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A Review of Recent Trends in Quantum Thermodynamics and a System's Behavioural Analysis of the Universe Originating as a Quantum Energy System

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Abstract

This paper combines a review of recent advances in quantum thermodynamics, including work on objective collapse (Zurek's quantum Darwinism) and quantum gravity (Verlinde's quantum gravity explanation), with a redefinition of entropy generation as systems' *change process*. These concepts are used as systems' behaviour analysis tools to allow us to revisit Hartle and Hawking's 1983 quantum universe and develop a hypothesis for how physically a universe starting in a quantum state could evolve into our current universe, based on systems analysis. The outcome of this analysis raises a question: do we already have the elements of a "theory of everything" hiding in plain sight within recent advances in quantum thermodynamics?

Keywords

Exergy, Entropy, Quantum Thermodynamics, Systems Behavioural Analysis, Quantum Universe

1. Introduction (Classical Thermodynamics and Recent Advances in Quantum Thermodynamics)

Quantum thermodynamics has undergone significant advances in the last two decades to now demonstrate how physical information creates entropy in quantum systems, including Zurek's Quantum Darwinism [1], as an explanation for the process of quantum system decoherence into classical outcomes. In the same period quantum cosmology has provided quantum, thermodynamic hypotheses for gravity, including Verlinde's hypothesis [2] in which gravity emerges as information-entropic force from displacement of matter.

In 1983 Hartle and Hawking [3] published a description of the universe beginning as a quantum state, to investigate how that could affect the dynamical behavior of the universe. This paper will take the Hartle-Hawking ground state [3] for the universe and analyze its system's evolution potential, using quantum Darwinism and quantum and classical thermodynamics as tools for systems behavioural analysis.

Classical thermodynamics is summarized in four physical laws. The zeroth law of thermodynamics states that if two systems are in thermal equilibrium with a third system, then they are in thermal equilibrium with each other. This introduces energy equilibration as a fundamental system property and temperature, as a heat energy parameter. The first law describes the internal energy "U" of a closed system as equal to total energy added to the system, so a closed system's change in internal energy when the system does work "W" is the balance of heat input to the system and work energy output from the system:

$$\Delta U = Q - W \tag{1}$$

Hence total energy of an isolated system is constant (energy is conserved). The second law describes spontaneous system state change as irreversible and introduces the concept of entropy in relation to energy equilibration. The second law also distinguishes between the energy able to do work (exergy) which is consumed in a system doing work and the energy not available to do work (anergy). The total entropy (S) generated by a system doing work (W) is proportional to its exergy consumption while it carries out the work required to change its state:

$$W = E - T_0 \Delta S\hat{}tot \tag{2}$$

where E = total energy and T_0 = environmental temperature.

The third law can be stated as: the entropy of a system approaches a constant value as temperature approaches zero. This can be described by using Boltzmann's relationship for the entropy "S" (which has units of energy/temperature) of a system at minimum temperature, in terms of possible microstate configurations "Ω" within the system:

$$S = k_B \ln \Omega \tag{3}$$

Consequently, at absolute zero, there is no uncertainty in microstate probability because only one microstate is possible (ln(0) = 1). The Boltzmann constant k_B has units of energy/temperature which relate the probability of a given microstate to an energy distribution. It is currently used in the SI system for reference temperature, but if the Boltzmann constant were left dimensionless the relationship would be purely statistical mechanical and equate to the Shannon information metric (measure of uncertainty) relationship [4]:

$$H = -\sum p_i \log p_i \tag{4}$$

At the quantum level, system behaviour is stochastic and state physical information is described by statistical mechanics. If the system information is not coupled to energy (as in the Boltzmann equation), quantum system entropy becomes the equivalent of the Shannon uncertainty 'H' for the information about a system's microstates. Quantum information is central to quantum thermodynamics. This is because quantum information theory provides the mechanism for what Schrodinger described as "the characteristic trait of quantum mechanics…"—the phenomenon known as entanglement.

At the quantum level, entanglement arises from the behaviour of physical information when a quantum system interacts with its environment (which is the population of quantum systems that quantum system is interacting with). Potential quantum interactions create information exchanges that create correlations. Correlations lead to information becoming unavailable—information entropy. The generation of correlations and information becoming unavailable to the "observed" system is the cause of entanglement. The environment in effect acts as the observer for a successfully decohering quantum fluctuation.

At the classical level these behaviors emerge as the relationship between system information in the form of the Shannon measure of information "H" and the free energy (exergy; "B") required to bring the system into equilibrium with its environment, in relation to environmental energy density (ambient temperature) "T_0":

$$H = B/T_0 \tag{5}$$

This relationship defines the work potential (the energy available to do work) of a system but also defines how thermodynamic change is brought about in a system and what thermodynamic information is for our universe [5]-[10]. When exergy (free energy) is consumed it cannot be destroyed (violation of first law of thermodynamics). Consumption of exergy is a redistribution (dispersal) of energy with some energy-information becoming unavailable for work (entropy) in the process of state change. Thermodynamic information is the difference—the distance—between the system energy structure and its environment. Change is relative (difference) in terms of system physical information and is brought about by work (consumption of free energy). Physical information describes the distinguish ability of a system from its environment for open interacting systems (or from the energy structure of its previous state, for an isolated internally changing system). A system is indistinguishable from its environment when it is at equilibrium with its environment.

An explanation for how quantum system states emerge (decohere) into objective physical reality has been provided by the work of Zurek. Any one quantum fluctuation towards a potential systems state change is one of many possible redistributions of energy to do the work required to effect a change of state that can successfully decohere. The mechanism by which the energy redistributed by a quantum system achieves decoherence is quantum Darwinism [1] [7]. In quantum Darwinism, the potential states that actually emerge from the range of possible states are termed pointer states. Quantum states which are not pointer states interact with the environment but decohere into mixtures.

A pointer state interaction is one that is information-conservative and results in least information loss (least quantum entropy generation) for the system interacting with the environment during system change of state. Sufficient mutual information needs to be generated between the quantum state change and interaction with the fraction of the environment being observed for a quantum state to decohere. Pointer states interacting with enough of the environmental subsystems of their environment maximize their redundancy through the number of imprints (correlations) they generate in that environment. The system decoherence entropy is equivalent to the classically accessible information for the state change. To simplify the understanding of this mechanism, one may view pointer states as the changes of state most aligned with the environment and the system's mode of interaction with it.

Hartle and Hawking [3] presented their specification of the quantum mechanical states of the universe as in terms of its Schrodinger wavefunction:

$$i\mathrm{d}\psi/\mathrm{d}t = \mathcal{H}\psi \tag{6}$$

The Schrodinger equation describes the evolution (over time) of the energy represented by the Hamiltonian energy operator in a quantum system as a wave function ψ. Zurek's derivation of Born's rule [8] from quantum Darwinism validates Born's original intuition that the amplitude of Schrodinger's wavefunction ψ was related to probability. On a physical information basis, the Schrodinger Hamiltonian can be interpreted as a statistical ensemble of energy microstates, to which Shannon uncertainty applies on a purely probabilistic basis as described by Ben Naim [4] *but with behaviour subject to the physics of energy*. The distinction is important because interferences can arise in quantum systems that would not arise in classical statistical mechanics [9] [10] In addition quantum Darwinism shows the importance of a quantum system's behaviour relative to its environment.

In 1994 [11], Hawking discussed what he termed his "greatest mistake" arising from his original assumptions in 1983 for the wavefunction—universe model with a cosmological constant and invariant scalar field implying a no-boundary state for the model. The no boundary condition determined the quantum state of the universe in the 1983 paper and implied an expanding then contracting universe for Hawking, with an initial interpretation of its thermodynamic direction of increasing entropy reversing when the model universe contracted. Hawking later realized this was erroneous and that both for an expanding and contracting phase of a non-boundary universe, entropy would continue to increase.

My analysis will take the Hartle and Hawking ground state universe and apply the logic of quantum thermodynamic system development to it, including Verlinde's identification of gravity as an entropic force and Zurek's quantum Darwinism. I use and extend a conceptual model quantum universe I first published in 2022 [12] to demonstrate that Hawking's correction of the no boundary universe to being one which increases entropy through its life, is supported from a completely different perspective (quantum thermodynamics and systems behaviour) [1] [2] [7] [13].

2. System's Behavioural Model: A Quantum Universe and Its Initial State

For this thought experiment, the universe in its initial state in the Planck era is assumed to be a closed, isolated quantum energy pure state, with its initial energy as undifferentiated internal potential energy and hence zero entropy, as no exergy has been consumed. The internal energy is here assumed to be quantum universe's vacuum or false vacuum. For this universe energy is the primitive physical quantity and is hence conserved for this isolated, closed system. The only physical change that this initial state can make is an energy redistribution (and exergy consumption) to create a change of state [11].

Unless the quantum energy fluctuation leading to the first change of state opens a pathway to successive ongoing state change, any other quantum fluctuation has a high probability of reversal (**Figure 1**). This model universe in state 0 is also timeless in the sense that one theory of time consistent with quantum mechanics describes its emergence from entanglement and quantum entropy [14] [15]. Therefore, until the state 0 universe undergoes a quantum fluctuation that does not reverse, "time" has not begun.

In state 0, at the start of the Planck era, this model quantum universe has an undifferentiated internal potential energy. The current assumption for development of the universe is an evolutionary sequence in physical (energy structure) emergence in which the four fundamental we are now familiar with (strong, weak, electromagnetic and gravity have not yet separated at this development stages, with gravity emerging first and the other not having separated out in the Grand Unification period following the Planck era.

This simple conceptual model assumes that Verlinde's explanation of quantum gravity and quantum Darwinism principles apply. I believe this leads to a reconciliation of quantum behaviour with the current expectations for the universe development in the Planck and GUT phases and is fully consistent with subsequent development of the universe to current expectations.

In the Planck era, this model universe as just described can only change state irreversibly [16] [17] through internal differentiation in energy structures (or

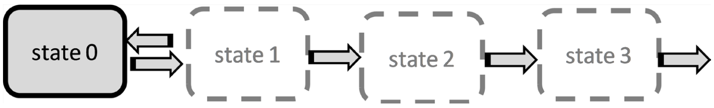

Figure 1. A scenario for the initial state of the quantum universe is as a closed system with all its energy as internal (vacuum) energy at the system's maximum exergy potential (100% potential energy, no exergy consumed). This state is highly reversible in that only a quantum fluctuation (energy structural change) that opens a path to successive onward change has a high probability of irreversibility. However, the system at this stage is highly reversible and hence also symmetric.

volume change facilitating energy redistribution form diversity) that creates a long enough path of successive exergy consumption and state change (**Figure 2**). The first change state zero will initially make will involve exergy consumption and energy redistribution which also represents a change in internal information to a surface or horizon (holographic principle). This is Verlinde's entropic gravity [2] [18] for which acceleration is related to an entropy gradient and inertia arises from lack of an entropy gradient. Consequently, initial state change creates an entropic force that we recognize as gravity. Another aspect contributing to the beauty of Verlinde's entropic gravity hypothesis is that it also provides an explanation and basis of emergence for dark energy and dark matter [18], with recent astronomical potentially providing supporting observations [19].

This universe is quantum and stochastic but in starting as a pure energy state, change is only possible through energy redistribution. An example of a possible sequence of quantum fluctuation events that provides the symmetry breaking and path development for this model universe which is consistent with current assumptions for the universe's development sequence from the Planck era to inflation via the grand unification, as schematically represented in **Figure 2**, is as follows.

From the initial vacuum state symmetry, exergy spent on instanton tunneling energy towards an electronuclear field emergence, initiated change and redistributed physical information, which also leads to the first entropic gravitational force being expressed. In this scenario (see **Figure 2** below), gravity and an electronuclear (unified weak, strong and electromagnetic) force have emerged during initial state changes and if the next fluctuation and exergy consumption is an inflaton field expression, the universe's development path is then open to significant further diversification in energy structure emergence, due to lowering of its energy density (lower temperature. The initial energy redistributions can now significantly further diversify into new forms. Consequently, the probabilities of state change-sequence reversal significantly decrease.

The information consequences of energy redistribution include entanglement (via mutual information creation of correlations), which in turn lead to other significant physical behaviors emerging.

The physical behaviors that arise from quantum entanglement include [12] [13]:

- quantum entropy,
- non-locality,
- decoherence (via quantum Darwinism),
- equilibration [9] [20] [21].

Recent work by Linden, Popescu, Short and Winter has provided proof for equilibration being a fundamental property of quantum systems arising from entanglement [20] [21]. Energy disperses in classical entropy because of the correlations that spread into the universe from entanglement, supporting Lloyds earlier work [9]. Increasing entanglement increases correlations between quantum systems and over the life of the universe, more energy information becomes

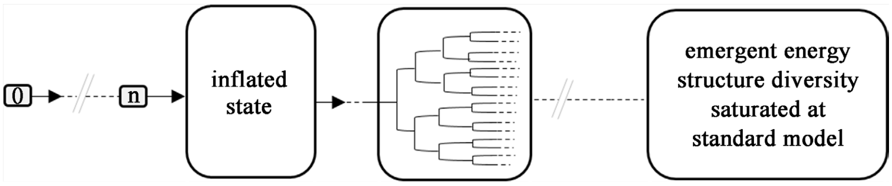

Figure 2. To avoid reversal the first changes in the pure, undifferentiated energy universe needs to redistribute that energy into state changes that create increasing opportunity for exergy consumption (and hence energy information redistribution), which effectively represent a general entropic force for ongoing state change and increasing energy structure diversity. The direction of that entropy—its asymmetry—is the asymmetry we attribute to time. The energy structure diversity that emerges from the initial state is then the environment that any quantum fluctuation has to interact with to decohere and emerge. The development of the internal environment of the universe is driven by positive feedback from exergy consumption into entropy production for increased diversity and increased population of exergy consuming state changes. This Planck era universe is already a complex system which fosters emergence of new forms of energy structure through positive feedback on energy redistribution. In the Planck era quantum universe, energy begins to partition into subsystems so that a system and environment relationship is established. The internal environment, itself evolving, sets the terms for which forms of energy structure can emerge. As per quantum Darwinism, pointer states which are the emergent energy microstates are those energy structures that are most compatible with their environment (which is itself growing in numbers and energy structure diversity as the universe develops). Eventually, the number of possible new pointer states that can emerge in the universe's internal environment becomes saturated when it is populated by a substantial diversity of environment—permissible quantum energy fluctuations. Saturation arises from the relationship between the environment and a range of energy expressions that limit the probability of new energy structure expressions emerging. The diversity of quantum fluctuations the present universe's internal environment permits is what we know now as the standard model. Quantum Darwinism has another Darwinian aspect in addition to pointer state fitness for decoherence in respect to the environment coming from lowest information entropy configuration for change of state. Quantum fluctuations are *competing* for exergy and these low entropy compatible energy structure changes are the most exergy conservative (exergy parsimonious).

unavailable. This corresponds to an increasing anergy fraction for the total energy of the universe (**Figure 3**.)

3. Entropy Is Not a Measure of Order or Disorder

A common mistake that many physicists still make is to describe entropy as a measure of disorder and order. Entropy is exergy consumed during state change where "consumption" represents energy information becoming lost from the object-system through entanglement at the quantum level. This is nothing to do with order or disorder and Ben-Naim [4] provides explanations as to why this is an erroneous and misleading assumption in relation to the statistical mechanical behaviour of physical systems. In quantum thermodynamic terms, energy disperses in entropy production because the correlations arising from entanglement lead to information becoming missing from the object-system. This information entropy (uncertainty) arises from change—from a state change in a universe which is fundamentally an energy system.

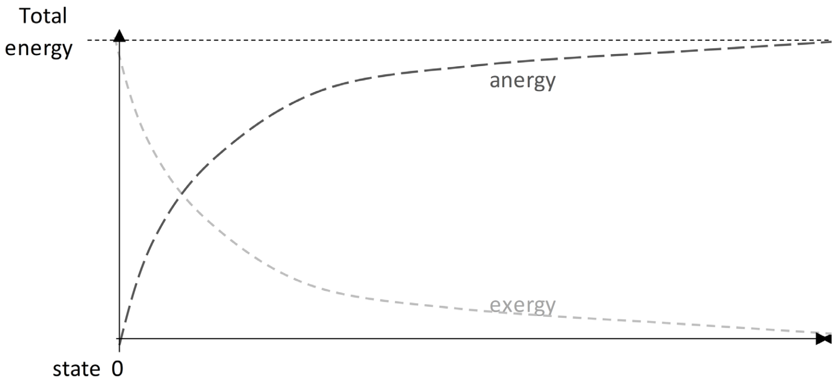

Figure 3. Equilibration of the universe. The shape of the trend lines shown is purely speculative but the key point being illustrated in **Figure 3** is that the universe's initial internal energy, from its initial vacuum state, partitions between free energy available for work (exergy) and anergy (energy not available for work) as the universes evolves and develops. As quantum interactions continue, mutual information correlations increase [9] [21], increasing the unavailability of energy information. This translates into an increasing fraction of the universe's exergy being consumed and consequently, the anergy fraction of the universe's total initial energy increases. As the correlations spread between interacting systems, unavailable information (Shannon missing information) increases. This supports Hawking's re-interpretation of the no-boundary condition for his geometric model for the universe's quantum wavefunction as one of increasing entropy throughout the life of the universe.

The thought-experiment model described in this paper illustrates how increasing diversity in quantum pointer states and their environmental population of quantum states feeds back into an increasing range of opportunities for exergy consumption and hence entropy generation in the universe as a system. Quantum fluctuations qualifying as pointer states are competing for free energy to create state changes. Increased energy structure diversity amplifies the demand for exergy—it increases the opportunities for energy redistribution.

The complexity of a macroscopic object is the outcome of how energy redistribution into structural complexity can create other routes and new opportunities for exergy consumption and hence *further* energy redistribution by the macroscopic object in question. In physical information terms, any physical system is indistinguishable from its environment when at equilibrium with its environment. Distinction from its environment is therefore equivalent to the thermodynamic depth [9] of a physical system. The degree and intensity of energy redistribution and entropy discharge to the environment from a physical system; the thermodynamic depth the system can achieve, is a function of its access to physical resources and its efficiency in using them. For *biological* systems this relationship is enhanced by *use of information* to optimize the (biological) systems' relationship with its environment and maximize its propagation within it. Care has to be taken in comparing physical and chemical systems to biological systems due to use of information as the defining characteristic of all biological systems [12] [13], an issue we will explore further, below.

In contrast to energy structure diversity increasing opportunities for energy, complex energy (and hence matter) structures represent a greater intensity of energy redistribution during entropy production, which translates into increased entropy intensity arising from creating (and maintaining in the case of biology) complex structures. Consequently, both diversity in energy structures and increasing complexity in energy structures can feed back into increased entropy through increased exergy consumption. All change is relative and a measurement needs a reference point. For a state to change it has to use free energy to arrive at a different state. Absolute energy level is not measurable; energy difference and change in energy state is measurable. There is no relationship to order and disorder in energy structure diversity or in energy structure complexity. Lloyd's thermodynamic depth [9] is a better candidate for objective assessment of complexity than order/disorder; another is a system's Kolmogorov complexity [22]. Referring to biological systems as examples of complex systems can be misleading, as explained further below.

The level of information in a changing system is a measure of its distance from its environment (or distance from its initial state for evolution of a single state). The difference in information between and system and its environment describe the system's distinguishability from its environment. None of these system characteristics is related to order or disorder in the structure of information.

Some of the confusion about the characterization of physical information arises from Schrodinger's "What is Life" [23] in which Schrodinger introduced the concept of negative entropy as the fuel for living systems, while making reference to order and disorder. Schrodinger later regretted introducing negative entropy in that context writing that "I should have let the discussion turn on free energy instead", which is the basis for distinguishability, which has no order/disorder implications. The problem in comparing biological systems to physical and chemical systems is biology works on a different thermodynamic basis to physical and chemical systems with information. All biological systems can be defined in thermodynamic-system terms as chemical systems with a chemical memory which is utilized for environmental fitness in order to reproduce the system [12] [13]. All biological systems are information utilizing systems in terms of them using information to adapt and compete. Although physical and chemical systems compete for exergy, they operate on a Markovian basis, with no utilizable memory. Markov dynamics dissipate initial information. In contrast all biological systems are inherently non-Markovian and are learning systems, either on an intergenerational basis through the genome or through both the genome and within their life cycle, through sensing and its feedback into regulation and (re)action.

The complexity, self-organization and perceived order of many biological systems arises from the successive utilization of information for environmental fitness which defines and distinguishes biological systems from purely physical and chemical systems. The structure of all biological systems can be viewed as a *history of their interaction* with their *environment*.

4. Conclusions

This paper presents a thermodynamic systems analysis of a model quantum universe based on advances in physical information theory, Verlinde's quantum gravity theory and quantum Darwinism. The thought-experiment described in this paper illustrates how the uncertainty (Shannon entropy) of physical information theory has become intertwined with energy behaviour described by classical thermodynamics. If the universe began as a pure energy system, its quantum thermodynamics would still follow Shannon information principles but with systems behaviour interactions sometimes particular to energy as a quantity.

This new overview of thermodynamics implies that thermodynamic entropy may be better understood as a *change process* arising from energy redistribution at the microscopic level, in which state change requires access to free energy and the probabilistic, statistical-mechanical microscopic process has consequences for the subsequent availability of energy-information.

This model of the universe also implies that the most complete mechanistic understanding of how the universe develops requires a microscopic (quantum) basis. Coarse graining in this model universe arises naturally from missing (unavailable) information created during system interactions. Coarse graining in terms of cosmology can also arise from top-down modelling (including geometry) of the universe that fails to fully appreciate the quantum basis of state change (statistical mechanical rather than geometric with energy peculiarities) and its consequences. Therefore, the best chance to secure fine graining is likely to be provided by including quantum-thermodynamic analyses for top-down modelling.

Hopefully, the thought experiment described in this paper offers some insights into what sort of fine graining is needed to reconcile quantum mechanics and relativity, in this case based on the advances already made by Zurek and Verlinde, among others. It is the author's belief that recent advances in quantum thermodynamics already suggest that a "theory of everything", if such an all-encompassing theory is ever possible, could already be present now, with parts of it sitting in separate areas of quantum thermodynamics.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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