converges to a unique steady-state dissipative process consistent with its steady-state boundary constraints and conservation laws.

Far from equilibrium, linearity breaks down. At a critical temperature gradient, for example, heat flow dramatically increases as a fluid spontaneously reorganizes itself from conduction to convection. Non-linearity can allow multiple dissipative solutions and multiple homeostates, all consistent with the system's boundary constraints and conservation laws.

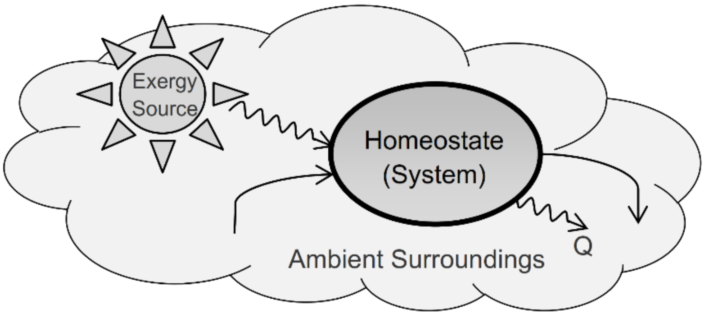

Figure 7. Homeostate Model. The system's nonequilibrium surroundings includes exergy source(s), either directly (e.g. sunlight) or indirectly, by high-exergy components. Ambient resources in the surroundings are also freely available to the system for processing and discharge. At homeostasis, time-averaged inputs of materials and energy equal outputs.

We can express a homeostate as a network of links, pods, and dissipative nodes. Figure 8 shows the dissipative network for the Brusselator reaction [33]. The Brusselator is a theoretical model for an autocatalytic chemical reaction exhibiting oscillations. It has two sources, one for component 1 in state A and one for component 2 in state B. Links are the pathways for energy and components to flow from external sources, through the system, and back to the surroundings. Pods provide transient storage capacity for components to accommodate fluctuations in flow rates. Nodes represent irreversible transitions of components from one state to another. All dissipation within the system is assigned to nodes. Elementary nodes and transitions are contextually defined by perfect measurement at the ambient temperature, and they have no internal details.

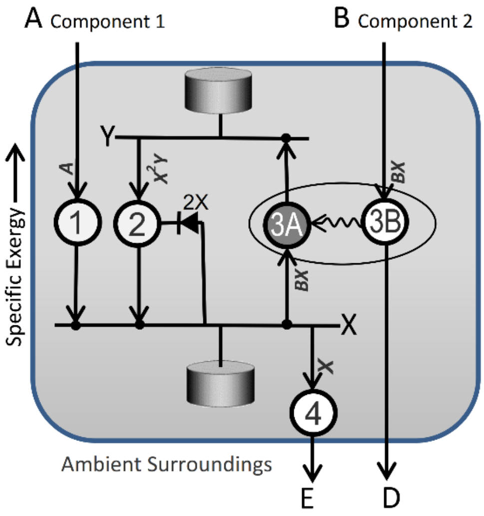

Figure 8. The Brusselator Network Model. Letters refer to the components' states. States higher on the diagram have higher specific exergy. The Brusselator comprises four reaction steps:
R1: External source A → X
R2: Y + 2X → 3X
R3: External source B + X → Y + D (discharge)
R4: X → E (discharge)

The Brusselator has four reactions, R1 to R4, listed in the Figure 8 caption. R1, R2, and R4 are exergonic transitions of component 1, represented by nodes 1, 2, and 4. An exergonic transition is a transition of a component from a state of higher specific exergy to a state of lower exergy. Reaction R3 couples two separate component transitions: X→Y and B→D. It is represented by nodes 3A and 3B. Node 3B is another exergonic transition, dissipating component 2 from state B to state D. The component's exergy is only partially dissipated, however. Some of the exergy is transferred to node 3A via an exergy link (wavy arrow). Node 3A is an endergonic transition. An endergonic node utilizes an exergy supply to lift a component "uphill" to a higher-exergy state. Node 3A lifts component 1 from state X to state Y.

Transition rates, based on simple reaction rate theory, are shown by the arrowhead expressions in the figure. The kinetic rate coefficient for the forward direction is set to unity, and the reverse direction is assumed to be much slower and is set to zero. So, for example, the transition rate for R3 (B+X→D+Y) is simply BX. Reaction 2 is an autocatalytic transition of component 1 from state Y to state X. Autocatalysis means that the product partakes in the reaction. For reaction R2 (Y+2X→3X), the transition rate is X^2Y, making the Brusselator non-linear.

Setting the net production rates of X and Y to zero yields the steady-state concentrations X=A and Y=B/A. For a sufficiently high value of A, the steady state homeostate is unstable to perturbations. Any perturbation from the steady state homeostate sends the system on a transient path that converges to a stationary periodic homeostate, in which the concentrations of X and Y cycle. Steady-state and periodic homeostates are graphically illustrated in Figure 9 as attractors [34]. The steady state homeostate is represented by the fixed-point attractor and the oscillating homeostate is represented by the limit cycle attractor. A homeostate can also be chaotic, represented by a strange attractor. In all cases, an attractor is a fixed and bounded trajectory in state-space, and it represents a stationary homeostate.

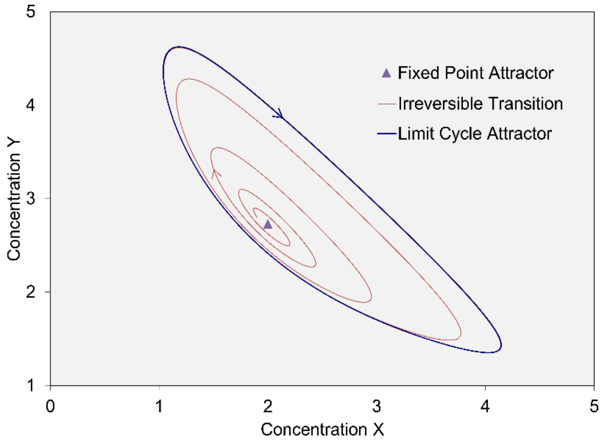

Figure 9. Brusselator Homeostates.

4.2 The Constructive Power of Dissipation

Dissipation can be much more than the dissipation of exergy into waste heat; it is the driver for all change, constructive as well as destructive. Nature is replete with examples in which systems become increasingly organized and evolve toward higher organization [33]. These changes occur within far-from-equilibrium systems that are sustained by external exergy sources.

Lord Kelvin recognized the constructive power of dissipation in an article he wrote in 1862 [35]. He began by describing heat death, when all directed activity ceases, as the inevitable end-result of dissipation within a finite universe. He then proceeded to express a much deeper and overlooked idea. Backing off on the inevitability of heat death, he continued that the universe is in a state of "endless progress…involving the transformation of potential energy into palpable motion and hence into heat." In essence, he asserted that a system tends to defer dissipation by first utilizing exergy for palpable work, before eventually dissipating it into heat.

When Lord Kelvin stated this idea, classical mechanics was well entrenched in physical thought. Kelvin's idea was incompatible with classical mechanics, so it never gained a foothold and was ignored. His idea is fully compatible with the DCM, however, and we formalize his insight with Postulate 5:

> **Postulate 5 (Kelvin Selection Principle)**: Of the multiple paths by which a system can take exergy from a source and dissipate it to the surroundings, the path that maximizes the system's rate of internal work is the most stable.

The Kelvin Selection Principle (**KSP**) is analogous to the Second Law of thermodynamics, but whereas the Second Law describes the selection and relative stability of states based on entropy, the

KSP describes the selection and relative stabilities of dissipative processes based on internal work. A system's internal work is contextually defined by measurable changes in exergy. We can measure the change in a component's exergy as an endergonic node pumps it to higher specific exergy. We designate the sum of exergy increases over all endergonic nodes as the work of transition, and we can adopt this as a measure of internal work:

$$\dot{W}_{int} = \sum_{i \in \left\{ \begin{matrix} ender- \\ gonic \\ nodes \end{matrix} \right\}} \langle \dot{W}_i \rangle, \tag{15}$$

where $\dot{W}_i = \Delta\bar{X}_i \times J_i$. $\Delta\bar{X}_i$ and J_i are the increase in the component's specific exergy and its flow across endergonic node i, and the angle brackets denote time-averaged values.

Postulate 5 states that the available pathway with the highest rate of internal work is the most stable. A familiar real-world illustration of the KSP is the stability of convection over conduction. Heat added to the base of a convecting liquid does work of thermal expansion of the fluid to maintain density gradients. This is the internal work on the liquid necessary to sustain convective flow. Heat added to a static fluid, in contrast, is completely dissipated by conductive heat flow, without doing any measurable work. The KSP therefore says that if boundary and system constraints allow both convection and conduction, convection is the more stable homeostate. Observations invariably show this to be the case.

A more revealing illustration of the KSP is the Miller-Urey experiment. Stanley Miller and Harold Urey took a mixture of gases, which they believed represented Earth's primordial atmosphere, and they stimulated it with electrical sparks to simulate lightning [36]. When they analyzed the system afterward, they found that the gas molecules had rearranged themselves into a variety of amino acids. The gas mixture started in a low-exergy near-equilibrium state and it ended up in a high-exergy far-from-equilibrium state. The sparks added exergy to the gas mixture, but instead of directly dissipating the exergy to heat, the gas mixture deferred dissipation and utilized it to do work of creating high-exergy amino acids.

In the case of convection, perturbation analysis shows that, given a heat source and an unstable temperature gradient, a random perturbation will send the fluid down any one of many deterministic paths, all leading to convection. Starting with an equilibrium mixture of gases, however, producing amino acids by random selection would seem extraordinarily unlikely. Yet, the Miller-Urey experiment is repeatable with similar results each time. The KSP offers an alternate explanation, in which amino acid synthesis occurs through a sequence of incremental steps. Each step selects from multiple possibilities, not based on random selection, but instead guided by the KSP. The end-result of successive increments of internal work is the creation of high-exergy amino acids.

The DCM recognizes two common paths toward higher internal work rate: 1) increasing the net rate of exergy supply (**R**xs) and 2) increasing functional complexity. Rxs is given by:

$$\mathrm{R}_{XS} = \langle\dot{\mathrm{X}}\rangle_{\mathrm{input}} - \langle\dot{\mathrm{X}}\rangle_{\mathrm{output}} = \sum_{\mathrm{i}\in\{\mathrm{inputs}\}} \langle\bar{\mathrm{X}}_{\mathrm{i}}\mathrm{J}_{\mathrm{i}}\rangle - \sum_{\mathrm{i}\in\{\mathrm{outputs}\}} \langle\bar{\mathrm{X}}_{\mathrm{i}}\mathrm{J}_{\mathrm{i}}\rangle = \langle\dot{Q}\rangle, \tag{16}$$

where $\dot{\mathrm{X}}$ and J_{i} are the rates of exergy and component flows into or out of the system and $\bar{\mathrm{X}}$ is the specific exergy. The last equality states that for a stationary homeostate, the average rate of dissipation $\langle\dot{Q}\rangle$ equals the rate of net exergy supply.

Perhaps the simplest way to increase Rxs is by expanding or replicating a dissipative process, given an expandable exergy source. This would proportionately increase both the exergy extraction rate and its internal work rate. Given sufficient resources, this path pushes a dissipative system or population of dissipators to expand, thereby increasing its net Rxs and internal work rate.

The second path toward a higher rate of internal work is increasing functional complexity. The term complexity is commonly associated with the amount of information required to specify a system's state. We are not interested here in the complexity of a state, however. Rather, we are interested in the complexity of a system's dissipative process. If, as proposed by Lord Kelvin, a system defers dissipation by doing palpable work on some other dissipative system, then that system could likewise defer dissipation. The recursive deferral of dissipation to sustain other dissipative systems leads to an expanding network of dissipative nodes of increasing interconnectedness and organization. This idea precisely expresses the concept of functional complexity.

We formally define functional complexity as the ratio of rates for internal work (15) and net exergy supply (16):

$$C_F = \frac{\dot{W}_{int}}{R_{XS}}. \tag{17}$$

Functional complexity is a measurable and well-defined property of a homeostate's dissipative process.

For a single pass of exergy and a single endergonic node, functional complexity can approach unity for perfect efficiency and no dissipation. However, a homeostate can increase its functional complexity well beyond unity by reprocessing and recycling exergy via feedback loops or by sustaining a network of endergonic nodes. Figure 10 illustrates a simple feedback loop resulting in function complexity greater than unity. Feedback loops are ubiquitous within biological systems, from cells to ecosystems, leading to higher functional complexity.

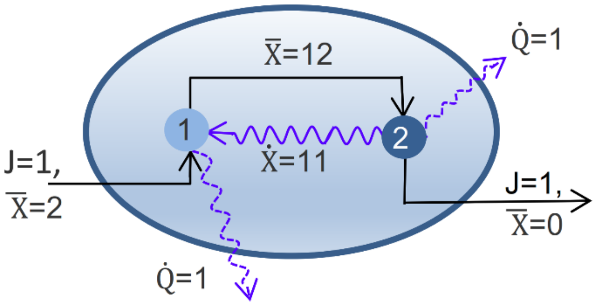

Figure 10. Simple Feedback Loop. A component flows through system (straight vectors) at a rate (J) of one mass unit/sec. Its specific exergy $(\bar{X})$ equals two units at input and zero at output. The rates of net exergy input $(J\times\bar{X})$ and total dissipation rate $(\dot{Q})$ equal two energy units/sec. Mass and energy inputs and outputs are balanced.
Exergonic node 2 takes the component with 12 units of specific exergy, dissipates one unit, and supplies exergy to endergonic node 1 (wavy vector) at a rate of 11 units/sec. Endergonic node 1 uses this exergy to do 10 units/sec of internal work to lift the specific exergy of component from 2 units of to 12 units, and in the process it dissipates one unit of exergy. The system's internal work of transition equals 10 units. With 2 units of exergy input, its functional complexity C_F equals 5.

4.3 Whirlpools and Entropy Production

We commonly observe whirlpools, indicating they can be more stable than radial flow of water directly toward the drain. A whirlpool provides an important counterexample to proposals that processes are stabilized by maximizing the rate of dissipation or entropy production. The Maximum Entropy Production Principle (**MEPP**) and related proposals have had success in a number of areas, but they are not universally applicable [37-39].

The MEPP is equivalent to maximizing the rates of net exergy supply and dissipation. This is one path toward maximizing internal work rate, but it ignores functional complexity. The centrifugal force of a whirlpool's circulation lowers the water level and pressure over the drain. This actually reduces the rate of water discharge. A stationary whirlpool therefore has lower rates of water and exergy supply, a lower rate of dissipation (from equation 16), and a lower rate of entropy production. The key to a whirlpool's stability turns out to be its higher functional complexity.

To model a whirlpool's functional complexity, we consider a 50 cm diameter cylindrical container of water partitioned into concentric shells radiating outward from a central drain (Figure 11). Water in each shell is modeled with uniform pressure and kinetic energy.

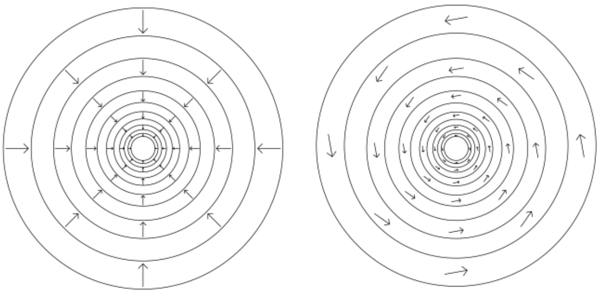

Figure 11. Models for Radial Flow and Whirlpool. Left: Radial flow. Right: Whirlpool. Each concentric shell is a single zone with uniform pressure (water elevation) and fluid speed. Arrows illustrate fluid flow directions only. Speed is constant within each zone but the radial speed increases inward in both cases due to the incompressibility of water. In addition, conservation of angular momentum requires that the rotational velocity for the whirlpool is inversely proportional to the radial distance and increases inward.

Water in the outermost shell is maintained at a constant 20 cm depth. The rate of drainage is proportional to the square root of the pressure (depth) of water over the drain, taken as the height of the water column in the central core. At each interface, a component of water transitions to a zone of lower pressure, higher velocity, and higher kinetic energy. This applies to both the radial flow and whirlpool models.

Figure 12 shows a detail of the network model for the transition between two zones in the whirlpool model. The surface water contour for the whirlpool is determined by conserving angular momentum and balancing hydrostatic and centrifugal forces.

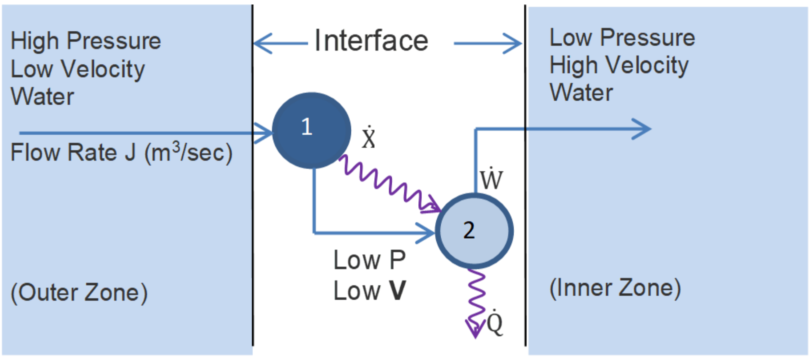

Figure 12. Paired Nodes at Whirlpool Zonal Interface. As water flows across a zonal interface, it undergoes both a decline in pressure and an increase in velocity and kinetic energy. An elementary node represents only a single transition, so each interface has two nodes. The first node is exergonic. It transfers exergy at a rate of $\dot{X} = J\Delta P$ to endergonic node 2. Node 2 uses this exergy for internal work of accelerating the water, given by $\dot{W} = \dot{X} - \dot{Q} = ½\rho\Delta V^2 J$, where $\dot{Q}$ is the rate of dissipation by node 2. The internal work for the system is summed over all interfaces.

For radial flow, the surface water contour is determined by energy conservation, with increasing kinetic energy toward the drain offset by lower potential energy and water column height. Viscous dissipation outside of the central core is negligible for radial flow and is ignored.

Figure 13 shows radial cross sections for the radial-flow and whirlpool homeostate models. In the case of radial flow (solid lines), the profiles show that the drainward decline in water level and the increase in kinetic energy are imperceptible at the plotted scale. In the case of whirlpools (dashed lines), the figure shows a dramatic decline in water pressure and height near the drain. This profile represents the whirlpool's shape. There is a correspondingly large increase in water velocity and kinetic energy as water approaches the drain. Figure 13 clearly shows that the increase in velocity and kinetic energy near the drain is much greater for the whirlpool than for radial flow.

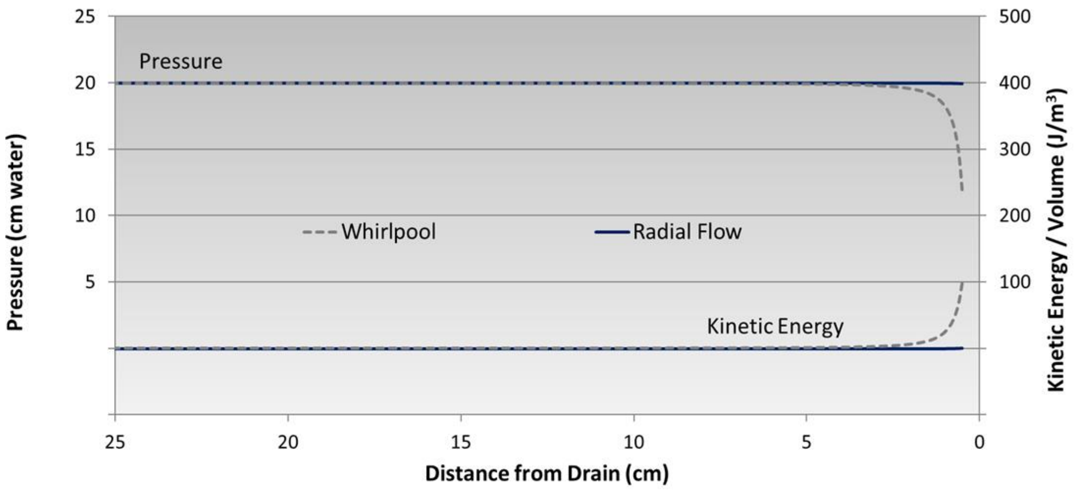

Figure 13. Pressure and Kinetic Energy Profiles for Whirlpool and Radial Flow. Fluid velocity and kinetic energy increase toward the drain for both the whirlpool and radial flow. The solid lines show an imperceptible drop in the pressure and a similarly imperceptible acceleration of water for radial flow. The dashed lines show an 8.1 cm (40%) pressure drop and a sharp acceleration of water for the whirlpool near its vortex. The lower pressure at the drain for the whirlpool corresponds to lower rates of water discharge, dissipation, and entropy production compared to radial flow.

Table 2 summarizes the results of the steady-state radial and whirlpool models. The table shows that the flow rate is higher for the radial flow, but the internal work rate is 4,000 times higher and the functional complexity is 5,000 time higher for the whirlpool. According to the KSP, the whirlpool should be more stable than radial flow, despite its lower rates of exergy supply, dissipation, and entropy production. The common emergence of whirlpools in draining water empirically documents the relative stability of whirlpools over radial flow, as predicted by the KSP. The stability of the whirlpool provides an important counterexample to the idea that "faster is better." It falsifies the maximum entropy production principle [37], which asserts that the rate of exergy dissipation and entropy production always tends to be maximized.

Table 2. Comparison of Functional Complexity for Radial Flow and Whirlpool Homeostates

	Steady state Flow Rate J (m³/sec)	$\dot{X}_{in}$ $\rho g h_o J$ (J/s)	$\dot{X}_{out}$ $\rho J^3/A_{drain}^2$ (J/s)	R_{XS} $\dot{X}_{in} - \dot{X}_{out}$ (J/s)	$\dot{W}_{int}$ $\Sigma \dot{X}_i$ (J/s)	C_F $\dot{W}_{int}/R_{XS}$
Whirlpool	3.00E−05	0.029	0.0022	0.027	2.9E-03	0.1
Radial Flow	3.88E−05	0.038	0.0047	0.033	7.4E-07	1.9E-05

$\dot{X}_{out}$ = Kinetic exergy of water exiting a 1 cm diameter drain with area A_{drain}.
ρ = Fluid density (1,000 kg/m³)
h_o = Water depth at perimeter (20 cm).
$\dot{X}_i$ = Increase in kinetic energy per volume of water at interface i (Figure 12).
$\dot{W}_{int}$ = Internal work of accelerating water from the perimeter zone to the core zone.

4.4 Oscillations and Synchronization

Figure 9 showed two homeostates for the Brusselator: a steady state homeostate (point attractor) and a periodic homeostate (limit cycle attractor). Any perturbation from the steady state homeostate sends the system to the more stable oscillating homeostate. We would expect that the oscillating homeostate's higher stability would be reflected by a higher rate of internal work, in accord with the KSP. However, the rates of internal work of transition (15) for the two homeostates are indistinguishable. The homeostates also have identical rates of net exergy supply and entropy production. Given the contextuality of internal work, Is there a more suitable measurement of internal work rate to discriminate between the two homeostates?

For the steady state homeostate, the concentrations of X and Y are fixed. For the oscillating mode, in contrast, concentrations of X and Y fluctuate. During the accumulation phases, the concentrations and exergy of states X and Y increase. A more suitable measure of internal work for a fluctuating system is the internal work of storage, given by:

$$\dot{W}_{int} = \sum_{i \in \left\{ \substack{com- \\ ponent \\ states} \right\}} \langle \dot{X}_i^+ \rangle. \tag{15'}$$

$\langle \dot{X}_i^+ \rangle$ is the increase in exergy of component state *i* during its accumulation phase, and the summation is over the Brusselator's component states (X and Y). Based on the measurable internal work of storage, the oscillating homeostate has a higher internal work rate than the steady-state mode. The KSP asserts that the oscillating mode is more stable, in agreement with perturbation analysis (Figure 9). Given equal rates of exergy input for the two homeostates, the oscillating homeostate also has higher functional complexity (17).

We can generalize this conclusion and assert that an oscillating homeostate is more stable than a steady state homeostate, other differences being negligible. The spontaneous emergence of resonance, commonly observed in mechanical or fluid mechanical systems far from equilibrium, illustrates spontaneous cycling and the arrow of increasing functional complexity.

Systems of linked oscillators often synchronize in a process known as entrainment. Christiaan Huygens, the inventor of the pendulum clock, first documented this in 1666, when two of his pendulum clocks mounted on a common support spontaneously synchronized [40]. Oscillations and synchrony are ubiquitous within biological systems, human behaviors and institutions, astrophysics and quantum mechanics [41].

Figures 14 and 15 describe the synchronization of a network of linked oscillators. As detailed in the figure captions, the analysis shows that a network of linked oscillators increases its exergy utilization when all oscillators synchronize. The KSP therefore predicts that networks of coupled oscillators are stabilized by synchronization, independent of their physical details.

As described in Figures 14 and 15, synchrony increases the utilization and stability for a network of linked oscillators. It would be incorrect, however, to conclude that the KSP drives a system of linked oscillators to synchronize. The transient changes over time modeled in Figure 15 are strictly deterministic, based on the oscillators' properties and their starting positions. For the same fixed properties as in Figure 15, other randomly assigned starting positions deterministically settle into a variety of attractors, including partially synchronized homeostates, in which subsets of oscillators are synchronized but the subsets are phase-shifted from each other, or no synchronization after 5,000 time steps. The KSP does not influence the deterministic dynamics of an individual set of oscillators, but if a random change promotes synchronicity, this has a stabilizing effect. Random internal changes or external perturbations can provide a system the opportunity to search for a homeostate of higher synchronization and stability. This suggests, for example, that the external shock of a defibrillator works by spurring the heart's pacemaker cells to jump out of a partially synchronized homeostate of fibrillation into a more stable homeostate of full synchronization.

The spontaneous synchronization of oscillators is another illustration of the arrow of evolving complexity. In his book, *Sync: The Emerging Science of Spontaneous Order*, Steven Strogatz [41] argues that complex systems have an intrinsic drive toward oscillations and synchronization. Empirical observations and simulations of dissipative systems show this is commonly the case. The KSP provides a general principle that explains oscillation and synchronization in terms of a general principle, independent of a system's specific dynamics.

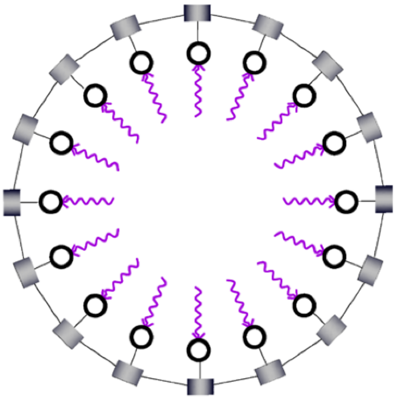

Figure 14. Coupled Oscillators. The figure shows sixteen oscillators linked in a circle. All oscillators have identical unit rates of exergy input (wavy arrows) into nodes, which pump a component (not shown) into pods. When concentrations reach a critical value, the component is released, and the cycle resumes. Coupling between adjacent pods allows component to leak from one pod to another. The leak rate equals the difference in concentrations, multiplied by a coupling coefficient.

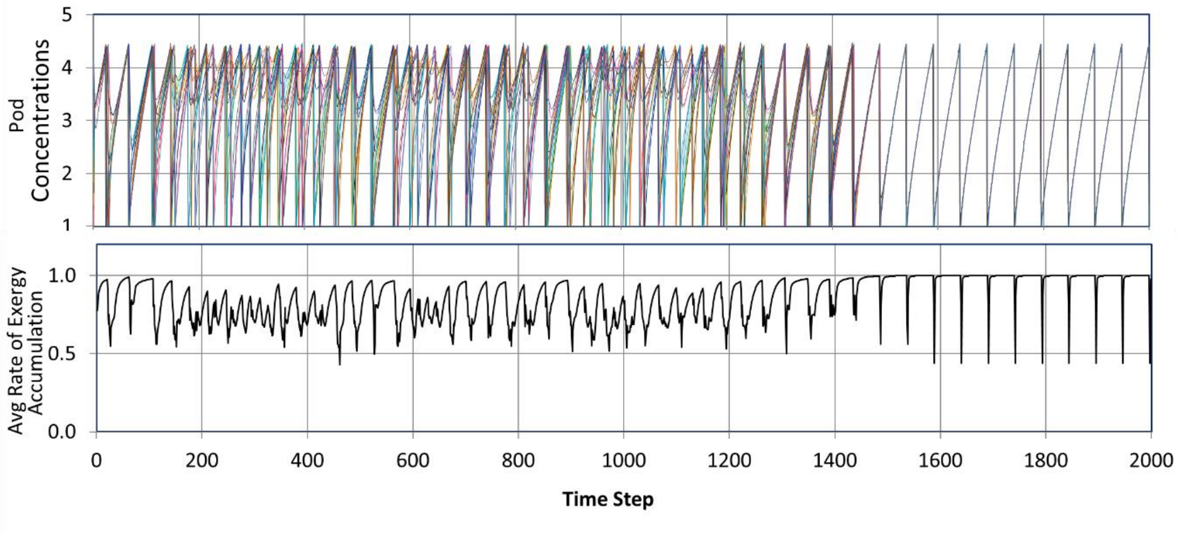

Figure 15. Synchronization of Coupled Oscillators. Top—Pod Concentrations: Oscillators are randomly assigned periods between 49.5 and 50.5 time units. They start at random points in their cycles. After about 1500 time steps, the oscillators synchronize. Bottom—Average Rate of Exergy Accumulation: Each oscillator has a unit rate of exergy input, used to pump component into its pod. When oscillators are not synchronized, some exergy is lost to diffusive leakage between adjacent oscillators. When all oscillators synchronize after 1500 time steps, concentrations are equal, there is no diffusive loss, and the pods' rate of exergy accumulation is maximized and equal to the exergy input (except at pod discharge). The rate of internal work is equal to the time-averaged accumulation of exergy by the pods, and this is maximized by synchronization.

5. Discussion

5.1 Why DCM?

The DCM and non-contextual HCM interpretations present alternative models of physical reality. They differ only in their definitions of perfect measurement, their assumptions, and their interpretations of empirical facts. Any viable interpretation must be fully consistent with empirical measurements. However, while consistency is essential, a model's assumptions should be empirically justifiable and its implications should be testable.

The HCM, without empirical evidence, interprets reality in the absence of thermal randomness. It extrapolates a system's microstate to infinite precision, and attributes empirical randomness to our inability to precisely measure or know the initial microstate. Infinite precision implies eternalism, in which the universe evolves deterministically and the future, as well as the past, is set in stone [42,43]. Eternalism means we either need to accept an exquisitely tuned and physically unexplained initial state of the universe to account for its current state of organization [44] or accept that we are a statistical outlier within a multiverse of universes [9]. And, the HCM means we must choose from among the following to explain empirical randomness:

1. The possibility for unobserved superposed cats and the unexplained role of observation or measurement on random wavefunction collapse [18];
2. an unexplained mechanism of random wavefunction collapse within an isolated system (or within a subsystem and its isolated surroundings);
3. an exponentially growing multiplicity of branching universes, in which everything that can happen does happen in some branch [16], or;
4. a subjective reality defined by empirical perception and agnostic on an underlying objective reality [15].

These and other interpretations of quantum mechanics are consistent with empirical observations, but their assumptions about objective reality are not empirically justified and their metaphysical implications are not testable.

The DCM is based only on assumptions that are empirically justifiable. It accepts empirical observations of irreversibility and randomness as fundamental facts. No system is perfectly isolated and real systems interact with their ambient surroundings at a positive absolute temperature. Consequently, the DCM defines a system as it exists within its actual context by perfect measurement from its ambient surroundings. The DCM's contextual framework with positive-temperature ambient surroundings provides objective and fundamental randomness of environmental fluctuations. This is the essential key required to fulfill Prigogine's ambition of establishing fundamental irreversibility and the end of certainty [6,7].

By abandoning non-contextuality, the DCM reconciles the physical coexistence of quantum nonlocality and relativity. It can explain the unfolding of the present from an indefinite future; it establishes irreversible dissipative process as a fundamental property of non-equilibrium systems, and it can explain the evolution toward higher functional complexity and stability, which is manifested across the cosmos at all scales. The DCM's explanations of these well-established empirical facts are retrodictions and validation of its implications.

The DCM is an improvement over non-contextual interpretations of physics, but it is still just a model of physical reality. Definition 2 for perfect measurement is based on effectively infinite ambient surroundings, so that it is fixed during interactions, including perfect measurement. The DCM models the state's ambient surroundings as equilibrium, defining a single unique ambient temperature. Reality is more complex, however. In a non-equilibrium universe, the surroundings are finite and not in equilibrium. Different components of a system might interact with different regions of the surroundings. A system might thermally interact with its adjacent surroundings, but electronic transitions might interact with energetic and non-equilibrium photons. A metastable state could interact with its environment over a spectrum of energies and temperatures. The DCM models a homeostate with respect to a stationary environment, but nothing is fixed for eternity. Exergy sources run out; the environment can become contaminated with waste heat and components; and expansion of the universe drives down its ambient cosmic microwave background temperature. The DCM is a key step forward from the HCM in modeling physical reality, but like any model, the DCM is a simplification of reality.

5.2 Is Contextuality Objective?

The DCM defines states and homeostates within the context of its ambient surroundings, with which a system interacts or potentially interacts, and from which the DCM defines perfect measurement. But in a non-uniform universe, a system's surroundings depend on the system's delineation. We can delineate an experimental system from its cryogenic detectors; we can delineate the system and its measurement apparatus from its laboratory setting; or we can delineate the laboratory and the rest of the Earth from space. In each case, the system's ambient surroundings and contextual properties of state differ. The DCM simply accepts the delineation between a system and its surroundings as part of the system's contextual definition. Given a system's definition, the DCM's model of the physical state is independent of any particular ambient observer or the existence of observers. In this weak sense, at least, the DCM is objective.

We have argued that the cosmic microwave background defines an objective ambient temperature for the universe as a whole. The CMB defines an objective ambient temperature of 2.7 kelvin, permeating the vacuum of space. Could the CMB provide a universal basis for an objective contextual delineation?

The interpretation of relativity in terms of 4D spacetime is a consequence of assuming non-contextuality of spacetime and its independence of any particular inertial framework. However, Thyssen [45] has shown that 4D spacetime and 3D space with universal time are both consistent with the empirical data for Special Relativity. The DCM already recognizes the CMB as a contextual ambient reference. The CMB can also define an objective state of rest, for which any directional anisotropy in the CMB's doppler shift is zero (or at least minimized). To the extent that our focus is local and we can ignore the expansion of space, the CMB can locally specify an objective ambient temperature and a rest state for contextually defining 3D space with universal time. This expresses the concept of Presentism [2], and it is logically consistent with special relativity and with the contextuality of the DCM.

It is not clear whether the CMB can provide objective contexts for ambient temperature and rest state across an expanding universe. A universal ambient temperature across an expanding universe needs to be reconciled with Gavassino's argument that thermal equilibrium can be unambiguously defined only for bodies at relative rest [46]. An expanding universe violates the "no red shift" condition for defining Einstein synchronization [47]. This would seemingly preclude an expanding 3D space with universal time. Further investigation is required to determine whether it is possible to define objective and universal contexts for ambient temperature or for 3D space across an expanding universe.

5.3 Cosmological Implications

Ellis and Drossel promote the evolving block universe (**EBU**) model to resolve indeterminism and the origin of time's arrows [3]. Whereas the block model of the universe is a static block in 4D spacetime spanning all past and future since the Big Bang, the EBU is bounded at "now" by the unfolding of the present from an indeterminate future.

Ellis and Drossel attribute the indeterminate unfolding of "now" to quantum randomness. However, given that the wavefunction is a deterministic function, there is a conflict between two of Ellis's statements in a related article [48]:

1. "The view taken here is close to the Copenhagen interpretation: it assumes firstly that the wave function is real (i.e., descriptive and objective rather than epistemic)."
2. "Our basic view is that measurement is truly a stochastic, nonunitary process … a 'wave function collapse.'"

The first sentence extends the determinism of the wavefunction to physical states. The second (correctly) acknowledges fundamental physical randomness associated with measurement, and this contradicts the first statement. Failure to explicitly reconcile this contradiction undermines EBU's logical consistency. However, Ellis and Drossel recognize a key limitation on determinism [3]:

> "when quantum effects are not dominant and suitable classical equations of state are given, as at times after the end of inflation, outcomes will be unique [i.e. determined]. However, this raises again the above-mentioned problem that deterministic equations require infinite precision"

As they point out, determinism depends on infinite precision. DCM's positive ambient temperature, however, leads directly to coarse graining of configuration space and therefore to a breakdown of determinism.

Coarse graining leads to indeterminate outcomes, but it does not establish the direction of indeterminate change or of time's arrow. In order to establish the direction of time's arrows, Ellis and Drossel invoke cosmic expansion and a past condition [3]:

> "A global Direction of Time arises from the cosmological context of an expanding and evolving universe; This overall context, and particularly the associated decrease of temperature of interacting matter and radiation with time, together with a Past Condition of low initial entropy, leads to local Arrows of Time"

David Albert introduced the Past Hypothesis, stating: "We make the cosmological posit that the universe began in an extremely tiny section of its available phase space," i.e. in an initial state of low entropy (quoted in [3]). This implies an extremely well-tuned past condition. The DCM has a different take on the past hypothesis. The universe started in a state of near-zero entropy, but we model it in equilibrium at its intensely hot ambient temperature. As an equilibrium ground-state microstate, it spanned the universe's initial configuration space. There was only a single possible initial state, so no fine tuning was required.

Expansion and a declining ambient temperature subsequent to the Big Bang led to the refinement of the universe's configuration space and to the indeterminate unfolding of its future by random actualizations of newly refined and contextually defined potentialities. The universe has evolved from an initially hot state of near-equilibrium and zero-entropy, to its current state of high-exergy and high-entropy with respect to its cold ambient microwave background. Its positive exergy drives irreversible processes and the emergence of dissipative structures. The universe will continue to produce and dissipate exergy, without ever reaching an equilibrium state of zero-exergy heat death, as long as it continues to expand and its ambient temperature continues to decline.

5.4 Origin and Evolution of Life

The DCM sheds light on another perplexing question, on the origin of life. Once self-replicating autocatalytic systems exist, Darwinian natural selection can act to propagate beneficial variations and guide the evolution of life, but selection of the fittest cannot account for the origin of life or for the evolution of complexity within non-replicating systems.

The Kelvin Selection Principle constitutes a fundamental law of evolution that applies to both replicating and non-replicating systems. The KSP can apply to a system of simple organic compounds that is open to exergy sources (e.g. Miller-Urey experiment), by progressively selecting dissipative processes and guiding the system toward higher functional complexity. By continually seeking to defer dissipation to do internal work on the system, the KSP guides a system toward expanding networks of links and feedback loops to recycle exergy. Over time, self-organization can lead to autocatalytic and self-replicating networks. At that point, Darwinian evolution can take hold.

Once life is established, the KSP guides its evolution through an interplay between Darwinian competition to increase fitness, and cooperation to sustain and increase functional complexity. Darwinian competition predominates when a species' dissipative cost of competition is small relative to the potential benefit of increasing its exergy supply. In this case, competition enables a species to achieve higher utilization by expanding its resource base. The KSP provides the drive for a species to expand up to the carrying capacity of its environment.

Cooperation predominates if resources are inelastic or the dissipative cost of competition is too high. When a rainforest's canopy completely covers the forest, for example, its solar resource base is inelastic to further gains. Over its fifty-million-year period of relative environmental stability and net exergy extraction rate, the Amazon rainforest has continued to evolve by developing highly complex webs of interaction for recycling components and exergy [49]. Ecological nutrient cycling [50] involves repeated utilization and renewal of the nutrients' specific exergy. From equation (17), this defines the system's functional complexity factor. By recursively deferring dissipation and recycling exergy, a dissipative system can increase its utilization by increasing its functional complexity, with no upper bound in the limit of perfect efficiency.

6. Summary and Conclusions

The DCM requires a fundamental change in how we think about reality, from one that can be defined in isolation to one that is intrinsically defined only in context of its actual surroundings. Quantum mechanics has dangled this conclusion in front of us since its beginnings, a century ago.

The DCM formally recognizes and embraces contextuality as its first postulate. The first postulate describes a system within the context of its ambient surroundings. The DCM defines a system's microstate by reversible measurement at a positive ambient temperature. If a system is not undergoing exergy dissipation and entropy production, it is reversibly measurable and it exists as a definite state, whether it is measured and known, or unmeasured and unknown.

The second postulate assumes no "hidden variables." This means the microstate, defined in the limit of perfect measurement, completely specifies the physical state. The third postulate expresses the conservation of energy (1st Law of thermodynamics), and the fourth postulate expresses the irreversible production of entropy (2nd law of thermodynamics). DCM's fifth postulate, also referred to as the Kelvin Selection Principle, states that the rate of internal work is a measure of stability for a non-equilibrium system's irreversible process of dissipation. The KSP selects dissipative processes of higher internal work rate and stability.

The DCM is a contextual interpretation of reality. The DCM augments the empirical descriptions of physics by adding entropy, exergy, and the dimension of irreversible time as contextual properties of physical states. It expands—but does not otherwise alter or replace—classical mechanics, quantum mechanics, and special relativity. The dimension of irreversible time expands physics beyond static states and their reversible transitions to irreversible dissipative processes and the spontaneous emergence of dissipative structures.

An interpretation is "good" if it is consistent with empirical observations; precise; parsimonious in its assumptions; explanatorily broad; falsifiable; and if it promotes scientific progress [51]. The Dissipative Conceptual Model and prevailing interpretations of physics all satisfy the consistency requirement. Prevailing interpretations define the physical state non-contextually, but observations are necessarily contextual, and they cannot empirically justify noncontextuality. The Dissipative Conceptual Model is parsimonious and avoids unjustified assumptions by defining a system's physical state contextually, as it exists with respect to its ambient surroundings.

The DCM explains the thermodynamic arrow of time and the evolution of complexity as fundamental physical responses of non-equilibrium systems, without invoking an exceptional and unexplained initial state or improbable accident. It explains the empirical randomness of quantum measurements and the coexistence of nonlocality and relativity in terms of fundamental principles, without invoking empirically consistent but implausible and untestable metaphysical implications such as superposed cats, an exponentially branching universe, or spooky action at a distance. And, it extends the scope of physics from its traditional focus on states to irreversible dissipative processes, thereby opening up new avenues of investigation within fields previously regarded as too high-level or too complex for fundamental physical analysis. Its quantization of space, without a minimum invariant length, may provide a framework for reconciling quantum mechanics and general relativity. By all measures, the DCM is a good interpretation of physical reality and a viable response to Ellis and Drossel's challenge [3]:

> "the challenge is to find some alternative proposal [to the Evolving Bock Universe] that does justice to the fact that time does indeed pass at the macro scale, and hence it must be represented by something like the EBU structure presented here. To deny that time passes is to close one's mind to a vast body of evidence in a spectacular way."

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