doi:10.20944/preprints202206.0353.v1

Article

MaxEnt: Selection at the Heart of Quantum Mechanics

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Abstract: The thermocontextual interpretation (TCI) defines the physical state with respect to a system's actual surroundings at a positive ambient temperature. The TCI provides a clear distinction between the Second Law of thermodynamics and MaxEnt. The Second Law dictates irreversible dissipation of free energy to ambient heat, and it establishes the thermodynamic arrow of time. MaxEnt describes reversible changes in statistical mechanical entropy in response to changes in the system's boundary constraints. We introduce new TCI postulates that establish the equality of thermal and statistical entropies and MaxEnt as a fundamental physical principle. We then apply MaxEnt to the double-slit experiment. Impacts of multiple particles symmetrically passing through parallel slits record a wave interference pattern over time. However, 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 and MaxEnt offer a simple explanation. The which-slit detector breaks the system's symmetry, and MaxEnt selects the higher-entropy asymmetrical state, enabling particles to pass through one slit or the other without wave interference.

Keywords: entropy; physical foundations; MaxEnt; thermocontextuality; quantum mechanics; thermodynamics; complex system

1. Introduction

The MaxEnt principle states that a system maximizes its statistical entropy, consistent with its physical constraints. MaxEnt and Bayesian logic enable extrapolation of limited information to create an unbiased statistical model of a system. Recent applications include problems in astrophysics [1], rapid medical diagnostics [2,3], thermodynamic computing [4,5], artificial intelligence and machine learning [6,7], ecological modeling [8], macroeconomics [9], imaging theory and applications [10-12], network analysis [13-15], and plasma science [16].

The theoretical foundation for applying MaxEnt and Bayesian logic to inverse problems is substantially based on the pioneering work of E. T. Jaynes. Jaynes [17] showed that if a system adopts the maximum statistical entropy consistent with its environmental constraints, then applying Bayesian logic produces an unbiased best-fit model based on available information. As a trivial limiting example, if there is zero information on a property's value over some range, then assigning equal probabilities over that range maximizes the statistical entropy, and this is the best-fit statistical model consistent with the available (null) information. Bayesian Logic and MaxEnt provide unbiased best-fit models, and they provide a powerful statistical tool to model complex systems.

The success of MaxEnt models in modeling physical systems empirically attests to the MaxEnt principle of maximizing entropy. MaxEnt is not, however, simply an alternative expression of the Second Law of thermodynamics, as is commonly thought. The Second Law and MaxEnt both assert that a system maximizes its entropy, but they differ in their meanings and in their definitions of entropy.

The original meaning of the Second Law was about the irreversible production of entropy. Thermodynamic entropy measures the irreversible dissipation of a system's free energy to ambient heat. MaxEnt, in contrast, is about how a system responds to changing environmental constraints to achieve and maintain its most probable statistical state. MaxEnt is reversible; if changes in the environmental constraints are reversed, changes in the statistical entropy are likewise reversed. Whereas the Second Law is about maximizing dissipation and minimizing free energy, MaxEnt is about statistics and maintaining a system's most probable state.

Prevailing interpretations of physics do not recognize entropy as a fundamental property of state. They interpret statistical entropy as a subjective measure of incomplete information on a system's actual state [17]. They likewise interpret the thermodynamic state and thermodynamic entropy as an incomplete description of a system's actual mechanical microstate. Prevailing interpretations do not recognize MaxEnt or the Second Law as fundamental principles. MaxEnt and the Second Law of thermodynamics are, however, firmly founded on the Thermocontextual Interpretation (TCI) of physical states.

The TCI generalizes thermodynamic and statistical mechanical entropies as thermocontextual entropies, and free energy as exergy, all defined with respect to the system's ambient surroundings [18]. It establishes thermocontextual properties as physical properties of state and the Second Law of thermodynamics as a fundamental principle. It provides an explanation for one of quantum mechanics' most perplexing phenomena, the superluminal correlation of measurements in EPR-type experiments, without untestable metaphysical implications such as superdeterminism, hidden variables, or "spooky action" [18].

This article extends that work and formalizes MaxEnt as a fundamental principle, distinct from the Second Law. MaxEnt asserts that a system reversibly maintains a state of maximum statistical entropy and maximum probability with respect to changes in the system's surroundings.

The article then applies MaxEnt to explain the behavior of quantum particles in the double slit experiment. If a stream of quantum particles passes through a pair of parallel slits, the particles record a distinct wave-interference pattern on a detector, 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 [19]. The TCI and MaxEnt provide a simple explanation for the double slit experiment and its delayed-choice variations.

2. The Three Entropies

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

$$\Delta S_{TD}=\Delta q/T, \tag{1}$$

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 relative to its initial reference state. Equation (1) is limited, however, to systems that maintain thermal equilibrium at a fixed temperature.

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

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

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 quasistatic transfers of heat, q_{rev} at the system's changing local temperature. The Third Law entropy is strictly based on an equilibrium process of change.

Equation (1) defines the classical thermodynamic entropy with respect to a reference state at the thermally equilibrated system's 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 therefore defined independent of the ambient temperature of a system's surroundings, and it is an objective property of the thermodynamic state (Figure 1-A).

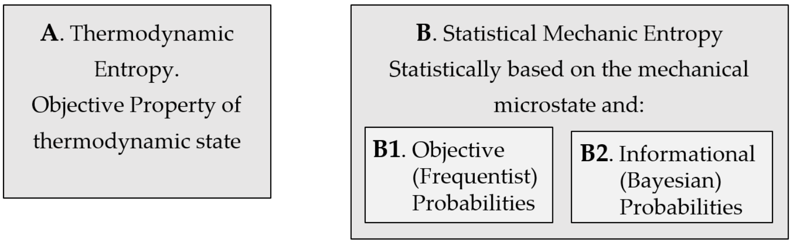

Figure 1. Three Interpretations of Entropy. (A) The classical thermodynamic and 3rd Law entropies are defined as an objective property of the thermodynamic state. (B) Statistical mechanics considers the thermodynamic state to be incomplete, and it defines entropy statistically in terms of the system's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

Mechanics provides a fundamentally different definition of entropy from thermodynamics (equations 1 and 2). Statistical 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 knowable about a quantum system.

Whereas thermodynamics defines thermal equilibrium by a uniform and steady temperature, without addressing a system's mechanical microstates, statistical mechanics asks: What is the statistical distribution of possible microstates for a system at thermal equilibrium? Classical statistical mechanics frames this question by its statistical definition of Gibbs entropy:

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

k_B is Boltzmann's constant and the P_i's are the probabilities that a thermally equilibrated system exists in the mechanical microstate 'i' at any given instant. The Boltzmann partition function, which describes the equilibrium distribution of energy levels, is based on the equal *a priori* probabilities hypothesis, which states that all possible microstates have equal probabilities. The *a priori* probabilities hypothesis is equivalent to the maximum entropy hypothesis, which states that an isolated system is stable when it reaches its maximum possible entropy.

The statistical mechanical entropy actually comprises two distinct interpretations: the frequentist interpretation and the Bayesian interpretation [17]. 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. An objective entropy implies that either fluctuations among the system's microstates are objectively random, or they are determined but objectively unknowable due to "hidden variables." The Bayesianism interpretation (Figure 1(B2)), in contrast, makes no assumption about an underlying physical state. MaxEnt and Bayesian logic provide unbiased and objective statistical expectation values based solely on known information [17].

Physics is unified in its interpretation of thermodynamics as an incomplete description of mechanical state. It recognizes entropy as a statistical measure of a system's possible microstates, but it is split on whether probabilities are objective or subjective. Even if we accept that probabilities and entropy are objective, it is intrinsically unknowable whether objectivity reflects objectively random fluctuations or the objective unknowability of hidden variables. It is a simply a matter of assumption and accepting the consequences. The consequences of rejecting fundamental randomness, however, include splitting universes, superdeterminism, and "spooky action" at a distance [18].

Jaynes rejected objective randomness of fluctuations because he considered it to be incompatible with mechanics [17]. He concluded that physical entropy is informational and a measure of incomplete information on a system's details. This is physics' prevailing interpretation of entropy. However, this interpretation simply shifts the question from the meaning of statistical entropy to the meaning of information. Is information a property of an observer's knowledge? Is it a property of a system's physical state? Is information always knowable? These questions underlie fundamentally different interpretations of the physical state. Quantum Bayesianism describes the physical state by an observer's actual knowledge, without directly addressing the nature of physical state itself [20]. Wheeler's famous statement "It from bit" expresses the idea that information is objective and that it completely defines the physical state [21].

3. Thermocontextual States and Transitions

The thermocontextual interpretation (TCI) defines a system's state by what can, in principle, be measured from the system's physical surroundings. Whereas thermodynamics defines entropy with respect either to the system temperature or to absolute zero, the TCI defines entropy with respect to an ambient reference state in equilibrium the system's actual surroundings at a positive ambient temperature. The TCI is based on postulates and definitions given in [18] and listed in Appendix A, with the addition of two new postulates introduced in section 4.

3.1. *Thermocontextual Properties of State*

The TCI contrasts with prevailing interpretations of physics by recognizing thermocontextual components of energy and entropy as physical properties of state. The TCI partitions a system's total energy into thermocontextual components, given by:

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

The total energy, E, is resolved into system energy, E_{sys}, and ambient-state energy, E_{as}. Ambient-state energy is the absolute energy of the ambient reference state, and E_{sys} is the system's energy relative to the ambient reference state. The TCI further partitions system energy into exergy, X, and ambient energy, Q. Exergy is the system's potential work capacity on the ambient surroundings. Ambient energy is defined by $Q=E_{sys}-X$. It has zero potential for work.

A system's exergy is then partitioned 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. A particle's potential energy includes both non-thermal internal exergy (e.g., a compressed spring or chemical free energy) and potential energy due to external fields such as gravity. Thermal exergy is the work potential of the system's particles' internal thermal energy, q. Thermal exergy is the measurable work potential of heat, 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. Ambient energy is related to heat at temperature T by:

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

Ambient energy is the equivalent heat at the ambient temperature, and we will often refer to it as ambient heat.

The TCI finally defines thermal entropy by:

$$S_q \equiv \frac{Q}{T_a} = \int_{AS}^{SS} \frac{dQ}{T_a} = \int_{T_a}^{T} \frac{dq(T)}{T}, \tag{7}$$

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 ambient reference state defines the zero values for system energy, ambient energy, and entropy. The last term of (7) follows from (6) for systems in which heat is expressed as a function of temperature only.

TCI's thermal entropy is thermocontextually defined with respect an ambient reference state in equilibrium at the positive temperature of the system's actual surroundings. It 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 absolute zero, (equation 2).

3.2. Irreversible Transitions

The Second Law of thermodynamics describes irreversible transitions by the production of thermodynamic entropy. Physics regards the Second Law of thermodynamics as a thoroughly validated empirical principle, but not as a fundamental physical law. It regards the thermodynamic state as an incomplete description of a system's state, and it regards entropy as a measure of an observer's uncertainty of the system's actual microstate.

The TCI contrasts with physics by recognizing irreversible change as fundamental. Postulate Four (Appendix A) describes irreversible change by the dissipation of exergy to ambient heat and the production of thermal entropy (7). Like thermodynamic entropy, thermal entropy of an isolated system can never decline. The reversibility of physics represents an idealized special case in the limit of zero entropy production.

The TCI also contrasts with classical thermodynamics by describing irreversible change by an operator. During an irreversible transition, the system cannot be reversibly measured; it has no well-defined exergy, and it does not exist as a state. The transition operator takes a system from a well-defined state of higher exergy to a well-defined state of lower exergy. An irreversible transition can approach a continuous quasistatic function, in which equilibrium and reversibility between the system and its slowly changing surroundings are continuously maintained, but it can never reach reversibility. An irreversible process is always resolvable into discontinuous states and dissipative transitions.

3.3. Statistical Entropy and Transition Probabilities

Section 3.1 defined thermal entropy as a thermocontextual generalization of thermodynamic entropy. This section presents a thermocontextual generalization of the statistical entropy of classical and quantum mechanics. The TCI expresses statistical entropy, S_p in terms of probabilities, exactly like the Gibbs entropy of classical statistical mechanics (3):

$$S_p = -k_B \sum_i P_i \ln(P_i), \tag{8}$$

but it interprets the probabilities very differently. The Gibbs entropy, and its extension to statistical quantum states, the von Neumann entropy, interpret the P_i's as a measure of incomplete information. Incomplete information is typically regarded as a subjective property of an observer's ignorance of a system's precise state, and it decreases whenever a new measurement result is observed. The TCI, in contrast, unambiguously defines the P_i's objectively. Equation (8) is summed over potential pathways that a positive-entropy system can take when it transitions to an equilibrium zero-exergy and zero-entropy ambient state (Figure 2) or to an intermediate metastable state. The TCI describes the probabilities in (8) as reflecting the objective randomness of which path the system takes as it transitions to a lower-entropy state.

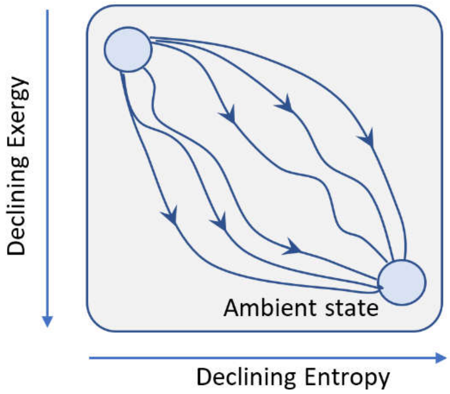

Figure 2. Multiple Pathway Potentialities. Each path represents a potential pathway for transition from an initial positive-entropy state to a zero-exergy zero-entropy ambient state. The transition involves reversible transfers of exergy, ambient heat, and entropy to the surroundings, and it generally also includes irreversible production of entropy within the surroundings. The initial system's statistical entropy (8), prior to interaction with the surroundings and transition, is summed over the potential pathways' probabilities.

The differences among the frequentist, Bayesian, and TCI interpretations of statistical entropy are succinctly highlighted by their respective interpretations of entropy and entropy changes for a coin flip (Table 1).

Table 1. The Frequentist, Bayesian, and TCI interpretations of Entropy and Information.

	Frequentist	Bayesian	TCI
Initial entropy of coin	Zero	Zero	Positive
Entropy of coin post flip	Zero	Positive	Zero
Interpretation of Probabilities	Objective uncertainty of a hypothesis's truth	Subjective uncertainty of a system's actual definite microstate	Objective randomness of instantiating one of a system's multiple pathway potentialities.
Interpretation of Entropy	Objective randomness of fluctuations	Subjective property of observer's knowledge of state.	Thermocontextual property of state with respect to an ambient reference state.
Interpretation of Information	Objective: what is measurable.	Subjective: what an observer knows	Objective: what is measurable from the surroundings.

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.

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 describes the coin prior to the coin flip as having a positive entropy and exergy. It describes the system prior to the coin flip as comprising the coin and its cocked coin-flipper. Its positive entropy (Table 1) reflects the objective randomness of the coin's transition potentialities.

Table 1 also shows the contrasting interpretations of information. The Bayesian interpretation defines information subjectively by an observer's actual knowledge. Bayesian

doi:10.20944/preprints202206.0353.v1

information is updated as measurements and observations are conducted. Both the frequentist interpretation and the TCI, in contrast, objectively define information by what can in principle be measured within their respective frameworks. They define information as an objective property of a system, independent of an observer's knowledge.

4. MaxEnt

Section 3 described irreversible transitions and changes in thermocontextual properties with respect a fixed ambient reference. In this section, we describe reversible changes in a system's thermocontextual properties in response to changes in the ambient surroundings.

4.1. Measurement, Instantiation, and Actualization

A perfectly stable state is in equilibrium with its ambient surroundings, and it has zero exergy and zero entropy with respect to its ambient reference state. If the system has positive exergy with respect to its surroundings, the system has a potential transition to its equilibrium state. Kinetics and statistics may delay that transition, however. Prior to transitioning, the system exists as a metastable state with positive exergy and generally positive entropy.

The TCI defines perfect measurement of a metastable state as a reversible and thermodynamically closed transition of the system to its new ambient reference state (definition 8 in Appendix A). Thermodynamic closure means that the system can exchange energy with the surroundings, but not mass. Reversibility means that the transition occurs in the idealized limit of a quasistatic process.

Figure 3(a) illustrates a reversible and continuous measurement. Figure 3(a) could describe the reversible measurement of a hot gas as it quasi-statically cools to its ambient state in equilibrium with its surroundings. The hot gas's thermal exergy is measured by the work recorded by a reversible heat engine, and Q is the measure of heat reversibly discharged at the ambient temperature. Thermal entropy is the ratio of ambient heat to ambient temperature (equation 7). Reversing the quasistatic measurement process using a reversible heat pump restores the ambient gas to its original exergy and thermal entropy.

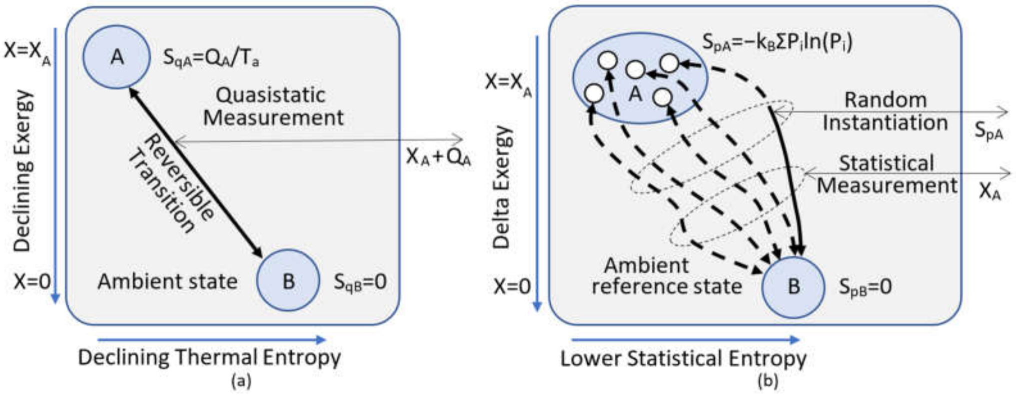

Figure 3. Perfect Measurement for continuous and statistical transitions. (a) Quasistatic measurement involves continuous and reversible transfers of exergy and thermal entropy to the surroundings. (b) An individual statistical measurement involves random instantiation and actualization. Transfer of entropy to the surroundings randomly instantiates a transition pathway, which then actualizes a measurement result. Reversal of a quasistatic measurement, whether continuous (a) or statistical (b), fully restores the system's initial exergy and entropy.

The TCI resolves statistical measurement into two distinct stages, instantiation and actualization (Figure 3(b)). Instantiation (Definition 8.1 in Appendix A) is initiated by interaction with the surroundings and transfer of statistical entropy from the system's initial state. This derandomizes state A and reduces its entropy to zero. From (8), this randomly instantiates a single zero-entropy potentiality and its transition pathway.

Actualization (Definition 8.2 in Appendix A) transfers the instantiated system's exergy and does work on the surroundings. Measurement is the work of actualizing a measurement result. If each pathway transition actualizes a distinct measurement result, then measurements are intrinsically and objectively statistical. The statistical entropy is given by equation (8), summed over the transition pathways, with P_i equal to the probability of instantiating pathway 'i.' Reversal of an individual perfect statistical measurement restores the system's initial exergy and entropy.

The continuous quasistatic measurement of thermal entropy (Figure 3(a)) records the ambient heat and thermal entropy transferred to the ambient surroundings. Multiple statistical measurements (Figure 3(b)) record the probability distribution of pathway potentialities and the statistical entropy by (8). The statistical entropy and thermal entropy have very different empirical definitions, and there is no *a priori* basis for their equivalence.

The perfect measurement of exergy, whether continuous or discontinuous, records exergy by the reversible work done on the surroundings. Reversibility can be approached, but real measurements and processes generally are not reversible. Exergy might be dissipated by irreversibly pushing ambient heat to the surroundings during instantiation, and it might be dissipated in the surroundings by irreversible actualization and work of measurement.

4.2. Minimization of Dissipation

A transition can approach quasistatic reversibility, but real transitions dissipate exergy. As a system approaches a zero-exergy and zero-entropy state of equilibrium with its ambient surroundings, total energy is conserved. If we measure what happens to the system's exergy, we find that it does work on the surroundings or on our measurement device. Increasingly sensitive measurements recover more and more of the system's initial exergy. Extrapolation of this observation to zero dissipation underlies the Hamiltonian conceptual framework (HCF), which views nature as fundamentally reversible, and which provides the foundation for the prevailing interpretations of physics [18]. Reversibility follows from the HCF's definition of perfect measurement at absolute zero, in the absence of thermal noise, ambient energy, and dissipation. The TCI recognizes the HCF as an idealization, but it also recognizes nature's tendency to approach reversibility as closely as possible. The TCI expresses this empirically validated tendency as Postulate Five, introduced here:

Postulate Five (MinDis): During transition of a component from an initial state to a more stable state of lower exergy, a system minimizes the relative dissipation of its energy.

We define relative dissipation of a system's energy by:

$$D \equiv \frac{\int_0^1 \left(\frac{\partial Q}{\partial \zeta}\right) d\zeta}{(E(0) - E(1))}. \tag{9}$$

Zeta (ζ) is a reaction progress variable. It ranges from zero for the initial state to one for the final state. It indexes the measurable changes in state properties and the dissipation of exergy to ambient heat within the system and its surroundings. Relative dissipation, D, describes the fraction of the system's initial energy that is dissipated. Relative dissipative ranges from zero for a reversible transition to one for a purely dissipative transition of an initially zero-entropy state. MinDis does *not* address the rate of dissipation or entropy production. Dissipation rates are based on phenomenological rate laws, but MinDis is defined strictly in terms of state properties.

MinDis provides a counterbalance to the Second Law. Whereas the Second Law states that dissipation of exergy is irreversible, MinDis states that a system minimizes relative dissipation to the extent possible. Whereas the Second Law describes the selection and relative stability of states based on minimum exergy, MinDis describes the selection and relative stability of dissipative processes, based on minimum relative dissipation of exergy.

4.3. Refinement and MaxEnt

The irreversible dissipation of exergy to ambient heat is one path toward higher entropy. The other path is refinement of a metastable system [18]. If a system's ambient temperature declines, then its ambient-state energy declines and, from (4) and the conservation of energy, its system energy increases. Any associated increase in exergy can then be dissipated. Postulate 5 minimizes the potential dissipation by minimizing the increase in exergy following refinement. From (4) and (7), this maximizes the increase in thermal entropy in response to a changing environment. We express this as Corollary 5-1:

Corollary 5-1—The Maximum Thermal Entropy Principle: Thermal refinement maximizes a metastable system's thermal entropy with respect to its new ambient surroundings.

To quantify the increase in entropy from refinement, we consider a system in state A and an ambient reference state B. From (6) and (7):

$$S_{qB}(A) \equiv \frac{1}{T_{aB}} \int_B^A dQ = \int_0^A \frac{dq}{T} - \int_0^B \frac{dq}{T}. \tag{10}$$

$S_{qB}(A)$ is the thermal entropy of state A with respect to reference state B, in equilibrium with the system's ambient surroundings at ambient temperature T_{aB}. If the ambient surroundings changes from state B to state C, then the thermal entropy of A changes to:

$$S_{qC}(A) = \int_0^A \frac{dq}{T} - \int_0^C \frac{dq}{T} = \int_0^A \frac{dq}{T} - \left(\int_0^B \frac{dq}{T} - \int_C^B \frac{dq}{T} \right) = S_{qB}(A) + S_{qC}(B). \tag{11}$$

Equation (11) shows the linearity of thermal refinement: the entropy of A with respect to C equals the entropy of A with respect to B plus the entropy of B with respect to C.

TCI's statistical entropy also depends contextually on the ambient surroundings, and it likewise increases with statistical refinement. We would like to show that statistical refinement is also linear, and that the statistical entropy is also maximized by refinement. To do this, we first need to express an analogue for conservation of energy that applies to statistical entropy. We express this by Postulate Six:

Postulate Six: Transition probabilities are independent of the ambient reference state.

We illustrate Postulate Six by Figure 4. Figure 4(a) shows the transition probabilities P_i for transition from state A to state B. Statistical refinement resolves the system's initial reference state, B, initially with zero entropy, into a positive-entropy state with distinct transitions potentialities P_j to the new ambient reference state C (Figure 4(b)). From Postulate Six, increasing the resolution of state B has no effect on the transition probabilities P_i. The increased resolution and entropy of reference state B is directly conveyed into increased resolution and entropy of the system's state A, as expressed by the transition probabilities $P_i \times P_j$ from A to the new reference state C (Figure 4(b)).

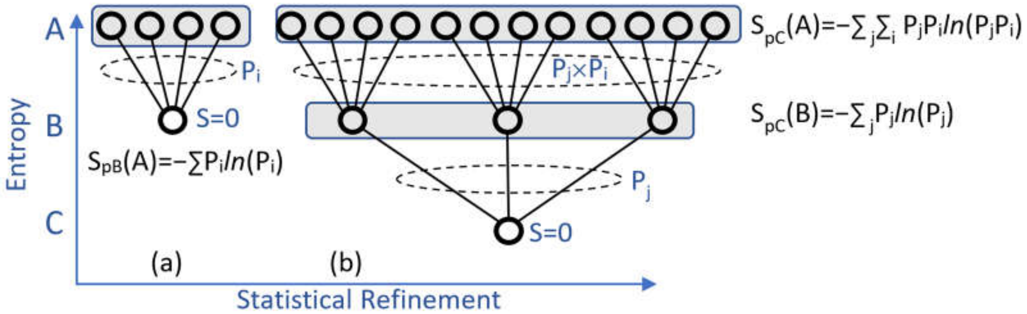

Figure 4. Statistical Refinement. The statistical entropies of states A and B are shown with respect to ambient reference states B and C. (a) The statistical entropy of A with respect to ambient state B. State B defines the zero-entropy ambient surroundings. (b) Statistical refinement of A. Refinement leads to the resolution of multiple pathways from state B to a new ambient reference state C, and to a positive entropy for state B.

We can now show the linearity of statistical refinement. From Figure 4 and using $\Sigma_i P_i = \Sigma_j P_j = 1$, the statistical entropy difference between states A and B, given ambient reference state C, is given by:

$$\begin{aligned} S_{pC}(A) - S_{pC}(B) &= -\sum_i\sum_j P_iP_j ln(P_iP_j) + \sum_j P_j ln(P_j) \\ &= -\sum_i P_i \sum_j P_j ln(P_j) - \sum_j P_j \sum_i P_i ln(P_i) + \sum_j P_j ln(P_j) \\ &= -\sum_j P_j ln(P_j) - \sum_i P_i ln(P_i) + \sum_j P_j ln(P_j) \\ S_{pC}(A) - S_{pC}(B) &= -\sum_i P_i ln(P_i) = S_{pB}(A). \end{aligned} \tag{12}$$

Equation (12) is the statistical analogue of (11) for thermal entropy. It shows that, like thermal refinement, statistical refinement is linear: the entropy of A with respect to C equals the entropy of A with respect to B plus the entropy of B with respect to C. Refinement linearly increases both statistical entropy and thermal entropy, either by increasing the system's resolution (Figure 4 and equation 12) or by lowering the ambient temperature (equation 7).

Postulate Six not only establishes the linearity of statistical refinement, but it also establishes the equality of thermal and statistical entropies. Thermal and statistical entropies are both defined to be zero for a system in equilibrium with its ambient reference state. The linearity of thermal and statistical refinement means that given an appropriate scaling factor and common reference, the two remain equal. For statistical entropy as expressed in (8), the appropriate scaling factor is the Boltzmann constant. The statistical entropy given by (8) is equal to the thermal entropy given by (7).

Postulate Five establishes the minimization of thermal entropy, and Postulate Six establishes the equality of statistical and thermal entropies. Together, they establish that both thermal and statistical entropies are maximized following refinement. We express this as the MaxEnt Principle:

MaxEnt Principle: Following refinement, a metastable system's entropy is the maximum value compatible with its new ambient surroundings.

The TCI recognizes MaxEnt and Postulate Four (irreversible dissipation) as two distinct processes by which an isolated system can increase its entropy. Postulate Four describes the irreversible increase in entropy due to dissipation with respect to fixed ambient surroundings. MaxEnt, in contrast, describes the increase in entropy of a metastable system due to refinement, in the absence of dissipation or interaction with the surroundings. Unlike dissipation, MaxEnt is reversible; if the surroundings reverts to its previous state, the entropy likewise reverts.

To illustrate the fundamental physical significance of MaxEnt, we apply it to the double-slit experiment and gain a deeper understanding of the particle-wave duality of quantum mechanics.

5. Double Slit Experiment

5.1. The Particle-Wave Duality

The double slit experiment clearly demonstrates the particle-wave duality of quantum mechanics. A particle is created and emitted from a source, 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 pass through both slits. The particle-wave duality is further indicated by placing a detector behind one or both slits. Measurements then indicate 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." [19].

To remain neutral on the nature of the emitted "particle," we simply refer to it as a "system" in transition between its source-state and its ambient state after detection. The system's state is thermocontextually defined by perfect measurement at the detector plate, with a finite resolution of measurement set by the ambient surroundings. The thermocontextual entropy for the particle between its source and prior to instantiation is given by equation (8), summed over the system's transition pathways, each terminating at a resolvable detection point. While there is no irreversibility or interaction with the fixed surroundings, the system exists as in isolated metastable quantum state. Prior to measurement, the system has fixed positive exergy and entropy, and its time-dependent wavefunction at A and A′ (Figure 5) represent two points on a thermodynamically reversible trajectory, defined over continuous and symmetrical time.

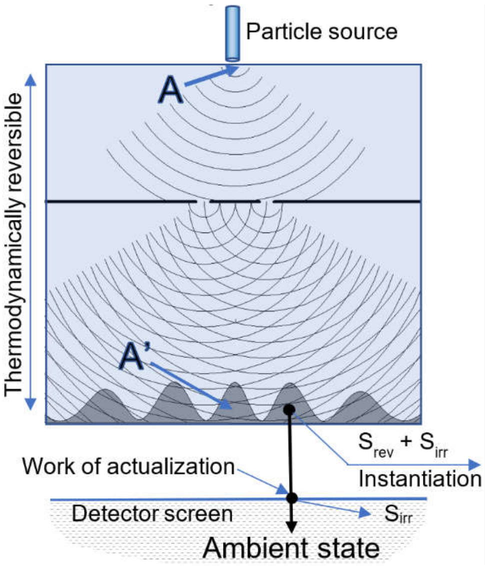

Figure 5. Double slit experiment. Between points A and A,′ the system is metastable, meaning no dissipation or interaction with its surroundings. It therefore has fixed exergy and entropy, and its time-dependent state is thermodynamically reversible. The shaded pattern at A′ represents the statistics of potential measurements. Interaction with the surroundings initiates a process of random instantiation of transition potentialities. Actualization of the instantiated transition records the point of impact on the detector screen. .

Figure 6 shows the probability profiles for detecting a particle on the detector plate. Curves show probability profiles for wave interference from double slits and for wave diffraction through single slits. Calculations are based on intensity profile calculations for light [22], using parameters shown in Table 2, and assuming that probabilities of photon detection are proportional to calculated intensities. Probabilities for the double-slit curves in Figure 6 are normalized to one, and they are normalized to 0.5 for the single-slit curves.

Table 2. 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)

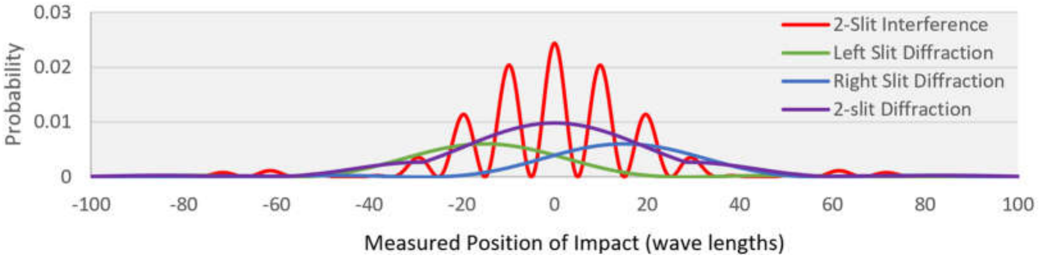

Figure 6. Probability amplitudes for photon detection from double-slits, with and without wave interference.

The probability profiles describe the actualized measurement results for multiple transitions. When both slits are open, multiple measurements show the statistical distribution of high and low intensities illustrated by the red line in Figure 5, characteristic of the wave interference pattern from double slits.

The probability amplitude profile for wave interference (red profile) and equation (8) define the entropy for the system with both slits open. The detector screen is 200 units long, and the detection resolution is 0.5 units, so probability amplitude is compiled from 400 bins. The dimensionless entropy (setting Boltzmann's constant to unity), based on the parameters in Table 2, is 4.69. This is the entropy for the metastable system as it existed with respect to its environment, prior to instantiation and the actualization of measurement results.

5.2. *MaxEnt and Which-Slit*

We now consider the case when we place a "which-slit" detector behind the slits. This represents a change in the system's environmental surroundings. If the system symmetrically passes through both slits and creates an interference pattern, the system's entropy, prior to instantiation, would be the same 4.69 as before. However, if the system randomly passed through one slit or the other, then, with the ability to determine through which slit it passed, there are now 800 information bins—400 bins for registering a particle from the left slit and 400 bins for registering a particle from the right slit. The probability amplitudes from each slit are shown by the green and blue curves in Figure 6, where each curve is normalized to a 50% total probability. Applying equation 8 and summing over the 800 probability bins yields a dimensionless entropy of 5.71 for the system as it existed prior to instantiation. This is higher than the entropy for the double-slit interference result. MaxEnt therefore selects the higher-entropy state, and the particle randomly passes asymmetrically through one slit or the other. Measurements of multiple transitions reveal that statistical impacts record the expected noninterference pattern.

The above discussion raises an interesting question. What would happen if we placed a which-slit detector behind the slits, but we somehow isolated it from measurement? There would be no way to know which slit, and there would only be the original 400 information bins. If the system passed through one slit or the other anyway, the predicted probability profile would be the normalized sum of the left and right probability profiles, given by the purple curve in Figure 6. It is spread over the same number of bins as the interference pattern, but it is smoother, so we would expect its entropy to be higher. From equation 8, in fact, its entropy is 5.28—not as high as when we could determine which slit, but still higher than the interference pattern. MaxEnt would still select the asymmetrical state with higher entropy, displaying the purple noninterference profile in Figure 6. A non-interference pattern, even if the which-slit detector was not observable, would support the idea that MaxEnt drives the selection of non-interference over interference, rather than the determination or the ability to determine which-slit information, as conventionally believed [9,23].

The TCI attributes the switch between double-slit interference and single-slit noninterference to breaking the system's symmetry. The which-slit detector provides the system an opportunity, not previously available, to select between symmetrical double-slit or the asymmetric single-slit profiles. Given this opportunity, MaxEnt selects the higher-entropy state and its single-slit noninterference profile. Without the which-slit detector, the system's symmetry and its wavefunction do not allow the higher-entropy state and asymmetric transition, and the symmetrical wave interference pattern is observed.

5.3. System Time and Delayed Choices

Effects have causes, and John Wheeler formulated a series of "delayed-choice" thought experiments to address the questions: What causes an electron to exhibit wave-like versus particle-like behavior? How and when does an electron switch between particle-like or wave-like behavior?

In a delayed choice double slit experiment, the experimental setup is changed while the system is in midflight [23]. For example, one of the slits could be covered or uncovered, or a which-slit detector could be inserted or removed between particle emission and detection. Other variations involve observation of entangled "idler" photons after the original "signal" photon has already interacted with a detector [24]. Results of delayed-choice experiments seem to show that the recorded result is not definite until the actual observation event. John Wheeler concluded that "no phenomenon is a phenomenon until it is an observed phenomenon," and that the Universe does not "exist, out there independent of all acts of observation" [23]. Other proposed explanations include retrocausality, in which observation changes the system's state prior to observation, and determinism caused by unobservable hidden variables [23].

Without going into details of the experiments and their experimental realizations, we will instead simply argue that the questions motivating delayed-choice experiments and the conclusions drawn are based on false premises.

Causality is premised on effects following causes, and this implies an asymmetry of time. As discussed in [18], there are two very different asymmetrical times. The familiar arrow of time is related to the irreversible production of entropy, which the TCI defines as thermodynamic time. Irreversible advances in thermodynamic time are simply measures of irreversible entropy production. The TCI recognizes thermodynamic time as the real component of complex system time. The imaginary component of complex system time is mechanical time, which can be expressed by an imaginary coordinate "*it*" in quantum mechanics and in relativity [18]. System time is a complex property of a time-dependent state, describing both reversible and irreversible change.

If a system has no dissipative forces, then there is no production of entropy. The TCI fully describes a reversible system as a superposed positive entropy wavefunction over imaginary mechanical time, within a single instant of real thermodynamic time. Like the changes in a mechanical microstate, changes in the mechanical time coordinate are reversible and deterministic. This is the special case assumed by the Hamiltonian Conceptual Framework (HCF) [18].

The second asymmetrical time is reference time. The TCI defines reference time by the irreversible advance of an external clock [25]. This is the time of relativity and relativistic causality. It is the time by which we measure velocities of objects or light, and it is the time by which an external observer distinguishes past from future and cause from effect. The irreversible advance of reference time provides the scale against which we observe and track a system's changes, whether those changes are reversible or irreversible over system time.

Observers of the double slit experiment experience the irreversible passage of reference time between particle emission and detection, but the system itself is metastable and remains thermodynamically reversible while effectively isolated from external measurement or observation. A reversible system cannot distinguish between past and future, and it has no cause or effect. It just is, completely described by a time-dependent superposed wavefunction defined over reversible and deterministic mechanical time. Questions of causality for a thermodynamically reversible system are based on a false distinction between cause and effect. There is no fundamental distinction between cause and effect over imaginary time-symmetrical mechanical time [18]. "Cause follows effect" and "arrow of causality" are thermocontextually defined only over irreversible reference time. Questions or conclusions about cause and effect within a thermodynamically reversible system, as it exists unobserved, are based on a false premise.

6. Summary and Conclusions

The Thermocontextual Interpretation (TCI) provides a conceptual framework for defining physical states, time, and changes in state with respect to a system's actual surroundings. It is firmly based on well-established empirical observations, and its implications are reasonable and intuitive [18]. The TCI recognizes thermal entropy and exergy as objective properties of physical states, and as thermocontextual generalizations of thermodynamic entropy and free energy.

The TCI recognizes two distinct paths for changes in exergy and thermal entropy. TCI's Postulate Four (Appendix A) expresses the Second Law of thermodynamics' original meaning, in terms of the irreversible dissipation of exergy to ambient heat. The second path of change in entropy and exergy is through changes in the ambient surroundings. When the ambient surroundings change, the ambient reference state and the state's thermocontextual properties change in response.

Among the multiple dissipative possibilities that are often available to a far-from-equilibrium system, Postulate Five (MinDis), introduced here, states that the process having the minimum relative dissipation is the most stable and most probable. Relative dissipation is the dimensionless fraction of initial energy that is dissipated during a transition. MinDis is not the minimum entropy production principle, which addresses the rate of entropy production and dissipation.

Minimizing a transition's relative dissipation can recursively lead to organized networks of transition-nodes. A transition can reduce its relative dissipation by deferring dissipation and doing work on other transition-nodes. Postulate Five guides the selection of dissipative processes, leading to the origin and evolution of dissipative structures [26]. The application of Postulate Five to dissipative systems is the subject of a separate article currently in preparation. The application of a related postulate to the evolution of dissipative systems is discussed in [27] (pp 18-24).

Postulate Six introduces a statistical analogue of the conservation of energy. Postulate Six and Postulate Five, together, establish MaxEnt as a fundamental principle. MaxEnt asserts that a metastable system maintains a maximum-entropy configuration. If a system's environmental constraints change, MaxEnt selects the state of maximum entropy from among the possibilities that are consistent with the system's new environmental constraints. The Second Law, in contrast, addresses entropy changes due to the irreversible production of entropy with respect to fixed surroundings. MaxEnt and the Second Law are two distinct paths for maximizing entropy and two distinct laws of physics.

MaxEnt sheds light on one of the oldest questions at the heart of quantum mechanics: When is a particle a particle and when is it a wave? MaxEnt provides a physical explanation for when and why particles in the double slit experiment record a wave interference pattern and when they do not.

We can define a quantum particle as a wavefunction with a definite zero-entropy position or momentum eigenfunction. In the double-slit experiment, the photon exists as a particle only at its source, when it has a definite momentum, and at detection, when it has a definite position. At all points between, it is a superposed wavefunction and it exhibits wave-like dispersion, with or without wave interference.

Wave interference is recorded when a particle's wavefunction passes through the double slit symmetrically. Placing a which-slit detector at the slits breaks that symmetry. This allows MaxEnt to select a higher-entropy asymmetrical quantum state, allowing particles to randomly pass through one slit or the other without wave interference. The existence of multiple state potentialities and the freedom to choose from among them does indeed express the heart of quantum mechanics, and it distinguishes quantum mechanics from the fundamental determinism of classical mechanics.

MaxEnt and Bayesian logic have proven to be powerful tools for modeling complex systems. A quantum system adjusts to changes in its physical constraints to maintain MaxEnt. Recognizing MaxEnt as a fundamental quantum principle provides a new perspective on quantum behavior, and this could potentially inspire new approaches for solving complex problems.

Funding: This research received no external funding.

Conflicts of Interest: The author declares no conflict of interest.

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Appendix A. Thermocontextual Interpretation's Postulates and Definition

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 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 ambient state when its temperature equals the ambient temperature, and its exergy equals zero. The system's ambient state is uniquely defined by equilibrium with its ambient surroundings.

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

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

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

Definition 8: Perfect measurement of state involves a deterministic thermodynamically closed process of transition from a system's initial state to its zero-exergy and zero-entropy ambient reference state. Perfect measurement is the reversible measurement of the exergy and entropy changes in state and the equilibrium measurement of the ambient reference state.

Definition 8.1: Instantiation is the reversible transition of an indefinite positive-entropy microstate to a definite zero-entropy microstate. Instantiation transfers the system's ambient heat and entropy to the surroundings, while preserving its mass and exergy.

Definition 8.2: Actualization involves the reversible transition of an instantiated zero-entropy microstate. Actualization is the work on an external system during the transfer of exergy from the system to the surroundings.

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

Postulate Four (Second Law of Thermodynamics): An irreversible process dissipates exergy to ambient heat. For irreversible change within an isolated system at constant T_a, $\Delta X<0$.

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

Postulate Five (MinDis)(New to TCI): During transition of a component from an initial state to a more stable state of lower exergy, a system minimizes the relative dissipation of its energy.

Postulate Six: (New to TCI): The transition probabilities are independent of the ambient reference state.