Article

Entropy and Selection at the Heart of Quantum Mechanics

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Abstract: The thermocontextual interpretation (TCI) establishes a system's exergy, entropic energy, and thermal entropy as thermocontextual properties of state, defined with respect to its positive temperature surroundings. This work extends previous applications of the TCI to irreversible and statistical transitions. The TCI defines statistical entropy as a transactional process of derandomization and transition to a negative-entropy state. Statistical measurements of a confined quantum particle's position are detailed in terms of reversible processes of instantiation and actualization. The TCI then formalizes the MaxEnt as a fundamental physical principle. We apply MaxEnt and statistical entropy measurements to the double-slit experiment. Particles passing through parallel slits record a wave interference pattern, but a "which-slit" detector eliminates wave interference. Richard Feynman called the double-slit experiment the only mystery, at the heart of quantum mechanics. The TCI offers a simple explanation. The which-slit detector breaks the system's symmetry, enabling particles to pass through one slit or the other, and MaxEnt selects the asymmetrical transition, which has no wave interference and a higher statistical entropy.

Keywords: entropy; physical foundations; MaxEnt; wavefunction collapse; thermodynamics; statistical mechanics

1. Introduction

Entropy is intimately connected to the Second Law of thermodynamics and the direction of time. The Second Law states that for any isolated system, entropy never decreases. The Second Law is widely recognized as a thoroughly validated and universal law. Einstein said of thermodynamics: "It is the only physical theory of universal content which I am convinced will never be overthrown, within the framework of applicability of its basic concepts" [1]. Einstein clearly expressed his belief that the Second Law is universal, but at the same time, his qualification acknowledged a deep conflict. Thermodynamics, in fact, is fundamentally incompatible with the conceptual framework that underlies the prevailing interpretations of physics [2].

Physics is interpreted in terms of mechanics—classical, quantum, and relativistic—and mechanics does not distinguish between past and future. Mechanics seeks to define the world in terms of precisely defined microstates, as they exist, objective and independent of any particular reference frame. Mechanics accommodates both Maxwell's Demon, who can reverse the flow of time, and Laplace's Demon, for whom the past and the future are equally present.

Thermodynamics, in contrast, describes the world as it appears, in terms of macrostates observable from the perspective of thermal equilibrium. From this perspective, we see the irreversible production of entropy as heat flows from hot to cold and as free energy is dissipated to heat. Thermodynamics is all about irreversible change and the flow of time toward higher entropy.

Starting with Boltzmann in the Nineteenth Century, physics sought to unite the mechanical and thermodynamic frameworks into a single statistical mechanical framework. Statistical mechanics describes heat statistically as dispersed motions at atomic scales. It describes entropy as a measure of uncertainty and a measure of a macrostate's missing information on a system's physical microstate. Statistical mechanics simply shifts irreversibility from a property of physical change to a property of an observer's knowledge or perception. It leaves intact the fundamental reversibility and determinism of a mechanical system, as it exists isolated and unperturbed.

Prevailing interpretations of physics cannot recognize entropy as a fundamental property of state. They interpret entropy as a subjective measure of incomplete information on a system's actual state [3]. They likewise do not recognize the Second Law as a fundamental principle. The Second Law and arrow of time are regarded as "emergent," which essentially just sweeps them aside to a separate reality unconnected to the fundamental principles of mechanics. Entropy and the Second Law of thermodynamics are, however, firmly founded within the thermocontextual interpretation (TCI) of physics [2].

The TCI defines the thermocontextual state with respect to a system's actual surroundings, which is always at a positive ambient temperature. The TCI generalizes free energy and thermodynamic entropy to exergy and thermal entropy. Exergy and thermal entropy are objective thermocontextual properties of state, independent of observation or measurement. It recognizes the Second Law of thermodynamics and the irreversible dissipation of exergy as a fundamental principle.

Wikipedia lists over a dozen "influential" quantum interpretations [4], but not one of them defines physical reality with respect to surroundings at a positive ambient temperature. This is key to defining entropy and irreversible change as fundamental physical properties, and it distinguishes the TCI from the other prevailing interpretations of physics.

The TCI previously focused on time and causality [2]. It provided an explanation for one of quantum mechanics' most perplexing phenomena, the superluminal correlation of measurements in EPR-type experiments, without invoking untestable metaphysical implications such as superdeterminism, hidden variables, or "spooky action."

This article expands application of the TCI to statistical and irreversible processes. A statistical process is defined by statistical measurement results. The TCI defines probabilities and statistical entropy by a reversible process of derandomization and transition to a measured state of negative entropy. The TCI defines an irreversible process by the dissipation of exergy and production of thermal entropy. The TCI formalizes MaxEnt [3, 5] as a fundamental principle of an isolated transition. It states that an isolated transition increases the system's entropy to the maximum extent possible.

The article applies the MaxEnt and statistical entropy to explain the behavior of quantum particles in the double slit experiment. If a stream of quantum particles passes through double slits, the particles record a distinct wave-interference pattern, suggesting that each particle passes through both slits. Inserting a "which-slit" detector to observe which slit particles pass reveals that each particle randomly passes through one slit or the other, never both, and the particles no longer produce a wave interference pattern. Richard Feynman referred to the double slit experiment as expressing the mystery at the heart of quantum mechanics [6]. The TCI provides a simple explanation for the switch between wave-like and particle-like behaviors, and it provides a clear description of statistical measurement and wavefunction collapse in terms of elementary reversible transitions.

This article applies the TCI to simple well-known and well documented physical observations. The observations discussed in this article are thoroughly established, but the TCI provides a new perspective and insights. Establishing the TCI for simple, even trivial, observations is a necessary first step before applying it to tackle more complex observations. The examples are simple, but the TCI's perspective on them is a break from convention.

2. The Three Entropies

Prevailing interpretations of physics reveal at least three distinct concepts of classical entropy. Classical thermodynamics originally defined entropy change for a thermally equilibrated system at temperature T by

$$\Delta S_{TD} \equiv \frac{\Delta q}{T}, \qquad (1)$$

where Δq is the system's heat relative to a reference state at the system's fixed temperature. Isothermal expansion of a thermally equilibrated gas, for example, extracts heat from its ambient surroundings, and therefore, from equation (1), the expanded gas has a higher entropy. Equation (1) is limited, however, to systems that maintain thermal equilibrium with a fixed-temperature reservoir.

Physics extended thermodynamic entropy by defining the 3rd Law entropy with respect to a reference at absolute zero. The Third Law entropy is defined by:

$$S_{3rd_L} \equiv \int_0^T \frac{dq_{rev}}{T}. \tag{2}$$

Integration can be done in parts for a non-isothermal system, but the Third Law entropy still assumes thermal equilibrium, at least locally, and reversible transfers of heat, q_{rev}, at the system's changing local temperature. The Third Law entropy is strictly based on an equilibrium process of interaction with a reversibly changing reference state.

Equation (1) defines the classical thermodynamic entropy with respect to a reference state at the system's equilibrated temperature. Equation (2) defines the 3rd Law entropy with respect to a reference state at absolute zero. In either case, the thermodynamic entropy is defined with respect to a temperature that does not explicitly reference the system's actual surroundings. Thermodynamic entropy is defined independent of the ambient temperature of a system's surroundings, and it is an objective property of the thermodynamic state (Figure 1-A).

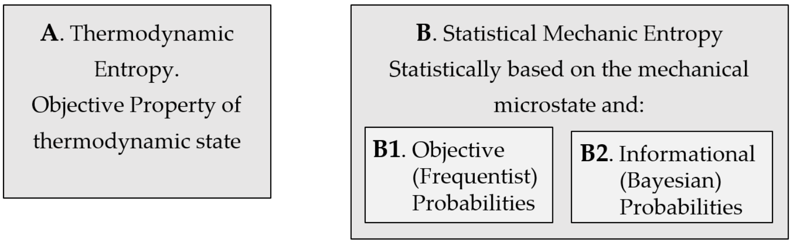

Figure 1. Three Interpretations of Entropy. (A) The classical thermodynamic and 3rd Law entropies are defined as an objective property of the thermodynamic state. (B) Statistical mechanics considers the thermodynamic state to be incomplete, and it defines entropy statistically in terms of the system's actual mechanical microstate. The Frequentist interpretation (B1) assumes statistical probabilities are an objective property of state; the Bayesian interpretation (B2) defines probabilities subjectively based on an observer's incomplete knowledge.

Mechanics provides a fundamentally different definition of entropy from thermodynamics (equations 1 and 2). Mechanics regards the thermodynamic state as an incomplete description of a system's actual mechanical microstate. A microstate is defined by everything that is possibly knowable about a system's state, and it is generally considered to be the complete description of the system's underlying physical state. Classical mechanics defines the classical mechanical microstate by perfect precision of position and momentum coordinates, in the absence of thermal noise. Quantum mechanics defines the microstate by the quantum wavefunction, which expresses everything measurable and knowable about a quantum system.

Whereas thermodynamics does not address a system's mechanical microstates, statistical mechanics explicitly addresses the statistical distribution of a system's microstates. Classical statistical mechanics defines the Gibbs entropy by:

$$S_{Gibbs} \equiv -k_B \sum_i P_i \ln(P_i). \tag{3}$$

The summation is over accessible energy levels. k_B is Boltzmann's constant, and P_i is the probability that, at any given instant, the system's energy is between E_i and $E_i+\delta E$. For the special case of a thermally equilibrated system at temperature T, the system's accessible microstates define a canonical ensemble, and the Gibbs entropy is equal to the Third Law entropy.

Gibbs' statistical mechanical entropy actually comprises two distinct interpretations: the frequentist interpretation and the Bayesian interpretation. Physics is unified in its interpretation of thermodynamics as an incomplete description of mechanical state, but it is split on the interpretation of entropy. The frequentist interpretation of entropy (Figure 1-B1) assumes that a system at thermal equilibrium has an objective probability distribution of available microstates, independent of observation or observers. The Bayesianism interpretation (Figure 1-B2) makes no assumption about a system's underlying physical microstate(s). Bayesian logic and MaxEnt only address unbiased expectation values, based solely on known information [3]. Physics recognizes entropy as a statistical measure of a system's possible microstates, but it is not settled on whether probabilities are objective or subjective.

Jaynes considered objective randomness to be incompatible with mechanics, and he rejected entropy as a measure of physical randomness [3]. He concluded that entropy is informational and a measure of incomplete information on a system's state. Random wavefunction collapse and classical chaos mean descriptions become increasingly incomplete, but this is simply an artifact of an observer's incomplete knowledge of an initial state.

Physics' prevailing interpretation of entropy follows Jaynes and regards probabilities as a measure of an observer's incomplete knowledge. However, this does not necessarily mean that probabilities are subjective. Pilot wave interpretations, for example, seek to maintain the determinism of physics, including wavefunction collapse, by asserting the existence of objectively unknowable hidden variables. Quantum Bayesianism does not deny objective physical states, but it simply describes a system by an observer's subjective knowledge [7].

The next section reviews the Thermocontextual Interpretation, which establishes a conceptual framework for defining thermal and statistical entropies as objective properties of state or change.

3. Thermocontextual States and Transitions

The thermocontextual interpretation (TCI) offers a fundamentally different conceptual framework for interpreting empirical observations compared to prevailing interpretations of physics [2]. The TCI empirically defines states by perfect measurement from a system's actual surroundings, which are always at a positive ambient temperature. Empirically defined states, by their definition, are distinguishable, and it follows that degenerate states do not exist.

The TCI's definition of physical states contrasts with quantum mechanics and statistical mechanics, both of which simultaneously define a system with respect to multiple reference states. Quantum tomography defines the quantum state with respect to all possible measurement frameworks [8], and statistical mechanics defines a system's macrostate and microstates with respect to different references. Statistical mechanics defines a system's microstates in the absence of thermal noise, with respect to a reference state at absolute zero, and it defines its macrostate with respect to a reference state thermally equilibrated with the macrostate. It defines a nonequilibrium macrostate by partitioning it into separate thermally equilibrated parts, each locally equilibrated with a different ambient reference state. The TCI, in contrast, defines a system with respect to a single reference state defined by equilibrium with the system's actual surroundings.

The TCI is based on postulates and definitions given in [2] and listed in Appendix A. The following subsections present a summary and review of the TCI, on which the rest of this article is based, with a focus on statistical and irreversible transitions and their measurements.

3.1. Thermocontextual Properties of State

As in mechanics, a system's absolute energy is defined with respect to a hypothetical zero-energy reference state at absolute zero. The TCI partitions absolute energy, E_{abs}, into thermocontextual components, given by:

$$E_{abs} = E + E_{as} = X + Q + E_{as}. \tag{4}$$

Absolute energy is resolved into system energy, E, and ambient-state energy, E_{as}. Ambient-state energy is the energy of the ambient reference state with respect to the hypothetical zero-energy absolute-zero reference state.

The system energy is defined relative to the ambient-state energy. It is resolved into exergy and entropic energy. Exergy is the system's potential work capacity on the ambient surroundings in the limit of reversibility. Exergy also defines the system's potential to transition to a lower-exergy state of higher stability (TCI's revised postulate four, Appendix A). The highest stability state is the equilibrium ambient state, with zero exergy.

Entropic energy is defined by $Q \equiv E - X$. Entropic energy was previously called ambient heat in [2], but it is renamed as entropic energy to distinguish it from the ambient energy of the surroundings. The system's entropic energy and ambient heat of the surroundings both have zero exergy, and they are freely exchangeable. Exergy, entropic energy, and entropy are all thermocontextual properties of state, and they define a system's energy state. The ambient energy state defines the zero values for a system's exergy, entropic energy, and entropy.

The TCI further partitions a system's exergy into the sum of mechanical exergy and thermal exergy. Mechanical exergy is the sum of kinetic energy and non-thermal potential energy of the system's particles. Thermal exergy is the work potential of the system's thermal energy, q. Thermal exergy is empirically given by:

$$dX_q = \left(\frac{T - T_a}{T}\right) dq, \tag{5}$$

where dq is an increment of heat at temperature T and T_a is the ambient temperature. Entropic energy is related to thermal energy at temperature T by:

$$\mathrm{d}Q = \left(\frac{T_a}{T}\right) dq. \tag{6}$$

The TCI finally defines thermal entropy by:

$$S \equiv \frac{Q}{T_a} = \int_{as}^{ss} \frac{dQ}{T_a} = \int_{T_a}^{T} \frac{dq_{rev}(T)}{T}, \tag{7}$$

where the first integration is from the ambient reference state (as) at the ambient temperature T_a to the system state (ss) at temperature T. The last term follows from (6) for systems in which heat is a function of temperature only.

Thermal entropy is a generalization of both the classical thermodynamic entropy, which is defined with respect to an equilibrium reference at the system temperature (equation 1), and the 3rd Law entropy, which is defined with respect to a reference state at absolute zero, (equation 2). Like other thermocontextual properties of state, thermal entropy is defined with respect to an ambient reference state in equilibrium with the system's actual surroundings at the positive temperature.

Thermocontextual properties of state are empirically defined by perfect measurement (Figure 2). Perfect Measurement involves a reversible and thermodynamically closed transition from an initial state (A) to the ambient reference state (B), which defines zero values for energy, exergy, and entropic energy. Thermodynamic closure means that the system can exchange energy and work with the surroundings, but not mass components. Reversibility means that heat is reversibly exchanged at the ambient temperature of the surroundings.

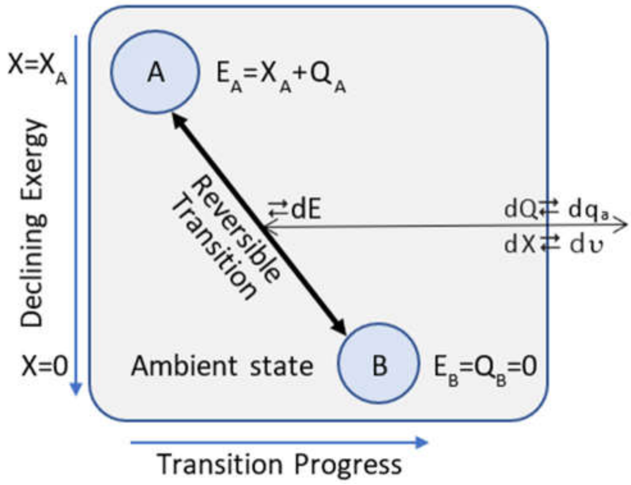

Figure 2. Perfect Measurement involves a reversible closed-system transition from an initial State A to ambient State B. The system's initial exergy (X_A), entropic energy (Q_A), and entropy ($S_A=Q_A/T_a$) are defined by reversible transfers of ambient heat q_a and utility υ (sum of work plus exergy). A hot fixed-volume gas can be reversibly measured by utilizing a perfect heat engine to extract exergy and reversibly discharge utility and ambient heat as the gas reversibly cools to its ambient temperature. Perfect measurement yields $X_A=\int d\upsilon$ and $Q_A=\int dq_a$, with integration over the temperature change. Perfect measurement of a compressed ideal gas as it reversibly and isothermally expands to its ambient pressure yields $X_A=\int PdV$ and $Q_A=\int dq_a$. To maintain constant temperature, the gas's PV work on the surroundings is balanced by input of ambient heat from the surroundings as entropic energy. The initial compressed gas therefore has positive exergy but negative entropic energy, and its energy is unchanged and equal to zero.

Energy can be transferred to the surroundings as ambient heat q_a at the ambient temperature, and as utility υ, which we define as the summed transfers of work and thermal exergy. For an open system, utility can include exergy of exported components. For perfect reversible measurement, exergy is output to the surroundings as utility, without loss from dissipation, and entropic energy is output as ambient heat (Figure 2). A system's exergy, entropy, and entropic energy are empirically defined by measurements of the utility and ambient heat reversibly transferred to the surroundings. A system's exergy is always non-negative, but as described in the Figure 2 caption, a system's entropic energy and entropy can be negative.

The ambient reference's energy state is uniquely and objectively defined by equilibrium with the system's ambient surroundings at a positive ambient temperature. An ambient reference additionally specifies a reference point and orientation in space and a reference clock to mark the passage of reference time [2, 9]. Reference states differing in their spatial and temporal properties but sharing the same energy state are related by a Galilean or Lorentz transformation, within their identical limits of spatial resolution. This means that all ambient reference states are reversibly equivalent, and thermocontextual state properties are objectively defined.

A system's energy state is uniquely defined by its exergy and thermal entropy (or entropic energy). Table 1 describes four classifications of energy states based on different thermocontextual constraints.

Table 1. Energy State Classifications.

Energy State Classification	Thermocontextual Constraint
Thermal equilibrium at system temperature > T_a	$S > 0$; $dS/dt = 0$
Thermal equilibrium at ambient temperature T_a	$S = 0$
Metastable state	$X > 0$; $dX/dt = 0$
Ambient reference state	$X = S = 0$

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3.2. Statistical Entropy

Figure 2 described reversible and deterministic measurements with respect to a system's ambient reference state. A system is not always measured with respect to its ambient reference state, however, and not all measurements are deterministic. Measurements of a quantum particle's position in a confined box, for example, are objectively random.

The TCI defines statistical entropy, σ, in terms of a probability distribution of measurable microstates by:

$$\sigma \equiv -\sum_{i=1}^{N} P_i \ln(P_i). \tag{8}$$

P_i is probability of measurable microstate i, and N is the number of measurable microstates. Given a positive temperature of measurement, the number of resolvable and measurable microstates is always finite.

Statistical entropy is mathematically equivalent to the Gibbs entropy (3) and its extension to statistical quantum states, the von Neumann entropy. The TCI, however, interprets the probabilities very differently. Classical and quantum mechanics both interpret probabilities as a measure of incomplete information due to imperfect measurement or wavefunction collapse. Incomplete information is typically regarded as a subjective property of an observer's incomplete knowledge of a system's precise mechanical microstate. The TCI, in contrast, describes the probabilities in (8) as reflecting the empirical randomness of actual measurements. Multiple measurements can yield a statistical distribution of measured results, and this defines a positive statistical entropy for the state as it existed prior to measurement.

The differences between the TCI's interpretation of statistical entropy and conventional Bayesian or frequentist interpretations are succinctly highlighted in Table 2 for a coin flip. The Frequentist and Bayesian interpretations both assert that prior to the coin flip, the coin has a definite and known zero-entropy state. After the coin is flipped but before the result is revealed, the frequentist interpretation asserts that the coin again has a definite and knowable, but unknown, zero-entropy state. Probabilities only refer to hypotheses about the coin's unknown state. The Bayesian interpretation, in contrast, asserts that the coin has a positive entropy, based on an observer's incomplete knowledge of the coin's actual state.

Table 2. The Frequentist, Bayesian, and TCI interpretations of Statistical Entropy.

	Frequentist	Bayesian	TCI
Initial entropy of coin	Zero	Zero	ln(2) > 0
Entropy of coin post flip	Zero	ln(2) > 0	Zero
Interpretation of Probabilities	Objective uncertainty of a hypothesis's truth	Subjective uncertainty of a system's actual definite microstate	Random instantiation (selection) of one of a system's multiple measurable potentialities.
Interpretation of Statistical Entropy	Objective randomness of fluctuations	Subjective property of observer's incomplete knowledge of state.	Transactional property of system's transition to a measurable reference state.

Like the frequentist interpretation, the TCI describes the flipped coin with a definite but unknown zero-entropy state. In contrast to both the Bayesian and frequentist interpretations, however, the TCI assigns a positive entropy to the coin's initial state, even if the coin's orientation is known. It describes the system prior to the coin flip as comprising the coin and its cocked coin-flipper. Its statistical entropy is a transactional property, reflecting the objective randomness of the coin's measurable potentialities. Entropy is a transactional property that depends on a transition's initial state and its measurable microstate potentialities.

Whereas thermal entropy is a thermocontextual property of state defined with respect to its ambient reference state, statistical entropy is a transactional property of a statistical measurement with respect to an arbitrary measurement reference. We can nevertheless relate statistical entropy (8) and changes in thermal entropy (7) by assuming the empirical conservation of statistical entropy for perfect reversible measurements. This means that for perfect statistical measurements of state A from state B, of state B from state C, and of state A from state C, the following relationship holds:

$$\sigma_{AC} = \sigma_{AB} + \sigma_{BC}. \tag{9}$$

If states A and B are thermally equilibrated states at positive temperatures, and we take state C as an ambient reference state at absolute zero, then states A and B define canonical ensembles of microstate potentialities, defined at absolute zero as mechanical microstates, and we have:

$$\begin{aligned} \sigma_{AB} &= \sigma_{AC} - \sigma_{BC} && (10a) \\ k_B\sigma_{AB} &= S_{Gibbs}(A) - S_{Gibbs}(B) && (10b) \\ &= S_{3rd_L}(A) - S_{3rd_L}(B) && (10c) \\ k_B\sigma_{AB} &= \Delta S. && (10d) \end{aligned}$$

Equation (10b) follows from equation (10a) and definitions (3) and (8) for canonical ensembles A and B. Equation (10c) follows from the equality of Gibbs entropy and the Third Law entropy. And equation (10d) follows from the definitions of Third Law entropy (2) and thermal entropy (7). Equation (10d) relates the statistical entropy of state A, defined by statistical measurements with respect to reference state B, to the difference in thermal entropy of states A and B. Equation (10d) is valid for any ambient reference state. A perfect statistical measurement is illustrated and described in the next section.

3.3. Irreversible and Statistical Transitions

Perfect measurement involves a reversible and deterministic transition between an initial state and a reference state. Real transitions, however, generally are not reversible and deterministic. The TCI models an irreversible transition as an isolated process, illustrated in Figure 3. An irreversible transition dissipates some or all of a system's initial exergy to entropic energy. The total energy of an isolated system is conserved, and the loss of exergy by dissipation equals the increase in the system's entropic energy.

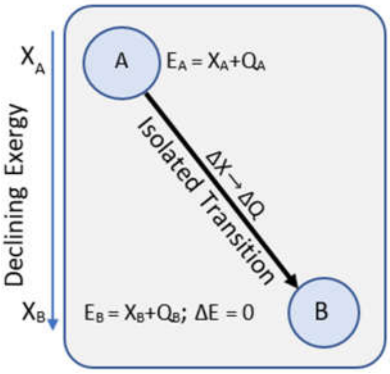

Figure 3. Isolated Transition. An isolated transition dissipates exergy to entropic energy, with $\Delta Q = -\Delta X$ and $\Delta E = 0$.

Energy, exergy, and entropic energy are state properties, and the energy relationships in Figure 3 are valid for any ambient reference state. If state A's exergy is only partially dissipated and the system reaches thermal equilibrium, state B's exergy is positive, and it is metastable.

If we are interested in state B as a definite zero-entropy state, then its equilibrium temperature defines the ambient temperature (Table 1). It follows that the entropic energy and entropy of the pre-transition state A are negative (c.f. isothermal expansion described in Figure 2). State B has a higher entropy than the sub-ambient (negative-entropy) state A, and from equation (10d), state B has a positive statistical entropy.

Figure 4 expands on these ideas to illustrate the statistical transition and reversible measurement of a quantum particle in a one-dimensional box. The overall process in Figure 4 takes the precursor state A to measured state D. States A and D are both defined by a minimum-energy quantum particle of mass m confined to a one-dimensional box of length L/N. They therefore have the same energy state, but they generally differ in their position coordinate. The exergy of state A, X_A, is given by the energy equation for a quantum particle in a box [10] minus the ambient-state energy.

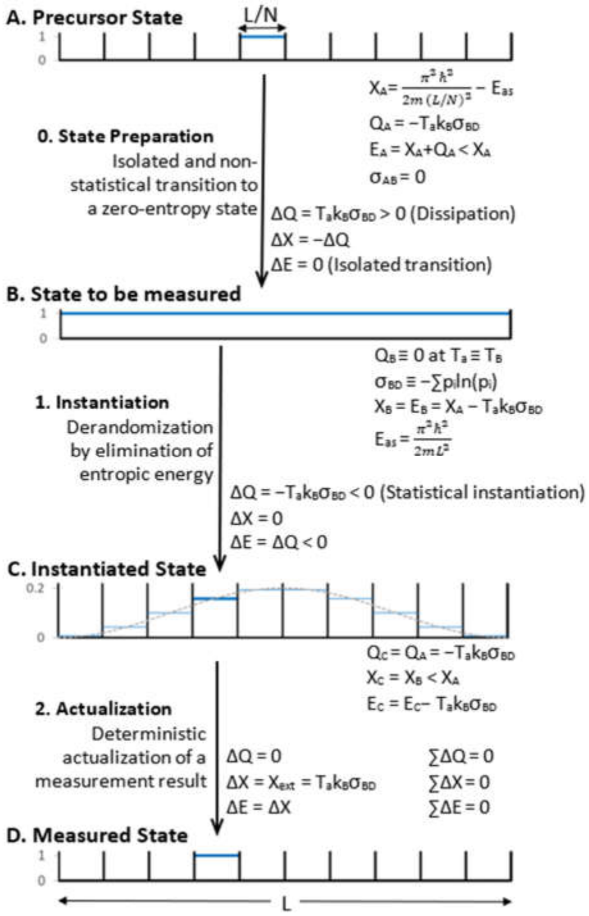

Figure 4. Measurement of statistical entropy. Step zero illustrates the preparation of the zero-entropy state B. Steps one and two illustrate the statistical measurement of state B with respect to a sub-ambient measurement reference state D of negative entropy. Statistical measurement involves two steps: derandomization and instantiation of a microstate potentiality (step one), followed by actualization of the instantiated microstate's measurement result (step two).

Expansion of the particle's confining box from state A to state B leads to dispersion and partial dissipation of the particle's exergy to entropic energy. Thermal entropy increases, but the transition from state A to state B is deterministic, so the transactional statistical entropy, σ_{AB}, is therefore zero. This is in apparent violation of equation (10d), but equation (10d) does not apply since the transition from A to B is irreversible.

We are interested in determining the complete state of B, as it exists prior to measurement. By completeness we mean a definite state without objective indefiniteness of entropic energy. This sets the ambient temperature to T_B and its entropy to zero. It follows that the entropic energy of state A, prior to its irreversible transition to the zero-entropy state B, was negative. State D likewise has negative entropy.

The reversible transition from state B to state D defines the statistical measurement of the zero-entropy state B with respect to the sub-ambient reference state D. Statistical measurement involves two steps. The first step is instantiation (step one, Figure 4). Instantiation involves reversible elimination of the entropic energy produced by dissipation in step zero. This derandomizes the system and instantiates a measurable microstate potentiality. The measurable microstate potentialities for state B prior to instantiation are represented by the horizontal bars in state C. The thick horizontal bar in state C designates the randomly instantiated microstate after step one. The statistical entropy, σ_{BD}, is defined by equation (8) and the potentialities' measurement probabilities. The probabilities are determined by discretizing the continuous particle-in-a-box probability profile and are indicated by the bars' vertical positions in state C.

The second step of statistical measurement is reversible actualization (step two, Figure 4). Actualization deterministically records a measurement result (state D) of the randomly instantiated measurable microstate. State D's energy state (energy, exergy, and entropy) is equal to state A's energy state, but state D's position within in the overall box of length L is random.

Actualization in step two requires the addition of external exergy, X_{ext}, to make up for the dissipation of exergy in step zero. However, this is an artifact of measuring state B to the same resolution as the definition of its precursor state A. If measurement in the last step is to a lower resolution such that its final exergy is equal to or lower than state C, then reversible actualization would require no external exergy.

As illustrated in Figures 4(B-D), statistical measurements are described by a reversible transition to a sub-ambient reference state of measurement. If a measured system is thermally equilibrated with its ambient surroundings, its entropy and entropic energy are zero. If the system then reversibly transitions to a negative-entropy measurement state, the loss of entropic energy derandomizes the system, and this randomly instantiates a measurable microstate. An individual transition is reversible and random, but the statistical distribution of measurable states and its statistical entropy reversibly and deterministically specify the system's pre-measurement state.

3.4. MaxEnt

During an isolated transition, a system is unobservable, and it is not definable as a thermocontextual state. It is an irreversible and discontinuous transition from an initial state of higher exergy to a more stable state of lower exergy. There is no exchange of heat or work with the surroundings, and the system's energy is therefore fixed. The quality of the system's energy, however, is not fixed. Heat spontaneously flows from hotter regions to cooler regions, mass flows from higher pressure to lower pressure, and unstable particles and particle configurations decay—all of these processes irreversibly dissipate exergy and produce entropic energy.

Postulate four (Appendix A) states that the most stable state is the state of minimum exergy. Postulate four is applicable to isolated, closed, or open transitions. It is a generalization of the Second Law of thermodynamics, which applies only to isolated systems (which might comprise a system and its surroundings). For an isolated system, the increase in entropy is simply a measure of the decline in exergy and increase in stability of the overall isolated system. It follows that for an isolated system, the most stable transition is one that produces the most thermal entropy and entropic energy. We state this as a corollary to Postulate four:

Corollary 4-1—Maximum Entropic Energy Principle (MaxEnt): An isolated transition produces the maximum entropic energy possible.

MaxEnt specifically applies only to isolated transitions. An isolated transition will dissipate a system's exergy to entropic energy as completely as possible.

In the next section, we apply TCI's statistical transition model and MaxEnt to the double-slit experiment, and we illustrate MaxEnt's role in the selection of quantum transition possibilities.

4. MaxEnt and the Double Slit Experiment

4.1 The Particle-Wave Duality

The double slit experiment demonstrates the particle-wave duality of quantum mechanics. A particle is created and emitted from a source with a well-defined state, and it is detected as a particle by its point-like impact on a detector screen (Figure 5). If a partition with double slits is placed between the source and detector screen, the accumulated impacts display an interference pattern, characteristic of waves, even when particles are transmitted one at a time. The interference pattern indicates that individual particles in some sense simultaneously pass through both slits. The particle-wave duality is further indicated by inserting a "which-slit detector" (WSD) behind the slits. With the which-slit detector activated, it can record which slit the particles pass through, and the wave interference pattern disappears. Richard Feynman famously described the double-slit experiment as the "*only* mystery," "which has in it the heart of quantum mechanics." [6]. To remain neutral on the nature of the emitted "particle," we simply refer to it as a "system" in isolated transition between its source-state A and its pre-measurement state B.

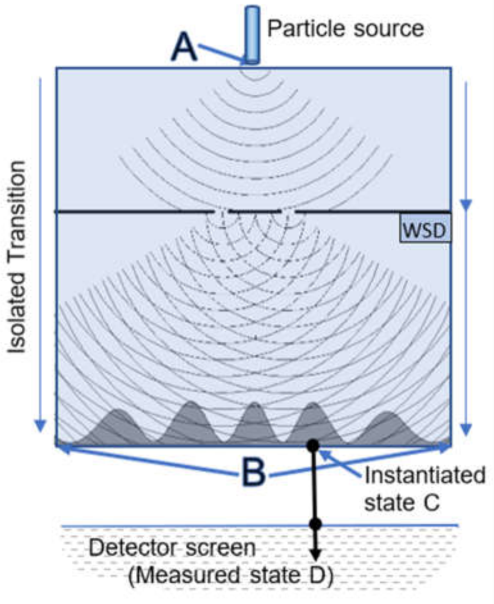

Figure 5. Double slit experiment. If the which-switch detector (WSD) is inactive, a particle transitions in isolation from its source in State A to its pre-measurement state B. The shaded pattern represents the wave-like probability distribution of state B's measurable microstate potentialities with the which-slit detector switched off. With the WSD activated, and the probability distribution of measurable microstate potentialities changes. Measurement randomly instantiates a microstate potentiality to a definite particle-like microstate on the detector screen.

The particle in Figure 5's state A is the precursor state, corresponding to state A in Figure 4. Figure 5's state B is the state that we want to measure. The pre-instantiation state B and instantiated state C in Figure 5 correspond with Figure 4's states B and C. The detector screen in Figure 5 is partitioned into multiple measurable bins. The measured state D in Figure 5 corresponds to the measured state D in Figure 4.

The transition from state A to state B corresponds to step zero of Figure 4, in which the state of interest (state B) is prepared. Preparation in the double slit experiment involves the particle's isolated interaction with the double slit with or without a which-slit detector. If the WSD is present and measurable by an external observer, the partitioned region is split into two separate isolated transitions.

Figure 6 shows the probability profiles for detecting a particle on the detector plate for different configurations of the isolated transition. Curves show probability profiles for wave interference for double slits with no WSD (red profile), for wave diffraction through single slits (green and blue profiles), and for double slits but with no interference (purple profile) as a normalized sum of the single slit profiles. Calculations are based on intensity profile calculations for light [11], using parameters shown in Table 3, and assuming that probabilities of photon detection are proportional to calculated intensities. All probability profiles span N=400 measurable microstate transitions, based on the detector screen width and resolution (Table 3). The probability profiles are all normalized to one.

Table 3. Double slit interference and diffraction parameters

Detector width	Slit width	Slit positions	Slit-detector separation	Detector Resolution
200 λ	7 λ	±15 λ	300 λ	0.5 λ

All measurements are given in units of wavelengths (λ)

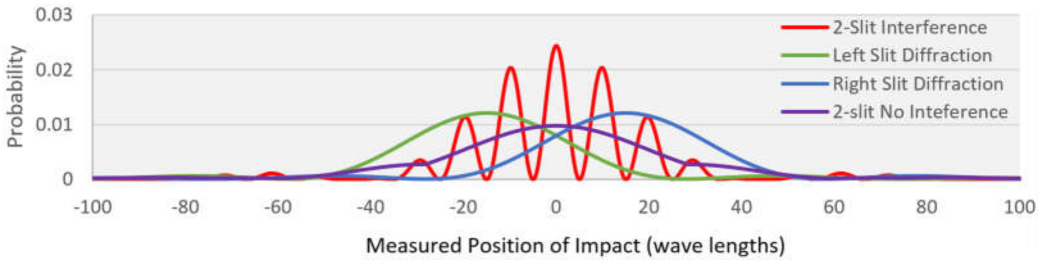

Figure 6. Probability distribution profiles for photon detection from double slits, with and without wave interference and from single slits.

The red curve shows the interference pattern based on multiple measurements of photon impacts in the absence of a WSD, after they pass through the double slits. The statistical entropy and relative dissipation for the transition to state B are σ=4.69 and $\Delta Q/E_{h\nu}$=4.9% (Table 4, Row 1). These results are based on the red probability distribution profile and details provided in the Table 4 footer.

Table 4. Entropy and Entropic Energy Transitions in Double Slit Experiment.

	$\sigma^{(1)}$	$\Delta Q/E_{h\nu}$ $^{(2)}$	Transition (normalized probability distribution)
1	4.69	4.89%	No WSD—source to detector (red curve)
2	0.69	0.72%	WSD on--source to double slit screen (50% - 50%)
3	5.02	5.24%	WSD on—instantiated slit to detector (green or blue)
4	5.71	5.96%	WSD on—source to detector (equals sum of rows 2 & 3)
5	4.69	4.89%	Entangled WSD—symmetrical wave interference (red)
6	5.28	5.51%	Entangled WSD—asymmetrical$^{(3)}$, no interference (purple)

(1) Statistical entropy from equation (8). (2) Relative dissipation: ΔQ from equations (7) and (10d) with T_a=300K, and $E_{h\nu}$ is the absolute energy for a photon of visible (green) light. (3) Transitions are individually asymmetrical but statistically symmetrical.

4.2. MaxEnt: Particle or Wave?

We now consider the case when we place a which-slit detector behind the slits. External measurement at the double slits breaks the overall transition into two separate isolated transitions: a transition from the source to the double slit and WSD, and a separate isolated transition to the detector plate. The first transition is to one of two equally probable measurable states through one slit or the other. The statistical entropy and relative dissipation are $\sigma=\ln(2)=0.69$ and $\Delta Q/E_{h\nu}$=0.72% (Table 4 row 2).

The second transition is from the instantiated slit to the detector screen. Its probability distribution is shown in Figure 6 by either the green profile or the blue profile. Multiple particles add up to the overall distribution pattern of the purple curve, but the WSD allows tracing each trajectory from one slit or the other to its corresponding the blue or the green profile. The statistical entropy and relative dissipation from each instantiated slit to its corresponding green or blue profile are σ= 5.02 and 5.24% (Table 4 row 3). The overall transition with the WSD is equal to the sum of results in rows 2 and 3: σ= 5.71 and 5.96% (row 4). The entropy and entropic energy for the overall transition are higher when the system passes through one slit or the other (row 4), compared to simultaneous and symmetrical passage through both slits (row 1).

Numerous results of double slit experiments with and without the WSD show that, given the opportunity of being measured, the transition spontaneously breaks the symmetry of simultaneously passing through both slits and a particle passes through one or the other. This increases the overall transition's dissipation of exergy to entropic energy, in compliance with MaxEnt.

This raises an interesting question: What would happen if the which-slit detector is isolated from the surroundings? There would be no way to measure which slit the system passed through. If the system symmetrically passed through both slits, there would be wave interference (red profile), as before, and the transition results would be the same as if there were no WSD (rows 5 and 1). If, on the other hand, the system passed through one slit or the other, the predicted probability profile would be the normalized sum of the left and right probability profiles, given by the purple curve in Figure 6. This is the same profile as the combined green and blue profiles in row 4, but because there is no measurement of which slit, the entropy production is different. The purple probability distribution has a statistical entropy of 5.28 and a relative dissipation of 5.51% (row 6)—not as high as the red profile for when we could determine which slit (row 4)—but still higher than the symmetrical interference pattern (row 5).

The TCI attributes the switch between double-slit interference and single-slit noninterference to the opportunity to break the system's symmetry and increase the system's entropic energy. If the WSD is connected to the environment, interaction with the WSD allows instantiation of the system as a particle and measurement of which slit it passes through. This is empirically well validated by experiments, and as discussed above, it increases the dissipation of exergy to entropic energy. If, however, the WSD is an entangled part of the isolated system, there is no possibility of measuring or knowing which slit the system passes through. The WSD's presence could nevertheless still allow transfer of entropic energy from the double slits to the entangled WSD as part of the isolated transition. This would allow symmetry breaking and instantiation of the system as a particle to pass through one slit or the other, with an increase in entropic energy. MaxEnt would select the higher-entropy non-interference pattern over the symmetrical interference pattern, even if the which-slit detection results were unobservable.

The author is not aware of this experiment having been conducted. A non-interference pattern, even if the which-slit detector was an entangled part of the isolated system, would support the idea that MaxEnt drives the selection of non-interference over interference, rather than hidden variables or the ability of an observer to determine which-slit information, as conventionally believed [12, 13]. Given an opportunity, MaxEnt predicts that an isolated transition will break its symmetry and increase its entropic entropy, even if there is no opportunity for which-slit measurement or for the system to interact with its surroundings during the isolated transition.

5. Summary and Conclusions

The thermocontextual interpretation (TCI) provides a conceptual framework for defining physical states and irreversible change [2]. It defines a system's physical state as it exists with respect to its actual surroundings at a positive ambient temperature, T_a. It defines exergy X as generalization of free energy, thermal entropy S as a generalization of thermodynamic entropy, and entropic energy by $Q=T_aS$. The TCI defines statistical entropy as a transactional property of statistical transition to a negative-entropy state of measurement.

The TCI defines changes of state in terms of both reversible and isolated irreversible changes. Reversible change is an idealized transition in which there is no dissipation or production of entropic energy. A reversible transition exchanges exergy, entropic energy, and components with the surroundings. An isolated transition, in contrast, has no exchanges, it is not measurable, and it therefore does not exist as a state. The system is in irreversible transition, during which its exergy is dissipated to entropic energy and its entropy increases to the maximum possible extent. The maximization of entropy is formalized as the MaxEnt Principle, a corollary of postulate four applied to isolated systems.

The TCI and MaxEnt provide a physical explanation for when and why statistical measurements of particles in the double slit experiment record a wave interference pattern and when they do not. Between its definite measurable states at its source and point of detection, a particle irreversibly transitions in isolation, dissipating exergy and increasing its entropic energy. Prior to its random measurements at the detector screen, the particle has a positive statistical entropy, as defined by the statistics of its measurement results and equation (8).

Statistical measurements record a wave interference pattern when particles' wavefunctions pass through the double slits symmetrically. With a which-slit detector in place, the statistical distribution of measurements instead records a pattern of wave dispersion from one slit or the other, without wave interference. The which-slit detector breaks the transition's symmetry, and MaxEnt selects the asymmetrical transition the with non-interference probability distribution and higher statistical entropy. The existence of multiple transition paths and the freedom to choose from among them it distinguishes the TCI from the fundamental determinism of prevailing interpretations of mechanics, and this does indeed express the heart of quantum mechanics.

TCI's model of statistical measurements also provides a simple explanation of quantum wavefunction collapse. Figure 4 illustrated its application to statistical measurements of a particle in a box, and it is applicable to statistical measurements generally. The TCI resolves statistical measurements into elementary reversible steps of instantiation and actualization. Instantiation is a consequence of the reversible elimination of entropic energy, which derandomizes the system and instantiates a measurable microstate potentiality. Actualization is the reversible and deterministic transition to a measured microstate.

The original article on the TCI focused on the nature of time and causality and provided an explanation of EPR type experiments without superdeterminism, hidden variables, or spooky action [2]. This article focused on irreversible and statistical transitions. It formalized MaxEnt as a fundamental principle for selecting the isolated transition of greatest entropy production, and it recognized the intrinsic randomness of reversible transitions to a negative-entropy reference state. MaxEnt and reversible derandomization provide new tools for exploring irreversible and statistical quantum processes.

As a final comment, we note that we have focused on isolated transitions, which are driven by the irreversible dissipation of exergy and production of entropy. TCI's postulate four, which asserts that states of lower exergy are more stable than states of higher exergy, also applies to open systems. Postulate four can propel an open positive-exergy system to lower-exergy and higher-stability states by becoming a source of power to its surroundings. Exergy sources are ubiquitous across the cosmos, and they are essential prerequisites for creating and sustaining networks of dissipative structures [14].

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Appendix A. Thermocontextual Interpretation's Postulates and Definitions

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

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

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

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

Definition 2: A system's absolute energy, E_{abs}, 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 ambient state when its exergy and entropic energy equal zero.

Definition 5: A system's ambient-state energy E_{as} is the ambient reference state's potential work capacity, as measured at the limit of absolute zero.

Definition 6: System energy is defined by $E \equiv E_{abs} - E_{as}$.

Definition 7: A system's entropic energy is defined by $Q \equiv E - X$.

Definition 8: Perfect measurement of state involves a reversible thermodynamically closed process of transition from a system's initial state to its ambient reference state. Perfect measurement reversibly records the outputs of exergy and entropic energy to the ambient surroundings.

Definition 8.1: Instantiation is the selection of a measurable microstate potentiality as a consequence of derandomizing a system by reversibly eliminating entropic energy.

Definition 8.2: Actualization is the reversible and deterministic transition of an instantiated microstate potentiality to a measured state.

Definition 9: A system's entropy is defined by $S \equiv Q/T_a$.

Postulate Four (revised) (Generalized Second Law of Thermodynamics): A state of higher exergy has a potential to transition to a state lower exergy, either by irreversible dissipation or by exporting exergy or work to the surroundings.

Definition 10: Physically separated particles are entangled if they have properties linked by a deterministic and thermodynamically reversible connection.

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