

Article

Time, Entropy, and Entanglement contextually defined

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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 as a fundamental physical property, and the inability to explain irreversible change, random quantum measurements, or nonlocality without untestable and implausible metaphysical implications. We propose a conceptual model that is based on empirically justifiable assumptions and consistent with observations. The WYSIWYG Conceptual Model (WCM) assumes no hidden properties: "What You can See Is What You Get." The WCM contextually defines a system's state with respect to its actual ambient background, and it extends existing models of physical reality by defining entropy and exergy as objective contextual properties of state. The WCM establishes the irreversible dissipation of exergy and the Second law of thermodynamics as a fundamental law of physics, it recognizes physical randomness, and it provides a physical explanation for nonlocality, consistent with Special Relativity, without hidden variables, superdeterminism, or "spooky action."

Keywords: Physical Foundations; Quantum mechanics; Nonlocality; Time; Entropy; Quantum information; Entanglement

1. Introduction

The nature of physical reality has been debated 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 debate are: 1) the problem of time, 2) the problem of measurement, 3) the problem of physical randomness, and 4) the problem of nonlocality.

1.1 The Problem 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 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. Classical mechanics further assumes that the microstate completely specifies the system's underlying **physical state**. Application of Newton's Laws of mechanics to a precisely defined state determines all future states.

Determinism does not by itself imply reversibility, however. Newton's laws of mechanics are deterministic, but they do not recognize heat as energy. Newtonian mechanics accommodates dissipation and the irreversible loss of energy by non-conservative forces, such as friction.

William Rowan Hamilton reformulated classical mechanics in 1832. He resolved a system into elementary particles, which have mass, but no internal energy. With no internal energy, a system's total energy equals the sum of its particles' kinetic and potential energies, and this defines the system's mechanical energy. Hamiltonian mechanics went beyond Newton's empirical laws of mechanics by eliminating the dissipation of mechanical energy to heat and non-conservative forces. Hamiltonian mechanics interpreted heat

as the mechanical energy of particles, and it formalized the conservation of energy into its conceptual model of mechanics. Later, in a series of experiments in the 1840s, James Prescott Joule confirmed the equivalence of heat and energy, and in 1850, Rudolf Clausius published the First Law of thermodynamics, which formally established the conservation of energy.

Mechanical energy is quantified by its potential to do work, so its conservation means the conservation of work potential. The conservation of work potential, along with determinism, implies 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, and it is a logical consequence of the Hamiltonian conceptual framework.

The Hamiltonian conceptual model is reversible, but observations reveal that heat flows irreversibly from high temperature to low temperature, and work can be dissipated to heat, but heat can only partially be converted back to work. Physics acknowledges this empirical arrow of time, as recorded by an irreversible increase in entropy.

Boltzmann described the entropy of a mechanical system by its disorder, which he defined by the number of accessible microstates consistent with its statistical mechanical **macrostate**. The macrostate is an imprecise description of the system's actual microstate, coarse-grained by thermal noise and imperfect measurement. 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' dispersal could be reversed, in principle, however, resulting in a decrease in entropy. This is the idea raised by Maxwell's Demon [5], who could reverse the increase in entropy without work and without violating any fundamental laws of physics. Physics regards entropy as a measure of a macrostate's imperfect description and uncertainty of a system's precise state, and not as a fundamental property of physics. It likewise regards the Second Law of thermodynamics as a well-validated empirical principle, but not as a fundamental law of physics.

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. Quantum mechanics describes the quantum state by the Schrödinger wavefunction. The wavefunction expresses everything that is measurable and knowable about a system, and it therefore defines the quantum mechanical microstate. The quantum mechanical microstate, like the Hamiltonian classical mechanical microstate, is both deterministic and reversible.

The determinism and reversibility of the wavefunction is a fact of its formulation. Whether the underlying physical state is deterministic and reversible or not, however, is a matter of interpretation and ongoing debate. Prevailing interpretations of quantum mechanics accept a key conclusion of Hamiltonian classical mechanics, that the fundamental forces of physics are conservative. This implies that an isolated quantum system's physical state is both deterministic and reversible, and that the wavefunction is complete.

Individual quantum measurements, however, are inherently random. The empirical randomness of quantum mechanics is often attributed to environmental perturbations, causing decoherence and physical collapse of a superposed state [6]. External perturbations can include, but are not limited to, observation and external measurement. Prevailing interpretations of quantum mechanics assert that a physical state, as it exists in isolation, unperturbed, and unobserved, is both deterministic and reversible.

The universe, by definition, has no surroundings or external perturbations. Quantum mechanics describes its physical state by a hypothetical wavefunction of the universe and its evolution by unitary change. Relativity describes it as a static block in 4D spacetime, spanning past, present and future. The wavefunction and relativity both describe all time—past, present, and future—as equally real, and this provides the conceptual foundation for Eternalism [2,7,8]. Reconciling the empirical arrow of time with a reversible universe is the unresolved conceptual problem of time.

1.2 The Problem of Measurement

Multiple measurements on an ensemble of identically prepared radioactive particles reveal a statistical mix of decayed and undecayed microstates. Individual measurements

are described as eigenfunctions of a quantum operator corresponding to an observable property or property set. An eigenfunction describes the definite measurable properties of a system's eigenstate, subsequent to a measurement. Quantum mechanics describes a system, as it existed prior to measurement, by a superposed wavefunction comprising a statistical superposition of all possible measurable results:

$$\Psi = \sum c_i \psi_i. \quad (1)$$

Ψ is the superposed wavefunction, the ψ_i are measurable eigenstates, and the c_i 's are complex weighting factors based on quantum-state tomography [9]. This uses statistical measurement results for an ensemble of identically prepared systems and the Born rule to reconstruct the system's microstate as it existed in isolation prior to measurement or observation, and independent of any particular measurement framework. After its preparation but prior to its measurement, a radioisotope is described a superposed wavefunction and statistical sum of its potentially measurable eigenstates.

If the superposed wavefunction is just a description of the system's physical state, then the collapse of a superposed wavefunction to a statistical mixture of measurable microstates would simply reflect the need for new measurement to update its description. This describes Max Born's statistical interpretation of the wavefunction. However, the Copenhagen Interpretation (CI), which emerged during the 1920s, followed classical mechanics by equating the quantum wavefunction and a system's underlying physical state.

Erwin Schrödinger tried to illustrate the absurdity of this assumption by considering a radioactive particle, a cat, and a detector which releases cyanide gas if the particle decays. He imagined all of this in a box isolated from observation and external perturbations. At preparation, the system's wavefunction describes a live cat entangled with the radioactive particle. Sometime later, it describes the probabilities of observing a dead cat or live cat. The change from eigenfunction to superposed wavefunction is deterministic. If the wavefunction defines the physical state, then the cat also evolves deterministically from an initial state of live cat to a superposed physical state of live-dead cat. Only when the veil of isolation is broken, can the superposed cat collapse into the dead cat or live cat that we observe. Schrödinger rejected the possibility of superposed cats and the Copenhagen Interpretation, and he proposed his experiment to illustrate the absurdity of its logical implications.

Hugh Everett proposed an alternative interpretation that avoids the possibility of superposed cats. In essence, his Many Worlds Interpretation (MWI) [10] says that everything that can happen does happen in separate branches of an exponentially branching universe. In one branch, Schrödinger's cat lives, and in the other, it dies. Even we, as observers, are split. Each of our split selves exists in a separate 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 MWI trades the possibility of superposed cats for an exponentially branching universe instead.

The CI and MWI both consider the wavefunction as a complete description of the physical state, as it exists isolated and unobserved, and both are consistent with observations. Despite their untestable and aesthetically distasteful metaphysical implications, they both rated well in a survey at a quantum mechanics conference [11]. The measurement problem, and the possible role of an observer on triggering the apparent randomness of observed measurement results, nevertheless remain unresolved conceptual problems of quantum mechanics [12].

1.3 The Problem of Nonlocality

Closely related to the measurement problem is the unresolved problem of quantum nonlocality [13]. Einstein, Podolsky and Rosen (EPR) raised the issue of nonlocality in an article they published in 1935 [14]. They argued that if the wavefunction description of a system's state is complete, then a pair of entangled particles, emitted from a common source, exists in an indefinite superposition of measurable states prior to their

measurement. Conservation of quantum information (e.g., quantum spin) means that if the particles are measured using parallel detectors, then the outcomes of measurement must be strictly correlated, even if measurements are simultaneous and spatially separated. EPR argued that this would violate relativity and the requirement of locality, which prohibits superluminal propagation of effects. EPR suggested that there are properties, inherited from the particles' common source, and that they carry information to determine the measurement results. Quantum mechanics does not recognize these "hidden" properties, and they suggested that quantum mechanics is therefore incomplete.

However, in 1964, John Bell devised a statistical test for hidden variables, based on the statistics of measurements using randomly oriented analyzers [13]. Numerous experiments have since demonstrated that spatially separated measurements do, in fact, statistically conserve quantum spin, but the statistics of multiple measurements violate Bell's test [15,16]. The results indicate that if hidden variables do exist, they must themselves be nonlocal, and that the assumption of local realism is inconsistent with quantum measurements [17]. The DeBroglie-Bohm Interpretation and its variants maintain physical determinism by positing the existence of nonlocal hidden variables, consistent with Bell's theorem. Nonlocality cannot be used to transmit signals superluminally, so there is no empirical conflict with relativity, but there is no known mechanism to explain the coexistence of relativity with nonlocality or nonlocal state properties. This is the problem of nonlocality, and it poses a significant conceptual problem [13,14].

There is a loophole in Bell's theorem, however. Bell's theorem implicitly assumes that the settings for the randomly oriented measurements are, in fact, random and uncorrelated. As Bell himself noted, the problem of superluminal speeds and spooky action at a distance is avoided if there is:

"…absolute determinism in the universe [and] the complete absence of free will. Suppose the world is super-deterministic, … the difficulty disappears. There is no need for a faster than light signal to tell particle A what measurement has been carried out on particle B, because the universe, including particle A, already "knows" what that measurement and its outcome will be." [18]

1.4 The Problem of Physical Randomness

Superdeterminism is the idea that the universe's past, present, and future are uniquely determined by its initial state. In this case, measurements cannot be random and uncorrelated, and Bell's Theorem falls apart. Superdeterminism is a logical consequence of classical mechanics, as famously expressed by Laplace's demon [19]. Classical mechanics regards empirical randomness as an artifact of imperfect measurement and incomplete information on a system's precise microstate.

Superdeterminism of quantum mechanics is similarly based on the idea that a system's past, present, and future are uniquely and completely determined by its initial state. In the case of quantum mechanics, however, superdeterminism assumes the existence of hidden nonlocal variables [20]. So even if the underlying physical state is deterministic and hidden quantum variables do exist, they are not just unknown, they are intrinsically unknowable. This means that the quantum microstate will be empirically random, even if the underlying physical state is deterministic.

Random fluctuations of a physical state's hidden variables are explicitly invoked by stochastic interpretations of quantum mechanics. For stochastic quantum mechanics, the source of randomness is unspecified, and for stochastic electrodynamics, randomness is modeled as zero-point field fluctuations [21]. However, whether random quantum fluctuations are physical, meaning that the physical state itself is objectively random, or empirical, meaning that physical state is simply unpredictable, cannot be empirically determined. The objective randomness of the physical state is a matter of assumption and an unresolved question concerning physical reality.

Superdeterminism is consistent with empirical randomness, but the idea that the course of the universe's evolution, including our own thoughts and choices, is determined by its initial state is so aesthetically distasteful that many physicists either ignore

superdeterminism or reject it outright. The costs of rejecting superdeterminism and asserting physical randomness, however, are steep. If we reject superdeterminism, we need to accept nonlocality and reconcile it with relativity, and we need to reconcile physical randomness with the deterministic laws of physics. This is the problem of physical randomness.

1.5 We Need a Better Conceptual Model

"It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature." -Niels Bohr [22]

As Niels Bohr acknowledged, quantum mechanics forced physics to abandon its historic goal of explaining nature, and to focus instead on what it can say about nature. Trying to explain nature has become widely viewed as a hopeless or pointless effort and no longer an appropriate role for science. A proper conceptual model, however, would provide a firm foundation for a clearer understanding and explanation of nature.

A conceptual model is an interpretation of physical reality. A good model of physical reality should be able to explain the empirical of arrow time and the randomness of measurements and fluctuations. It should explain the superluminal conservation of information while respecting the requirement of locality.

The nature of a system's physical state, while it is isolated and unobserved, simply cannot be resolved experimentally. It is strictly a matter of the assumptions by which experimental results are interpreted. Interpretations mentioned in the preceding sections equate the microstate and physical state, and they define state properties with respect to a noise-free reference state at absolute zero. Logical implications are the conservation of work potential, and the determinism and reversibility of physical states as long as they are isolated, unperturbed, and unobserved. In addition, if properties are defined with respect to absolute zero temperature, then any inertial reference can be transformed via a Galilean or Lorentz transformation to any other inertial reference, without loss of information. This means that the state's information is independent of its particular absolute-zero inertial reference. I refer to any such interpretation as a Non-Contextual Model (**NCM**) of physical reality. The key implications of NCMs are the determinism and reversibility of isolated physical states.

NCMs are consistent with empirical observations, but a good conceptual model should go beyond simply accommodating empirical facts. It should explain empirical facts with a minimum of assumptions and untestable implications. As described in the preceding sections, existing NCMs have untestable and aesthetically distasteful metaphysical implications. Superposed cats, splitting universes, and eternalism are speculative and untestable implications of their assumptions. They have no empirical evidence, and by any reasonable assessment, they are not plausible.

Not all interpretations of quantum mechanics adhere to the NCM assumptions. The Consistent Histories Interpretation [23], for example, asserts that physical states are defined by eigenstates, which are contextually defined by the system's measurement framework. It also abandons the strict objectivity of physical reality, however, by abandoning Unicity. In Quantum Bayesianism [24], the state is contextually defined and updated by an observer's information. The Von Neumann-Wigner interpretation attributes the physical collapse of the wavefunction to consciousness of an observation event [25]. Contextual interpretations are motivated by efforts to resolve conceptual problems of quantum mechanics, but they typically define context by an observer or its choices. Existing interpretations falsely frame the debate on physical reality as a choice between 1) accepting implausible and untestable metaphysical implications and 2) abandoning objective reality.

Any viable interpretation of quantum mechanics necessarily makes predictions consistent with observations. This begs the question of what difference any particular interpretation really makes? Reflecting Bohr's sentiment, there has been an aversion among many physicists toward 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!" [26].

We take a different position. Seeking an objective and realistic 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 are essential if we want to understand how nature works. To advance physics beyond its current focus on states and to understand the dynamics of complex systems confronting us, we need a conceptual model that embraces fundamental irreversible change. This requires nothing less than a major shift in our interpretation of physical reality.

2. The WCM Interpretation of State

The WYSIWYG conceptual model (**WCM**) is an alternative to existing non-contextual or subjective models of physical reality. Its paramount premise is that there are no hidden or unmeasurable properties: What You can See Is What You Get. Like any conceptual model of physics, the WCM is an axiomatic system based on 1) empirically validated physical facts, 2) fundamental premises, and 3) a definition of perfect measurement. The WCM accepts as true the empirically validated laws of physics. These include:

- Empirical conservation laws (e.g., energy, momentum, and charges)
- Empirical laws of motion
- Empirical laws of interaction (e.g., Law of gravitation, Planck's Law of radiation)

A conceptual model is a simplification of reality, based on well-documented empirical laws. Empirical laws are accepted as facts, but they are valid only within the domains of their empirical validation. A conceptual model is a simplification of reality, and it likewise is valid only within the domain of its definition.

2.1 Postulates and Definitions of State

In addition to empirical facts and physical laws, the WCM's interpretation of physical state is based on the following postulates:

Postulate 1: *There are no unobservable "hidden" variables. Physical properties of state are measurable, and perfect measurement completely describes a system's physical state.*

Postulate 2: *The Zeroth Law of Thermodynamics establishes that the temperature of a thermally equilibrated system is a measurable property.*

Postulate 3: *The Third Law of thermodynamics establishes that absolute zero temperature can be approached but never be attained.*

... and definitions:

Definition 1: *A system's ambient temperature, T_a , equals the positive temperature of the system's ambient surroundings, with which it interacts or potentially interacts.*

Definition 2: *A system's total energy, E , equals the system's potential work as measured on the surroundings in the limit of absolute zero.*

Definition 3: *A system's exergy, X , is defined by its potential work as measured at the ambient surroundings.*

Definition 4: *A system is in its ground state when its temperature equals the ambient temperature, and its exergy equals zero. The system's ground state is uniquely defined by equilibrium with its ambient surroundings.*

Definition 5: *A system's ground-state energy Q_{ss} is the potential work of the ground state as measured on the surroundings in the limit of absolute zero.*

Definition 6: *System energy is defined by $E_{sys} = E - Q_{ss}$.*

Definition 7: *A system's ambient heat is defined by $Q = E_{sys} - X$.*

Definition 8: *A system's entropy is defined by $S = Q/T_a$.*

Definition 9: Perfect measurement is a reversible and open process of transformation from a system's initial state to its ground state.

The WCM's postulates are firmly based on thoroughly validated empirical facts. Together with the definitions and the empirically validated fundamental laws of physics, they provide the logical foundation for the WCM and its explanations of empirical facts.

Postulate 1 is a statement about the WCM's interpretation of physical reality. Postulate 1 defines physical reality by perfect measurement. The microstate, which expresses everything measurable and knowable about a system, is therefore a complete description of the physical state. "State," without qualification, will refer both to a system's measurable microstate and to its underlying physical state.

Postulate 2 establishes temperature as a measurable property. The Zeroth Law of thermodynamics defines a system's temperature by the measurable temperature of the surroundings with which it is thermally equilibrated.

Postulates 1 and 2 enable the definition of ambient temperature as a contextual property of state (Definition 1). A system's ambient temperature is the temperature of the system's ambient surroundings, whether or not the system is equilibrated with or actively interacts with its surroundings.

Postulate 3 says that absolute zero temperature can be approached, but never reached. No system is perfectly isolated from its surroundings, and all systems have a positive ambient temperature. Even the universe, which by definition has no physical surroundings, has a boundary for the exchange of ambient photons, defined by the energy of its cosmic microwave background temperature at 2.7 kelvins.

Postulates 1 to 3 allow defining the ground state and its ground-state energy (Q_{gs}), system energy (E_{sys}), exergy (X), and ambient heat (Q) (Definitions 3–7). These are related to total energy (Definition 2) by:

$$E = Q_{gs} + E_{sys} = Q_{gs} + X + Q. \quad (2)$$

The total energy is independent of the ambient temperature, and it is non-contextual. All other energy components are contextually defined with respect to the system's ambient ground state reference. The ground state (Definition 4) has a positive ground-state energy, but, by definition, it has zero exergy and zero ambient heat.

Exergy includes the kinetic and potential energies of the system's resolvable parts. It is measured by the potential work on the ambient surroundings. Ambient heat is the randomized thermal energy at the ambient temperature, and it has zero potential for work on the ambient surroundings. The thermal exergy and ambient heat of an increment of heat dq at temperature T_{sys} are empirically given by:

$$dX_q = \left(\frac{T_{sys} - T_a}{T_{sys}} \right) dq \quad \text{and} \quad dQ = \left(\frac{T_a}{T_{sys}} \right) dq. \quad (3)$$

When combined with the Law of Conservation for energy, we can rewrite equation (2) as:

$$dE = dX + dQ + dQ_{gs} = 0. \quad (4)$$

If the ambient surroundings is fixed, then dQ_{gs} equals zero, and equation (4) shows that dissipation of exergy is offset by an increase in ambient heat. Equation (4) also expresses conservation of energy during changes in the ambient surroundings. A change in the ambient surroundings changes the ground-state energy, and from (3), it redistributes the system energy, but in the limit of perfect isolation, a system's total energy does not change.

2.2 Entropy

Definition 8 defines entropy by $S=Q/T_a$. Like ambient heat, entropy is a physical property of state, contextually defined relative to a system's ground state. The ground state has zero entropy, by definition.

The WCM entropy is a function of three independent variables: system temperature, ambient temperature, and a reaction progress variable, zeta (ζ). Zeta tracks the exchange

of ambient heat with the surroundings during an isothermal process at the fixed ambient temperature. It ranges from 0 to 100%. The WCM resolves entropy into two components, the ambient entropy, S_{amb} , and the entropy of refinement, S_{ref} . These are defined in (5) and illustrated in Figure 1:

$$\begin{aligned} S_{WCM} &= (S_{amb}) + (S_{ref}) \\ &= \left(\int_0^1 \left(\frac{\partial S}{\partial \zeta} \right) d\zeta + \int_{T_a}^{T_{sys}} \left(\frac{\partial S}{\partial T_{sys}} \right) dT_{sys} \right) - \left(\int_{T_a}^{T_{a,new}} \left(\frac{\partial S}{\partial T_a} \right) dT_a \right) \\ &= \left(\int_0^1 \left(\frac{\partial Q}{\partial \zeta} \right) \frac{d\zeta}{T_a} + \frac{1}{T_{sys}} \int_{T_a}^{T_{sys}} C_v(T) dT \right) - \left(\int_{T_a}^{T_{a,new}} C_v(T) \frac{dT}{T} \right). \end{aligned} \quad (5)$$

$C_v(T)$ is the temperature-dependent volumetric heat capacity, defined by $\left(\frac{\partial q}{\partial T} \right)_{v,\zeta}$ (and from (3), equal to $\frac{T_{sys}}{T_a} \left(\frac{\partial Q}{\partial T} \right)$). The negative sign for S_{ref} is because WCM entropy is defined relative to the ambient ground state, and as $T_{a,new}$ declines, S_{ref} increases.

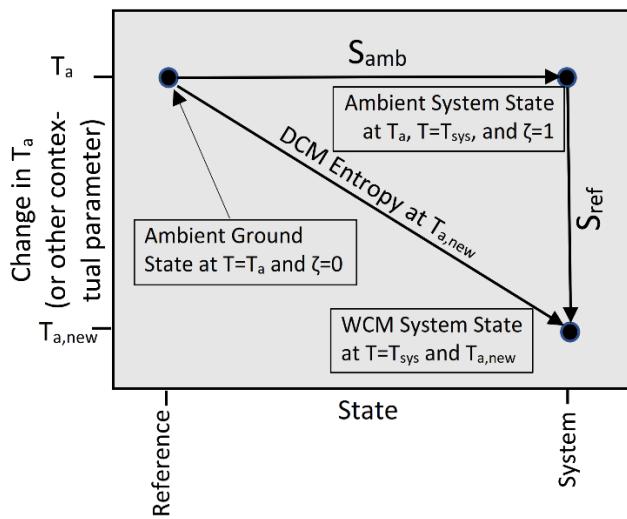


Figure 1. The Two Components of Entropy. The WCM resolves a system's entropy into the ambient entropy (S_{amb}) and the entropy of refinement (S_{ref}). S_{amb} describes the entropy due to changes in the system's temperature and ζ , at a fixed T_a . S_{ref} describes the entropy due to a change in ambient temperature or other contextual property of the ambient surroundings, prior to interaction with the system's new surroundings.

The ambient entropy (S_{amb} , horizontal vector in Figure 1) is the change in entropy as the system exchanges ambient heat with the surroundings at a fixed ambient temperature. As detailed in (5), this change is resolved into 1) an isothermal exchange of ambient heat at the ambient temperature, as the system progresses from $\zeta=0$ to $\zeta=1$, followed by 2) exchanges of ambient heat as the system's temperature progresses from T_a to T_{sys} at fixed $\zeta=1$. The entropy of thermal refinement (S_{ref} , vertical vector in Figure 1) is a consequence of a change in the ambient reference from T_a to $T_{a,new}$ at fixed zeta and system temperature.

In the limit of absolute zero ambient temperature, there is no ambient heat, so S_{amb} equals zero and S_{ref} equals S_{WCM} . This implies that for a system initially at its ambient temperature, as the ambient temperature approaches zero, we get (from the last term of (5)):

$$S_{WCM} \xrightarrow{T_{a,new} \rightarrow 0K} \int_0^{T_{sys}} \frac{dq}{T} = -k_B \sum_i p_i \ln(p_i). \quad (6)$$

The middle term is the third-law thermodynamic entropy, which is defined with respect to absolute zero. The right hand term is the Gibbs entropy of classical statistical mechanics [27], which is equal to the Third Law entropy. The p_i in the Gibbs entropy is the probability that observation reveals a microstate with energy E_i , where energy is defined with respect to absolute zero.

Equation (6) indicates that the WCM entropy is a contextual generalization of the thermodynamic and Gibbs entropies for real systems, as they exist with respect to ambient surroundings at a positive temperature. The WCM also generalizes the non-contextual Gibbs entropy (6) so that it is equal to the contextual WCM entropy:

$$S_{WCM} = -k_B \sum_i P_i \ln(P_i). \quad (7)$$

Whereas other generalized entropies, such as Rényi and Tsallis entropies, revise the mathematical formulation of the Gibbs entropy, equation (7) is mathematically identical to the Gibbs entropy. The WCM instead revises the interpretation of the P_i .

The Gibbs entropy and its statistical generalizations interpret the P_i as the probability that the system is actually in microstate 'i.' They are "informational" entropies, expressing the subjective uncertainty of a system's actual state. As discussed in Section 3, the WCM entropy interprets the P_i as the objective probability that uninstantiated potentiality 'i' will become instantiated as the system's observable microstate. The WCM entropy is a physical property of state, describing the system's positive-entropy microstate prior to instantiation of its potentialities and wavefunction collapse.

2.3 Perfect Measurement

Perfect measurement is defined by Definition 9 as a reversible transformation between a system and its ground state. It is an open reversible process involving an observer and a record of the system's changes during measurement (Figure 2). The record of the transformation process preserves the exergy needed to reverse the process and restore the system to its initial state. If the same change in state occurs in isolation, without a record of the changes, the initial state cannot be restored, and the process is not reversible.

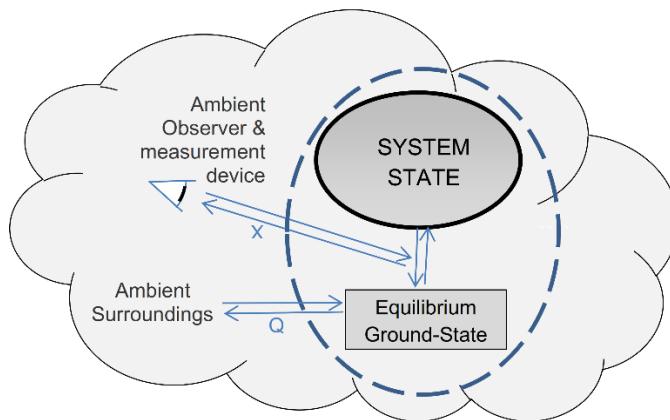


Figure 2. Perfect Measurement. Perfect measurement is a reversible transformation from the system's positive-exergy state to its ground-state reference in equilibrium with its ambient surroundings. Perfect reversible measurement involves an ambient observer or measurement device to record the process 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 state, but reversible measurement is not always possible. The Quantum Zeno effect shows that a continuously measured (and measurable) state does not change irreversibly [29]. The contrapositive of this is equally true; an irreversibly changing system is not continuously measurable. A system can be reversibly measurable *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 WCM state. It is in irreversible transition between states.

2.4 Classical and Quantum States

Table 1 describes the WCM interpretations of an ideal classical gas and a hydrogen atom. We initially consider the ground-state gas and hydrogen atom in equilibrium with

their ambient surroundings. We assume that the gas is in equilibrium with a thermal bath at T=500K and the hydrogen atom is in equilibrium with a black body at T=6000K.

Table 1. WCM States and Contextual Properties

Energy Component	n-Particle Ideal Gas	Hydrogen Atom at Temperature T	Contextual?
NCM Description	Thermodynamic State (T,P,V)	$\Psi(T) = \sum_i c_i(T) \psi_i$ where $\sum_i c_i(T) ^2 = 1$	No
Energy (total)	$E = n k_B T$	$\langle E(T) \rangle = \sum_i E_i \times c_i(T) ^2 = \sum_j p_j(T) E_j$ ⁽¹⁾	No
Q_{gs} (ground-state energy)	$Q_{gs} = n k_B T_a$	$Q_{gs} = \langle E(T_a) \rangle = \sum_j p_j(T_a) E_j$	Yes
E_{sys} (system energy)	$E_{sys} = E - Q_{gs}$	$\langle E_{sys}(T) \rangle = \langle E(T) \rangle - Q_{gs} = \sum_j E_j (p_j(T) - p_j(T_a))$	Yes
$Q = T_a(S_{ref} + S_{amb})$ (ambient heat)	$Q = T_a \left(\int_{T_a}^{T_{sys}} C_v \frac{dT}{T} + 0^{(2)} \right)$	$\langle Q(T) \rangle = T_a \left(\int_{T_a}^T \left(\frac{\partial \langle E(T) \rangle}{\partial T} \right) \frac{dT}{T} + 0^{(2)} \right)$	Yes
X (exergy)	$X = E_{sys} - Q$	$\langle X(T) \rangle = \langle E_{sys}(T) \rangle - \langle Q(T) \rangle$	Yes
$S_{WCM} = Q/T_a$ (entropy)	$S_{WCM} = \frac{Q}{T_a} = \int_{T_a}^{T_{sys}} C_v \frac{dT}{T}$	$\langle S_{WCM}(T) \rangle = \frac{\langle Q(T) \rangle}{T_a} = \int_{T_a}^T \left(\frac{\partial \langle E_{sys}(T) \rangle}{\partial T} \right) \frac{dT}{T}$	Yes

k_B = Boltzmann constant. C_v =volumetric heat capacity. $\langle \rangle$ indicate the time-averaged properties.

(1) The expectation energy value is defined by a weighted sum over the eigenfunction energies E_i , which typically includes numerous degenerate and unresolvable eigenfunctions sharing the same energy. The WCM expresses the energy expectation value as a weighted sum over their discrete microstate energies E_j .

(2) The only change considered is the ambient temperature. From (5), S_{amb} therefore equals zero.

Thermodynamics defines the gas's state non-contextually, in terms of its temperature, pressure, and volume (Table 1, rows 1 and 2). The WCM, in contrast, defines the gas's state contextually, by recognizing the gas's ambient surroundings and by including the system's contextual properties of state (bottom five rows).

If we lower the gas's ambient temperature from 500K to 300K. The change in ambient temperature immediately changes the gas's contextual properties, as shown in Table 1. If the gas is perfectly insulated so that there is no heat loss and the gas temperature remains undisturbed, the non-contextual thermodynamic state is unchanged, but the gas becomes metastable. The WCM microstate has a positive exergy, which defines its potential to approach its new ambient ground state at 300K. Its positive exergy is measured by the work that could be reversibly extracted by a perfect heat engine. The gas at 500K also has positive entropy with respect to its ground state at 300K. The metastable state describes the gas after refinement, but prior to interaction with the new surroundings.

In the case of the equilibrium ambient gas at 500K, the gas defines its own ground state. The ambient temperature equals the gas temperature, the ground state energy equals its total energy, and all other contextual properties equal zero. The non-contextual thermodynamic state and the contextual WCM state are essentially identical descriptions for the special case of an equilibrium ground-state gas.

Quantum mechanics defines the hydrogen atom's quantum state by its superposed wavefunction (Table 1, row 1). The eigenfunctions are independent of temperature, but their complex weighting coefficients, and the wavefunction, are functions of the hydrogen atom's equilibrium temperature. The non-contextual wavefunction uniquely specifies the atom's total energy, defined in Row 2.

If we perfectly isolate the hydrogen atom and lower its ambient temperature to 300K, the hydrogen atom is "frozen" in a metastable microstate. The WCM microstate is

contextually defined by its measurable properties: the non-contextual energy, defined by the last term of row 2 as a function of the measurable temperature, and the atom's contextual properties. For the special equilibrium case, the ground-state energy equals the total energy and the other contextual properties are all zero. The equilibrium ground state is defined by its temperature and energy alone.

The wavefunction plus the system's contextual properties also completely specify the atom's microstate, but the wavefunction provides much more information than the expectation energy function. This is because the wavefunction is defined by quantum tomography to include measurable information from all possible measurement frameworks. The wavefunction plus contextual properties uniquely specifies the atom's WCM state, but WCM microstate constitutes a minimally complete definition of state.

In the limit of absolute zero ambient temperature, particles' coordinates are precisely definable. At absolute-zero ambient temperature, there is no possibility of dissipation, randomness, or irreversibility. Contextual properties either equal zero (ambient heat, entropy, ground-state energy), or, in the case of exergy, it equals the total energy. The state becomes essentially non-contextual. The WCM state was previously seen to become essentially non-contextual in the limit of equilibrium ground-state systems. In both cases, change is reversible and deterministic. Between these two idealized extremes, the WCM describes systems as they exist with respect to positive temperature ambient surroundings, as non-equilibrium metastable states with positive entropy and exergy. This is the zone of contextuality, and this is where irreversibility and randomness occur.

3. State Transitions

The WCM makes a fundamental distinction between states and transitions. A state is static, with reversibly measurable properties. An irreversible transition involves a process of change from one state to another state of higher stability. During irreversible change, state properties are not reversibly measurable, and the system does not exist as a state.

3.1 Dissipation of Exergy

Postulate 4 formalizes the definition of irreversible change by the dissipation of exergy:

Postulate 4 (Second Law of Thermodynamics): *An irreversible process dissipates exergy to ambient heat.*

The Second Law of thermodynamics defines irreversible change by the production of entropy. Thermodynamic entropy is formally defined non-contextually with respect to a fixed reference, either at absolute zero (Third Law entropy) or at the fixed temperature of a heat bath with which the system is thermally equilibrated. The WCM generalizes entropy by defining it with respect to the positive ambient temperature of the system's surroundings, which is not necessarily fixed or equal to the system's temperature. The WCM nevertheless follows the Second Law's convention, by defining irreversibility by the increase in ambient entropy:

$$dS_{amb} = \frac{dQ}{T_a} = -\frac{dX}{T_a} = -d\left(\frac{F}{T}\right) \quad (\text{at fixed ambient surroundings}). \quad (8)$$

The first equality follows from Definition 8 and (5) at fixed ambient temperature; the second equality follows from (4) at fixed ambient temperature. The WCM defines irreversibility by the dissipation of exergy ($-dX$), and this equals the increase in the ambient entropy. Irreversibility notably does not include the increase in the entropy of refinement. Change in the entropy of refinement simply reflects a change in the ambient surroundings and a reversible shift in the scale for measuring entropy.

Equation (8) also shows the thermodynamic free energy. Free energy (F) is similar to exergy, but it is defined by work potential measurable at the system's local and generally variable temperature. The free energy of a non-isothermal system is not defined with respect to a well-defined reference state, and it is not a state property within the WCM.

The Second Law of thermodynamics has been thoroughly validated by empirical observations. NCMs do not recognize it as a fundamental law of physics, however, because they do not recognize entropy as a fundamental physical property of state. The WCM does establish entropy and exergy as physical properties, and it establishes Postulate 4 and the thermodynamic arrow of time as a fundamental law.

3.2 Refinement and Metastability

If a system has no exergy, then by Postulate 4, there can be no irreversibility. An equilibrium system with zero exergy can acquire exergy through refinement, however. In section 2.2, we defined thermal refinement due to a decline in the ambient temperature. A decline in ambient temperature shifts energy from ground state to system energy. It also shifts system energy from ambient heat to exergy (3). Table 1 detailed these effects for thermal refinement of an ideal ambient gas. A transition from a system initially at equilibrium with zero exergy starts with the creation of exergy by refinement.

We can quantify the increase in entropy of thermal refinement by differentiating entropy (5) with respect to $T_{a,new}$ at fixed ambient temperature and reaction progress variable. This gives:

$$dS_{ref} \equiv \left(\frac{\delta S}{\delta T_{a,new}} \right)_{T_a, \zeta} dT_{a,new} = -C_v \frac{dT_{a,new}}{T_{a,new}}. \quad (9)$$

Equation (9) shows the increase in entropy due to a decline in the ambient temperature, prior to any adjustment to the changed reference. As previously noted, the increase in entropy by refinement is a reversible process, only involving a reversible shift in the entropy scale.

The concept of refinement was originally introduced by Robert Griffiths in his Consistent Histories Interpretation of quantum mechanics [23]. Quantum refinement entails a change in measurement framework, replacing an eigenfunction and single measurable potentiality with a superposed wavefunction and multiple compatible potentialities.

To illustrate quantum refinement, we consider a quantum particle confined to a one-dimensional infinite-potential well. The physical system is illustrated in Figure 3A, and its quantized energy levels are illustrated in Figure 3B. The energies for the particle's eigenfunctions are given by [30]:

$$E_n = \frac{n^2 \hbar^2}{2mL^2}, \quad (10)$$

where n is the energy eigenstate's quantum number, \hbar is the reduced Planck constant, m is the particle's mass, and L is the length of the one-dimensional configuration space over which the wavefunction is defined.

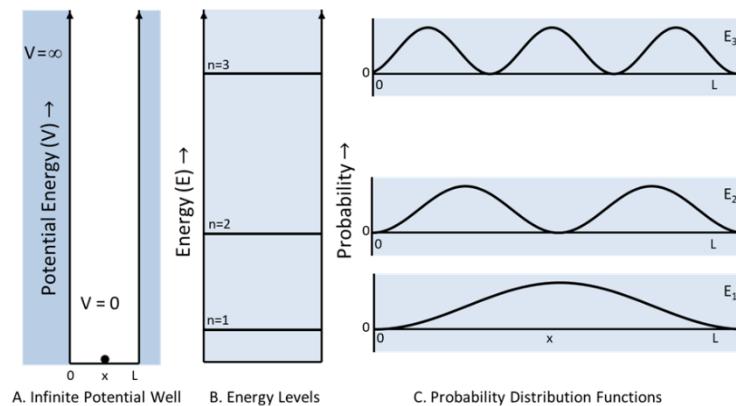


Figure 3. Quantum Particle in a 1D Potential Well.

Figure 3C shows the probability distribution function (PDF) for each energy level. The PDFs are defined over the configuration space of positions. Positions are statistically and irreversibly measured in the limit of zero thermal noise and infinite resolution (i.e., at

absolute zero). Each PDF corresponds to the particle's energy eigenfunction, except that the amplitude is squared, so the PDF's value reflects the probability of measuring the particle at a particular location. The PDF outside the well is zero, and the area under each PDF within the interval is one, meaning that measurement of the particle's position would find it somewhere within the interval 0 to L with a 100% probability.

PDF_3 describes the statistical results of position measurements for a particle with energy E_3 . PDF_3 has three equal humps spanning the particle's configuration space. This means that irreversible measurements on an ensemble of identical systems would find the particles' positions equally distributed among the three distinct intervals, with probabilities declining to zero at the intervals' edges.

If the particle is in equilibrium with its surroundings, then the particle's ground-state energy E_{gs} equals E_3 , and from the definition of perfect measurement (Figure 2) and Postulate 1 (no hidden variables), PDF_3 expresses everything that is measurable and knowable about the particle. PDF_3 therefore defines the particle's position as a single three-humped microstate and a single "pixel" spanning the particle's configuration space.

We now consider the effect of reducing the energy of the ambient surroundings, so that the particle's new ground-state energy equals E_1 and the ground-state quantum number is $n_{gs}=1$. The particle's energy, however, remains E_3 , its energy quantum number remains $n=3$, and PDF_3 remains its energy microstate.

Refinement increases the microstate's entropy and exergy. Its higher exergy expresses the particle's potential to transition to its new stable ground state. Its higher entropy expresses the fine graining of PDF_3 from a single microstate spanning its configuration space to three distinct microstate potentialities, each spanning a length of $L_{pot} = L/3$. L , L_{pot} , n and n_{gs} are related by:

$$L/n = L_{pot}/n_{gs}. \quad (11)$$

Prior to refinement, PDF_3 spans a single microstate potentiality. With a single potentiality, its probability equals 1 and from (7), its entropy is trivially equal to zero. Following refinement, PDF_3 is fine-grained into three separate microstate potentialities. If each potentiality has equal probability, then $P_1 = P_2 = P_3 = 1/3$, and from (7), $S_{wcm} = k_B \ln(3)$. The positive entropy of refinement expresses the objective randomness of selecting and instantiating one of its $L/3$ microstate potentialities.

A real-world example of refinement is the casting of a radioisotope from its environment of formation within a supernova or merging neutron stars. During the radioisotope's formation, it is near equilibrium with its local ambient surroundings, and its entropy and exergy are near zero. After it encounters the cold of interstellar space, refinement creates a positive exergy, reflecting the particle's potential for radioactive decay, and a positive entropy, reflecting the objective randomness of instantiating one of its new microstate potentialities.

A metastable system has a potential to irreversibly transition to a state of higher stability, but it can delay its reequilibration and persist as a metastable state with positive exergy. The thermodynamic stability of nonequilibrium metastable states has been investigated by Glansdorff et al. [31]. The rates and dynamics of the equilibration process are the subject of reaction kinetics. These fields are beyond the WCM's scope, but the WCM provides a firm foundation to support their analysis.

Refinement and metastability is the first stage of a transition process for a system initially at equilibrium. A reduction in the ground-state energy creates exergy and makes an initially equilibrium system become metastable with respect to its new ground state. Dissipation of a metastable system's exergy can occur as an isolated process or as an open-system process. Each of these is discussed in the following sections.

3.3 Isolated Process of Irreversible Dissipation

A purely dissipative process of irreversible change occurs in isolation. In the WCM, isolation means ambient isolation, in which a system is closed to exchanges of mass and exergy, but open to the exchange of ambient heat. The rate of ambient heat or photon

exchange can be reduced, but it cannot be eliminated, and there is no perfect isolation of ambient energy.

Irreversible dissipation to the ground state occurs as an ambient-isolated process. Ambient heat, which is initially present following refinement and subsequently produced by dissipation, is leaked to the ambient surroundings. This leaves the system in its final equilibrium ground state, with zero ambient heat, zero exergy, and zero entropy. The initial and final states are measurable and uniquely defined, but in between, the system is isolated and irreversibly changing. During isolated dissipation, the system is in irreversible transition between states and it is not measurable.

3.4 Open-system Selection and Actualization

A metastable system more commonly interacts with its surroundings during its transition towards its equilibrium ground state. To illustrate an open-system transition, we again consider the particle in a box example (Figure 4).

PDF₃ in Figure 4A describes the energy eigenstate for the particle in a box with energy E₃ in equilibrium with its ground state. Its energy defines its ground-state energy, and it has zero entropy. Lowering the ground-state energy from E₃ to E₁ refines PDF₃ from a single microstate potentiality to three microstate potentialities spanning configuration space (Figure 4B). The refined PDF₃ represents a superposed wavefunction spanning three distinct position eigenfunctions. Its positive WCM entropy expresses the objective uncertainty of which microstate potentiality will be randomly selected and instantiated. In contrast, the von Neumann entropy [28], which is the quantum mechanical extension of the Gibbs entropy, considers a superposed wavefunction as a pure state, with zero entropy.

PDF₃ in Figure 4C describes a statistical mix of measurable eigenfunctions following collapse of the superposed wavefunction in Figure 4B and the instantiation of one of its potentialities. The process is random, but it is a reversible process, involving the reversible transfer of ambient heat to the surroundings. The transfer of ambient heat to the surroundings sets the system's entropy to zero, and from (7), this instantiates a single microstate potentiality. The WCM entropy equals zero, but the informational von Neumann entropy assigns the mixed state a positive entropy, which it attributes to irreversible and random collapse of the 4B and to the subjective uncertainty of the instantiated microstate. Subsequent observation reveals the existing state and resets the informational entropy to zero.

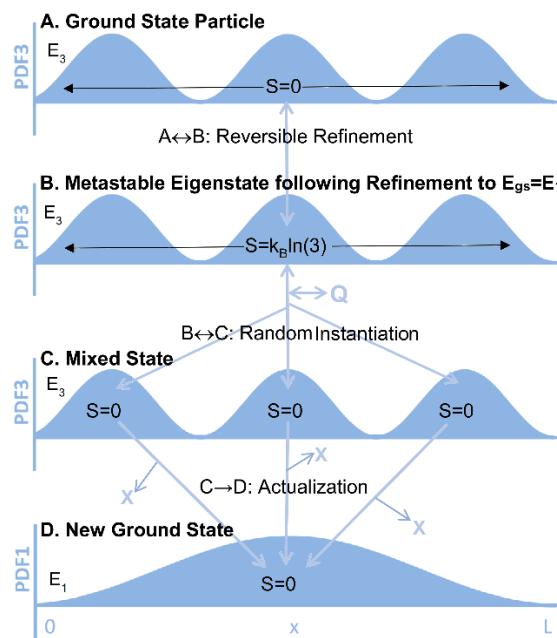


Figure 4. Open Transition Steps for Particle in a Box.

A: PDF₃ represents a ground-state eigenstate with energy equal to E₃.

B: PDF₃ represents a positive-entropy metastable state following reversible refinement of "A" to E_{gs}=E₁. Each hump represents a microstate potentiality. Refinement is the first step of transition

from the initial ground-state eigenstate “A”.

C: PDF_3 represents a mixed state following random selection and instantiation of one of the potentialities in “B.” Randomness of selection is reversibly offset by a transfer of ambient heat and entropy to surroundings. The instantiated eigenstate has zero entropy, but its energy is still E_3 .

D: PDF_1 represents the new ground state. During transition of the selected potentiality in “C” to the new ground state, some of the system’s exergy is utilized to do work of actualizing changes in the surroundings.

The final stage of transition is actualization. During the process of actualization (transition C→D), the system’s exergy is partially utilized to actualize changes in the surroundings. In the idealized case in which the system’s exergy is fully utilized, the process is thermodynamically reversible. This describes the process of perfect reversible measurement, illustrated in Figure 2, in which there is no dissipation within the measured system. For a real process of actualization, the system typically dissipates some of its exergy to the surroundings. Dissipation is irreversible, even while the system’s entropy remains zero.

The objective randomness of instantiation and actualization are key to resolving the measurement problem. At some unknowable point in time, the radioisotope in Schrödinger’s cat experiment randomly instantiates a potentiality, which then irreversibly decays to a more stable state. As the particle decays, some of its exergy actualizes the measurement device, which triggers the cat’s death. During the decay process, the system is in irreversible transition *between* measurable states of live-cat and dead-cat. At no time, however, does the particle or its entangled cat exist as part of a physically superposed state. The measurement problem thereby vanishes.

3.5 Maximizing Work

When a metastable system transitions to a more stable state, there is an opportunity to utilize some of the system’s exergy for work. Lord Kelvin recognized this in an article he wrote in 1862 [32]. 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 expressed the empirical observation that exergy is first utilized for palpable work, before it is eventually dissipated 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. It is compatible with the WCM, however, and we formalize his empirical observation with Postulate 5:

Postulate 5: *During transition of a metastable system to a more stable state, the system tends to maximize its work on the surroundings.*

Postulate 5 is similar to the Second Law of thermodynamics, but whereas the Second Law describes the relative stability of a state based on its lower exergy, Postulate 5 describes the relative stability of a transition based on its higher work output. In the limit of perfect efficiency, there is no dissipation of exergy, and the transition is reversible.

Postulates 4 and 5 operate in concert during a transition. Postulate 4 recognizes that dissipation of exergy is the driving force for irreversible change. Postulate 5 seeks to increase the efficiency of irreversible change.

4. Information, Time, and Entanglement

Information is strictly conserved in non-contextual interpretations of quantum mechanics. The conservation of information within a spatially extended entangled system, however, presents a conceptual challenge to relativity and the principle of locality, which states that effects and information cannot propagate faster than light. The WCM provides a logically consistent framework for reconciling relativity with the instantaneous correlation of measurements of entangled particle pairs.

4.1 Information and the Conservation of Symmetry

Claude Shannon defined information by the Shannon entropy [33]. Like the statistical mechanical entropy on which it is based, Shannon entropy is an informational entropy. It interprets the P_i as the probability for each possible meaning of a message. It is the “surprise factor” of a message’s actual meaning, relative to prior knowledge.

The WCM similarly defines the information of a physical state by its informational entropy:

Definition 10: A system’s information content is defined by its informational entropy $S_{info} = -\sum_i P_i \log(P_i)$, where P_i is the probability that the system currently exists in state ‘ i ’.

Informational entropy is a subjective property of an observer’s uncertainty, and unlike WCM entropy, it is not a physical property of state.

Dissipation destroys information by irreversibly transitioning a metastable state towards its unique and known equilibrium ground state of zero informational entropy. The WCM also allows for the creation of information. To illustrate the creation of information and the conservation of a property’s underlying symmetry, we consider the Stern-Gerlach experiment [34]. The Stern-Gerlach experiment first established quantized spin as a measurable property of state.

The Stern-Gerlach experiment sent a horizontal stream of silver atoms through a magnetic field. The magnetic field was uniform in the horizontal directions, but it diverged vertically downward. Silver has one unpaired electron, and its spin creates a magnetic dipole. The experiment showed that in the absence of the magnetic field, the silver atoms traverse a straight trajectory to a target. When the magnetic field is applied, it exerts either an upward or downward force on the atoms, depending on the orientation of the dipole and the vertical gradient in the magnetic field. Observations revealed two discrete diverging trajectories, indicating that the quantum spins were quantized, described as either “spin-up” or “spin-down.”

Non-contextual models interpret each atom’s state, prior to encountering the magnetic field, as an indefinite superposition of spin-up and spin-down states. After an atom encounters the magnetic field, measurement reveals either an upward acceleration or downward trajectory, which the NCMs interpret as collapse of the superposed state to a definite state of spin-up or spin-down.

The WCM has a different interpretation. Before an atom encounters the magnetic field, its spin is not measurable, and it therefore has no spin. Encountering the magnetic field leads to refinement and to the creation of spin-up and spin-down potentialities. Experimental data show that spin-up and spin-down potentialities have equal probabilities of being instantiated. From (7), refinement by the magnetic field increases its WCM entropy to $S=k_B \ln(2)$. This occurs prior to any interaction between the system and its surroundings. Whereas the refinement increases the particle’s physical entropy, it has no effect on the informational von Neumann entropy, which remains zero following refinement to a superposed wavefunction (Figure 4B). Refinement does not alter a system’s information content.

Interaction with the surroundings and reversible transfer of ambient heat resets the system’s physical entropy to zero and, from (7), this randomly instantiates one of its two potentialities. Refinement and instantiation create a new measurable property of spin-up or spin-down, where previously there was no property. This creates uncertainty of the actual state, where previously there was no uncertainty. From Definition 10, this constitutes the creation of information. Uncertainty and informational entropy are created as a consequence of transferring ambient heat and physical entropy to the ambient surroundings.

The instantiation of either the spin-up or spin-down potentiality violates the symmetry of an atom’s initial null spin state. Empirical data show that the probabilities of the two potentialities are equal, however, and this ensures that over multiple measurements, the spin symmetry of the atoms’ initial null spin state is statistically conserved.

The conservation of spin for individual particles is necessarily statistical, but conservation of spin symmetry can be and is imposed on pairs of entangled particles. If a particle decays into a pair of entangled particles and the pair encounters the magnetic field, there are four possible spin-state potentialities: $\uparrow\uparrow$, $\uparrow\downarrow$, $\downarrow\downarrow$, and $\downarrow\uparrow$. Experimental data show that the probability of $\uparrow\uparrow$ or $\downarrow\downarrow$ being actualized is zero, and the probability of $\uparrow\downarrow$ or $\downarrow\uparrow$ being actualized is each fifty percent. This ensures that only an anticorrelated entangled pair is randomly selected, thereby conserving the null state's spin symmetry. (Even as spin symmetry is conserved, however, information is still created by the random instantiation of either $\uparrow\downarrow$ or $\downarrow\uparrow$.)

The conservation of spin is accepted as a fundamental principle of physics, but this immediately leads to the question of how instantaneous correlations in spatially separated spin measurements can be reconciled with special relativity and the principle of locality. This is the question of nonlocality, posed by Einstein and colleagues in their 1935 article [14]. The WCM offers a resolution to this problem, but we first need to address the WCM's interpretation of time for an irreversible relativistic system.

4.2 The Two Components of System Times

The WCM makes a fundamental distinction between reversible and irreversible change, and it recognizes fundamentally distinct components of time for each.

Thermodynamic time records the irreversible dissipation of a system's exergy at a fixed ambient temperature. The exergy for a first-order kinetic system¹, for example, is given by:

$$X(t_q) = e^{-\lambda t_q} X_0, \quad (12)$$

where X_0 is the initial exergy, λ is a dissipation rate constant, and t_q is thermodynamic time. Equation (12) can describe the dissipation of exergy during macroscopic radioactive decay. At time zero, the system's exergy equals its initial exergy, X_0 , and as time advances toward infinity, the system's exergy approaches zero at equilibrium (100% decayed). Thermodynamic time is an objective contextual property of state and a logical consequence of empirical data and the postulates of state. As a contextual property, it is incompatible with, and it is ignored by, NCM interpretations.

Mechanical time describes the reversible and deterministic change of a system, while it is reversibly measurable and exists as a state. It is represented by classical mechanics as a position coordinate on a system's trajectory in phase space, and in special relativity, as a coordinate on the time axis of spacetime. Mechanical time has no direction, and it can be treated like a dimension of space.

Mechanical time is conventionally defined as a real-valued coordinate in complex Minkowski spacetime, but this is merely a matter of convention. The WCM 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 coordinate of imaginary mechanical time. The WCM changes mechanical time to an imaginary parameter, but it leaves all equations of mechanics unchanged. For example, the WCM expresses the time-dependent quantum wavefunction for an isolated (fixed energy) and metastable (non-reactive) quantum system, by:

$$\psi(x, it_m) = e^{\frac{-it_m E}{\hbar}} \psi_0(x). \quad (13)$$

Except for the change in the function's argument for time, (13) is identical to the conventional expression for the system's time-dependent wavefunction.

System Time: Equation (12) describes the continuous dissipation for a many-particle thermodynamic system. In the quantum limit, dissipation by a metastable particle is discontinuous. Periods with no dissipation mark intervals during which the particle exists as a well-defined and reversibly measurable metastable state. Its time evolution is indexed by a reversible time coordinate. At some point, however, the particle irreversibly

¹ One in which the system's rate of exergy dissipation is proportional to its exergy.

transitions to a more stable state. An irreversible transition marks an interval of dissipation and an irreversible advance in thermodynamic time. A metastable particle therefore requires both mechanical time and thermodynamic time to describe its behavior.

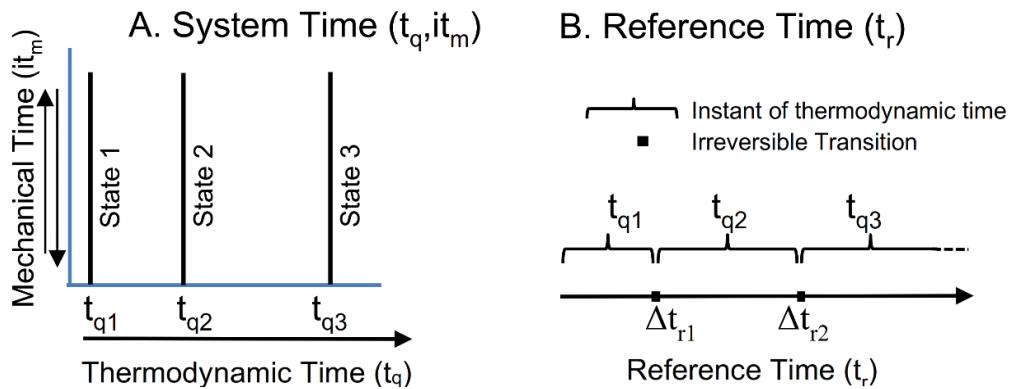


Figure 5. Complex System Time and Reference Time. Figure 5A shows the complex system-time plane, spanned by real-valued thermodynamic time (horizontal axis) and imaginary mechanical time (vertical axis). Figure 5B shows the irreversible advance in an observers' reference time during changes in system-time. 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.

The WCM 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 in a state, within a single instant of thermodynamic time. A change over real thermodynamic time (horizontal axis) describes the irreversible dissipation of exergy and transition to a more stable state.

4.3 Reference Time

Reference time is the time recorded by an observer's clock, and it provides the time scale across which a system's events and velocities are recorded. Reference time is the time of relativity, which states that the speed of light, as measured by a reference clock, is the same for all inertial reference frames. Relativity equates the mechanical time (coordinate of spacetime) and reference time, but in the WCM, they are distinct.

System time, whether it proceeds reversibly or irreversibly, is empirically measured by the advance of reference time, t_r (Figure 5B). Reference time marks the continuous and irreversible "flow" of an observer's time.

4.4 Entanglement and Nonlocality

We can now consider how quantum nonlocality coexists with relativity. We consider the irreversible decay of a metastable particle into two particles emitted in opposite directions. For simplicity, we will consider the emission of a photon pair, illustrated in Figure 6. The photon pair is created at point O, and, after an interval of time, Alice and Bob simultaneously measure the photons' polarizations at points A and B. Measurement results are strictly and instantaneously anticorrelated; if Bob measures a vertically polarized photon, then Alice measures a horizontally polarized photon. 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 anticorrelated measurement results. Einstein famously referred to nonlocal correlations as spooky action at a distance.

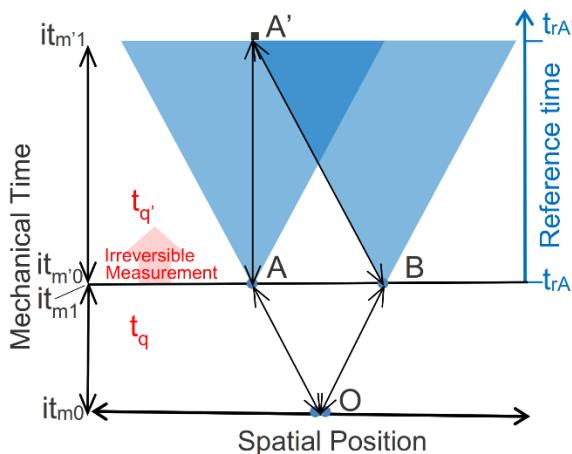


Figure 6. Instantaneous Correlation of Spatially Separated Measurements. The figure spans space (projected onto the horizontal axis) and mechanical time (left vertical axis). Mechanical time spans two reversible intervals at two distinct instants of thermodynamic time, separated by the irreversible actualization of photon measurement results. Alice and Bob reversibly record their measurement results for the photons at points A and B, at system time ($t_q, it_{m'0}$). Superimposed on the diagram are light cones advancing across reference time (right vertical axis), from the measurement events at A and B. Each shows the domain of causal effects within the empirical constraints of relativity and locality. Alice records her results at reference time t_{rA} and at subsequent reference time $t_{rA'}$, she receives the results recorded by Bob at point B and transmitted to Alice via a light signal.

Quantum mechanics describes the photon pair prior to measurement as entangled particles within a single quantum state. The entangled state instantly collapses into a definite measurable state upon measurement, regardless of its physical extent. The question is: how can spatially separated entangled particles instantly coordinate their measurement responses within the constraints of special relativity and Bell's theorem (without invoking superdeterminism, in which case the measurement results were predetermined at the beginning of time)?

Before addressing this question, we need to address the meaning of entanglement. The WCM defines entanglement by:

Definition 11: *Physically separated particles are part of an entangled quantum system if they are connected by a reversible chain of causality.*

From the creation of the photon pair up to the irreversible actualization of measurement results, the photons reversibly evolve across mechanical time within an instant of thermodynamic time at t_q (Figure 6). Reversibility means no irreversible dissipation and no arrow of mechanical time. With no arrow of mechanical time, mechanical time is not just reversible; it is also time symmetrical. With time symmetry, asserting that a cause produces an effect and asserting that an effect produces a cause are equally valid. This expresses the idea of retrocausality [35,36], and it exists over time-symmetrical mechanical system time. The photon pair is connected by a time-symmetrical chain of causality and retrocausality, illustrated in Figure 6 by $A \leftrightarrow O \leftrightarrow B$. From Definition 11, the photon pair exists as an entangled system from the instant of its creation up to the moment of irreversible measurement.

The photons encounter vertical polarizing filters prior to their measurement. The filters change the photons' surroundings and reversibly refine the pair, creating spin-state potentialities. A reversible chain of causality links the photon pair across a single instant of thermodynamic time at t_q , and spin conservation limits the pair to the two anti-correlated potentialities, ($\uparrow\leftrightarrow\downarrow$) and ($\downarrow\leftrightarrow\uparrow$). Instantiation preserves spin symmetry, regardless of which potentiality is randomly selected.

When the anti-correlated measurement results are irreversibly actualized, thermodynamic time advances from t_q to $t_{q'}$, and mechanical time is set to a new interval of time

symmetry, it_m . Alice and Bob simultaneously observe their measurement results at system time (t_q, it_m) . Bob transmits his results via a light signal, Alice receives the signal at point A' and system time (t_q, it_m') , and she is able to verify that Bob's results are anticorrelated with hers. Alice's and Bob's observations of their measurement results, Bob's transmission of his results, and Alice's recording of his results are reversibly conducted within the instant of thermodynamic time t_q .

Whereas Alice and Bob reversibly record their measurement results within a single instant of thermodynamic time, their record of events across reference time is very different. The righthand axis of Figure 6 shows the record of Alice's measurement events at points A and A', as measured by her reference clock. Even when the events at A, A' and B are reversibly linked within an instant of thermodynamic time via $A \leftrightarrow A' \leftrightarrow B$ (Figure 6), her reference clock continues to mark the irreversible passage of her reference time. Alice experiences the irreversible passage of time between recording her measurement at time t_{rA} and her recording of Bob's measurement result at $t_{rA'}$. The irreversible flow of an observer's reference time and the empirical constraints of relativity preclude superluminal exchange of information between observers across reference time.

There is no conflict between nonlocality and relativity or locality, because nonlocality expresses the action of a reversible process across mechanical time, within a single instant of thermodynamic system time, whereas the speed of light and the light cone of causality are defined across irreversible reference time. The WCM resolves the problem of nonlocality by distinguishing between complex system time and reference time, as measured by the continuous advance of an observer's reference clock. The WCM successfully explains the mechanical details of nonlocality and it explains how relativity and quantum nonlocality compatibly coexist, without spooky action, hidden variables, or superdeterminism.

5. Discussion

5.1 Quantum Randomness

Quantum thermodynamics [37], stochastic quantum mechanics [21], and quantum decoherence interpretations [6] attribute time's arrow to random environmental fluctuations. Like the WCM, they separate a system from its surroundings. However, they then assert the theoretical existence of a wavefunction for the entire universe. This implies that time change for the universe as a whole is unitary, deterministic, and reversible. Fluctuations within a system's surroundings may be unknowable and their effects on the system may be unpredictable, but their randomness is not fundamental.

The universe, by definition, has no physical surroundings, but the WCM recognizes the vacuum state as an ambient energy boundary. We have focused on the quantum electrodynamic field, but each type of field has its own non-zero ambient energy. The vacuum state's positive ambient energies define the ground state for the universe. The ambient energy boundary contextually partitions the universe's energy into exergy, ambient energy, and ground-state energies.

The first step of a metastable particle's transition is to randomly and reversibly instantiate one of its potentialities. That potentiality then approaches its equilibrium zero-exergy ground state. As the particle decays, its exergy is utilized to the extent possible to actualize changes in the ambient surroundings, in accordance with Postulate 5. A random transient fluctuation occurs in the surroundings when that change quickly dissipate its just-acquired exergy. We see that rather than causing irreversible change, random environmental fluctuations are a consequence of a metastable system's irreversible changes.

In their book, *The End of Certainty*, Prigogine and Stengers document mechanical instabilities that can amplify quantum fluctuations to macroscopic and measurable scales [38,39]. Given the objective existence of quantum randomness, their work describes the physical process of amplifying quantum randomness to measurable randomness and novelty. Their work and the objective existence of quantum randomness resolves the problem of measurable physical randomness.

5.2 The Cosmological Arrow of Time

It is generally accepted that the entropy of the universe has increased over time. Non-contextual interpretations describe increases in entropy over time using statistical mechanics. However, statistical mechanics is based on time-symmetrical laws, and it cannot by itself define a direction of entropy increase. Statistical mechanics describes a probabilistic increase in entropy both forward and backward in time. It requires an initial boundary condition in time, a “past condition” of low entropy, in order to establish a direction of time.

Ellis and Drossel subscribe to the evolving block universe model, which attributes the cosmological arrow of time to cosmic expansion and a past condition [3]. They state:

“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.”

They describe the low-entropy past condition as an extremely tiny section of the universe’s available phase space, i.e., as a well-tuned and highly improbable initial boundary-condition state.

The WCM takes a different position. The universe started in a state of near-zero entropy, but the WCM models it at or near its ground state, in equilibrium with the intensely hot ambient temperature of its formation. As an equilibrium system, the universe comprised a single potentiality spanning its configuration space, and its selection was a certainty; no improbable initial state was required. The WCM defines the thermodynamic arrow of time by the irreversible dissipation of exergy. Dissipation is a fundamental principle of physics, so, no boundary condition is needed to impose a direction of time.

Rapid expansion and cooling during the early universe led to its progressive refinement and increasing entropy, and to the random instantiation of new potentialities. Refinement also created exergy, which provided the drive for irreversible change. Deferring the dissipation of exergy, in accordance with Postulate 5, would have actualized other changes within the young universe, creating new particles of positive exergy. As long as the universe’s vacuum-state temperatures continue to cool, refinement will continue to create new exergy, and this will fuel continued refinement and actualization. The universe will never reach an equilibrium state of zero-exergy heat death, as long as it continues to expand. This describes the cosmological arrow of time.

5.3 The Arrow of Functional Organization

The thermodynamic arrow of time is not the only empirical arrow of time for a system with fixed ambient surroundings. Thermodynamics describes the relative stabilities of states and the potential for a metastable state to transition to a state of higher stability, but it does not address the irreversible process of dissipation or the relative stability of dissipative processes. It does not account for the empirical arrow of self-organization. Self-organization refers to the spontaneous formation of dissipative structures within dissipative systems. Prigogine and colleagues have thoroughly documented numerous types of systems in which far-from-equilibrium dissipative systems become increasingly organized and evolve toward higher organization [40]. Examples include the self-organization of convection currents within a fluid heated from below, the spontaneous formation of amino acids from simple gas mixtures stimulated by electrical sparks [41], and most spectacularly, in the origin and evolution of life, sustained by radiant energy from the sun.

The WCM establishes dissipation and dissipative processes as fundamental. Crecraft applies a corollary of Postulate 5, which he refers to as the Kelvin Selection Principle (**KSP**), to dissipative systems (Section 4 of [42]). The KSP selects stationary dissipative systems, which are sustained by an external source of energy, on the basis of their rate of internal work. Internal work defers a transition’s dissipation of its exergy input by utilizing exergy to actualize changes elsewhere within the system. The rate of internal work is a measurable property and the measure of a dissipative system’s relative stability.

The KSP attributes the stability of convection over conduction, for example, to the internal work of thermal expansion, which sustains convective flow. It attributes the

relative stability of amino acid synthesis to the electrical sparks' work of creating high-exergy amino acids from a low-exergy gas mixture. The KSP is a principle of selection, guiding dissipative systems toward processes of higher functional organization and complexity, and it defines the arrow of functional complexity. The ubiquity of self-organizing systems, as documented by Prigogine and others, provides empirical validation for the KSP and Postulate 5.

6. Summary and Conclusions

The WCM and existing Non-Contextual Models start with the same empirical facts, but they differ in the assumptions by which they interpret those facts. Non-contextual models can be divided into two distinct conceptual interpretations: superdeterminism and equilibrium interpretations.

Superdeterminism interpretations include classical mechanics and hidden variables theories of quantum mechanics. They completely define the physical state in terms of precise coordinates of position and motions. Implications are a noise-free ambient reference at absolute zero, no dissipation, and superdeterminism.

Equilibrium interpretations include quantum thermodynamics, the Copenhagen interpretation and the many worlds interpretations. They all assume that the wavefunction is a complete description of the physical state. But within the WCM, a superposed wavefunction is complete only if it describes an equilibrium ground state system, in which there is no entropy, no exergy, and no irreversible change.

Superdeterminism and equilibrium interpretations define two extreme special cases of the WCM, both of which are essentially non-contextual and describe zero-entropy states. In the case of superdeterminism, the state is non-contextually defined with respect to absolute zero, which allows arbitrary change in the reference state with no loss of information. In the equilibrium case, a system's state is non-contextually defined with respect to itself. By abandoning the assumption of non-contextuality, the WCM fills the gap between these extremes. The WCM assumes a contextually defined ambient surroundings at the positive temperature of the system's actual surroundings. This allows the WCM to accommodate non-equilibrium metastable physical states with positive entropy and positive exergy. This is precisely where irreversible and random change occurs.

The WCM defines system time as a complex property of state spanning both reversible mechanical time and irreversible thermodynamic time. It distinguishes between system time and reference time, as recorded by an observer's clock. Reference time is the time of relativity, with respect to which the speed of light and the light cone of causality are defined. Distinguishing among mechanical, thermodynamic, and reference times reconciles nonlocality with relativity, without hidden variables, spooky action, or superdeterminism.

A model is "good" if it is consistent with empirical observations; precise; parsimonious in its assumptions; explanatorily broad; falsifiable; and if it promotes scientific progress [43]. The WCM, like all viable interpretations of physics, satisfies the consistency requirement. WCM is parsimonious by assuming no hidden variables and by rejecting non-contextuality, which cannot be empirically validated.

The WCM explanations are broad and falsifiable. It explains the thermodynamic arrow of time 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. And it can provide an explanation for the evolution of open dissipative systems toward higher functional organization and stability. The WCM's implications and explanations are well documented and thoroughly validated by empirical observations.

The WCM also suggests new avenues of scientific progress. 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. It opens up the physical analysis

of self-organizing dissipative structures within open non-equilibrium systems. The WCM discretizes configuration space, but its quantization of space is contextual, so it does not conflict with relativistic length contraction. The WCM's contextual discretization of space and its recognition of fundamental dissipation and entropy might yield new insights into quantum gravity and the evolution of the universe.

Like any model, the WCM is a simplification of reality, but its non-contextuality is a major step forward. Non-contextuality establishes the irreversible dissipation of exergy as a fundamental law of physics, and it expands physics beyond the investigation of static states and their transitions to the investigation of irreversible dissipative processes. By all measures, the WCM 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 Block 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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