



# Comprehensible dynamics of quanta: from the quantum of action to the 2nd law of thermodynamics

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**Abstract** The 2nd law of thermodynamics is derived from the principle of least action, positing that the quantum of action is the indivisible and indestructible basic building block of everything. On their least-time paths to balance, the quanta move from the system to its surroundings, or vice versa, so that the kinetic, potential, and dissipated energy tally. When re-expressed in logarithmic terms, this current toward more probable states with decreasing free energy equates to the principle of increasing entropy, the 2nd law of thermodynamics, including path-independent dynamic and path dependent geometric phase shifts. Despite being exact, the equation of evolution to entropy maximum, equivalent to free energy minimum, cannot be solved because evolution, consuming its own driving forces, becomes path dependent. Thus, the future remains open within free energy bounds. As discussed, the entropy derived from the statistical physics of open quantum systems sums states distinguishable in energy; whereas, Boltzmann's entropy enumerates microstates indistinguishable in energy. Consequently, the statistical physics of open systems differs from that of closed systems: The irreversible evolution in the state space toward thermodynamic balance contrasts with the steady-state revolution in phase space between conceivable configurations. This concrete comprehension explains, among other things, that increasing disorder is not a law of nature itself but a consequence of the law to attain balance with incoherent surroundings in the least time.

## 1 Introduction

The aspiration of deriving macroscopic properties from microscopic constituents is deeply ingrained in physics [1]. Famously, Boltzmann understood thermodynamics as expressing statistics of constituents, but infamously, his statistical mechanics was limited to only stating the equilibrium partition, not evolution from state to state, finally arriving at the most probable state. In a backward manner, this endpoint of an irreversible process by the second law became the starting point for theorizing non-equilibrium. First, probability distributions were modeled to spread out through stochastic fluctuations, as if without any cause, then to shift in interactions between the system and its surroundings, but only linearly and weakly, precluding fast changes, and more recently, to evolve by dissipating and decohering, but still closing the entire system environment into mere unitary [r]evolution in phase space, thereby precluding truly path dependent irreversible evolution from state to state [2–6].

Paradoxically, expanding reversible steady-state formulations with perturbations to account for data from irreversibly evolving systems has only complicated comprehending the dynamics of basic constituents, the quanta. For example, the master equation in Lindblad form,

$$\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar}[H, \rho] + \sum_i \gamma_i \left( L_i \rho L_i^\dagger - \frac{1}{2} \{L_i^\dagger L_i, \rho\} \right) \quad (1)$$

expands the coherent and unitary phase revolution,  $d\phi/dt = \omega$ , of the density matrix,  $\rho = \sum_{j,k} \rho_{jk} |a_j\rangle\langle a_k|$ , in a coherent superposition of the basis states  $|a_j\rangle$  and  $|a_k\rangle$ , spun by the stationary state Hamiltonian,  $H$ , with non-unitary environment-imposed dissipation modeled with jump operators,  $L_i$ , and decay rates,  $\gamma_i \geq 0$ . Although correlations, the non-zero off-diagonal elements  $\rho_{jk} = \sum_i p_i \langle a_j | \psi_i \rangle \langle \psi_i | a_k \rangle$  subject to the trace-preserving condition,  $\sum_i p_i = 1$ , do decay along with dissipation, the formalism is not explicit about what drives evolution from state to state and why the wave function,  $\psi$ , shifts in phase and why coherence degrades during a transition from one state,  $j$ , to another,  $k$  [7], besides its path-independent Markovian dynamics contrasting the path dependent 2nd law,  $dS = \delta Q/T$ .

In short, mere modeling for a good fit can obscure what is obvious: The system evolves irreversibly quantum by quantum from state to state, minimizing free energy in the least time. This natural process terminates at thermalization, where the system has

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decohered in incoherent surroundings [8] just as it has synchronized with the surrounding cycles [9]. In other words, the challenge in quantum thermodynamics [10, 11] lies in comprehending exactly how the dynamics of quanta en masse sum up to thermodynamics.

Besides the difficulties in explaining irreversibility and path dependence, the measurement itself presents a problem: The Copenhagen interpretation distracts  $\psi$  from its physical essence by invoking an instantaneous probabilistic collapse to an observed state from a superposition  $|\psi\rangle = \sum_i c_i |\psi_i\rangle$  in phase space satisfying the stationary state condition  $\sum_i |c_i|^2 = 1$  of probability amplitudes.

Rather than reinterpreting quantum mechanics, we distance ourselves from instrumentalism, recapped by the phrase “shut up and calculate” [12], by adopting the modern atomistic axiom: The basic building block of everything embodies the quantum of action,  $A_0 = \int E dt = \int \mathbf{p} \cdot d\mathbf{x} = h$  [13–15]. This elemental action, such as a photon, integrates energy,  $E$ , on its period,  $t$ , and equivalently momentum,  $\mathbf{p}$ , on its wavelength,  $\mathbf{x}$ , to Planck’s constant,  $h$ . In other words, we discard virtual photons and off-shell particles for concrete quanta to ensure correspondence with reality and falsifiability.

Logically, photons constitute both particles and space, given that matter–antimatter annihilation emits photons into space; while, pair production absorbs them from there. Despite the difficulties in detecting all photons, especially when they appear in pairs with opposite phases canceling each other’s electromagnetic fields, the idea of the photon as the fundamental element [14, 16] has not been disproven. So we hold onto it [17] to offer an ontological outlook on quantum thermodynamics to account for the path dependence and phase changes during the irreversible course toward balance.

## 2 The essence of the least action

As per Fermat’s principle, the photon takes the path of least time. This is observed, for example, in the bending path and shifting frequency as the photon traverses space of varying densities, ultimately on its way from the energy-dense nascent universe to the sparse space of the present [17, 18]. Thus, despite integrating the invariant  $h$ , the photon itself, as an element of the least-time path, is open to changes in its conjugate variables to attain and maintain balance in energy and coherence in phase with surrounding quanta.

Assuming all systems consist solely of discrete quanta of action, the evolution of any system from state to state along the least-time path toward thermodynamic balance is determined by minimizing the total (abbreviated) action in its original open, Maupertuis’ form [19, 20],

$$A = \int L dt = \int \mathbf{p} \cdot d\mathbf{x}, \quad (2)$$

so that the variation,  $\delta A$ , is stationary in multiples of  $h$ . This condition defines the relations in  $L$  between the energy gradients in kinetic, potential, and dissipative forms, as the open quantized system evolves toward thermodynamic balance with surrounding systems by emitting or absorbing quanta [20–22]. The gain or loss of a quantum breaks the symmetry of a stationary state and introduces new properties in the system or removes old ones from it [13, 23]. Thus, the arrow of time, macroscopic irreversibility derives from the microscopic system either absorbing or emitting quanta [24, 25].

In contrast to Lagrangian and Hamiltonian, the Maupertuis form’s (Eq. 2) time dependence is not predetermined but depends on the pursued path due to changes in forces that derive from the changes in momentum themselves [26]. For example, chemical potential differences decrease depending on reaction products that open new paths for further reactions. In general, evolution redirects as it consumes its driving forces. Therefore, the final state of the action integral is open in the initial state. Such path dependence is contained in Maupertuis’ action (Eq. 2). Even the integrable, path-independent Lagrangian and Hamiltonian mechanics closely correspond to reality when the force is conservative to an excellent approximation despite the changes in momentum. Similarly, Feynman’s probabilistic path integral formulation of quantum mechanics is statistically deterministic, i.e., solvable, unlike non-deterministic, path-dependent processes. Despite the practical utility of computable approximations, exactness is still essential for understanding how the path dependence and irreversibility of 2nd law derive from the dynamics of quanta.

The non-determinate evolution from state to state, quantum by quantum, can be quantified with the statistical measure of a state known as probability,  $P$ , and differentiated into the master equation,  $dP/dt = LP \geq 0$ . This natural process toward the most probable state can be rewritten in terms of change in entropy,  $dS/k_B = d \ln P = dP/P = L dt$ , per Boltzmann’s constant,  $k_B$ , toward the free energy minimum, equivalent to the entropy maximum. However, the  $dS$  equation cannot be solved because the changes affect their own driving forces in the generator,  $L$ . Since the variables cannot be separated in Eq. 2, the integration limiting to the state of balance remains non-determined at the initial state. In other words, the surrounding systems co-evolve by absorbing the quanta that the system emits and vice versa [27]. The future remains open as much as there is free energy [28]. Only after attaining balance can trajectories be computed precisely. This non-determinate nature of evolution, distinct from the determinate motions of classical mechanics and the statistically determinate (i.e., random) motions of quantum mechanics, is the foremost insight into comprehending natural processes.

Non-determinism deriving from the interdependence between forces and changes in momentum might seem to go against physics’ goal of predicting [29]. However, non-determinism does not mean that just anything can happen; only that can occur for which there is free energy. The surroundings of many a system are so superior thermal baths that there is only a little freedom for where the system ends up. In such a case, determinism is an excellent approximation for non-determinism. Accordingly, macroscopic systems with substantial bound energy rarely have enough free energy to undergo radical changes. In contrast, microscopic systems with only

little bound energy may even be annihilated altogether, or at least transformed dramatically [30–32]. As the double-slit experiment demonstrates, mere tracking of events imposes enough force to alter the outcome from wave-like to particle-like.

Moreover, thermalization does not invariably lead to decoherence but equally to coherence since systems balance dynamically by binding and freeing quanta in pace with surrounding processes, incoherent or coherent alike [9, 33]. Although these and other phenomena have been modeled to agree data [34–36], the least variation of quantized action offers concrete comprehension into what happens at the quantum level when a state changes to another. Since this universal principle derives from the atomistic axiom rather than from data, any data remains available for attempts to falsify it in the spirit of science. To date, however, we are not aware of such success.

### 3 Evolution from state to state

The evolution from state to state quantum by quantum toward balance in the least time transforms free energy to bound energy. Its equation is found from the vanishing expectation value in the variation of the total quantized action, given in terms of the momentum,  $\hat{p} = -i\hbar\partial/\partial x$ , and coordinate,  $\hat{x}$ , operators integrated over space spanned by the wave function,  $\psi$ ,

$$\begin{aligned} \langle \delta A \rangle &= \left\langle \int \left( v \cdot \nabla - \frac{\partial}{\partial t} \right) L dt \right\rangle = 0 \\ &\Leftrightarrow \int \int \psi^* \left( \frac{dx}{dt} \frac{\partial}{\partial x} \frac{\hbar}{i} \frac{\partial}{\partial x} x - \frac{\partial}{\partial t} \frac{\hbar}{i} \frac{\partial}{\partial x} x \right) \psi dx dt = 0 \\ &\Leftrightarrow \int \left( vp + x \frac{\partial U}{\partial x} - Q \right) dt = 0 \end{aligned} \tag{3}$$

where kinetic,  $2K = pv$ , and potential,  $U$ , energy and dissipation,  $Q$ , derive from  $\langle \partial p/\partial t \rangle = -\partial U/\partial x$  and from the evolution,  $i\hbar\langle \partial/\partial t \rangle = i\hbar\langle \partial/\partial t \int \psi^* \psi dx = i\hbar \int (\psi^* \partial \psi/\partial t + \partial \psi^*/\partial t \psi) dx = -Q$ , of the spatial norm,  $N(t) = \int \psi^* \psi dx$  [20, 37–39].

Thus, the integrand totaling nil (Eq. 3) ensures that no quantum of action goes lost in a change of state, but every emitted  $\hbar = h/2\pi$  is counted as those absorbed in a reverse transition. In fact, it is not the quanta of the bare system, such as a particle, but the quanta comprising surrounding fields that carry energy over time between the system and its surroundings. For example, when an electron returns from an excited state to the ground state, the atom emits a photon from its field while leaving the electron itself and the nucleus intact. Even in the reaction where the electron itself breaks, the resulting particles, the  $W^-$  boson and neutrino, have their own fields embodied by quanta. Accordingly, the statistical treatise, denoted by the integration over space spanned by the wave function, is warranted since transformations of even the most elementary systems invariably involve numerous quanta that constitute their fields, represented by  $\psi$  [40].

The integrand of Eq. 3, conditioned to zero by the least-time principle,

$$vp - \frac{\partial p}{\partial t} x - \frac{\hbar}{i} \frac{\partial}{\partial t} = 0 \Rightarrow \frac{\partial}{\partial t} 2K = -\mathbf{v} \cdot \nabla U + \frac{\partial Q}{\partial t} = 0, \tag{4}$$

means that the change in kinetic energy,  $2K = vp$ , is balanced by the change in potential energy,  $-\partial U/\partial x = \langle \partial \hat{p}/\partial t \rangle$ , and dissipation,  $Q = -i\hbar\langle \partial/\partial t \rangle$ , in orthogonal direction. In other words, the system evolves along the lines of force [41], the least-time gradients in energy. Other paths cannot be pursued because then the force carriers would appear out of nothing or disappear into nothingness, violating the axiom that the quantum of action is indivisible and indestructible.

As the system steps down in free energy, the equation of motion for  $\psi(x, t)$  is found from the least-time condition,

$$\begin{aligned} \frac{\partial}{\partial t} \left\langle x \left| \frac{\partial}{\partial t} \delta A \right| \psi \right\rangle &= 0 \\ \Leftrightarrow (2K + U - Q) \frac{\partial \psi}{\partial t} &= - \left( \frac{\partial}{\partial t} 2K + \frac{dx}{dt} \frac{\partial U}{\partial x} - \frac{\partial Q}{\partial t} \right) \psi, \end{aligned} \tag{5}$$

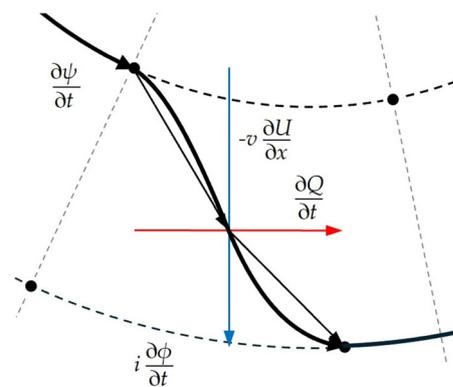
and similarly for  $\psi^*$ , which is the mirror image of  $\psi$  (Fig. 1). In this way, it is understood that the imbalance, i.e., gradients in energy, forces the system to evolve until attaining the dynamic balance where net dissipation vanishes,  $\langle Q \rangle = 0$ , and the virial theorem,  $2K + U = 0$ , holds.

Since all entities are embodied in quanta, the density,  $\rho(x, t) = \psi^*(x, t)\psi(x, t)$ , is not merely interpreted as the probability of finding a particle at position  $x$  at time  $t$ , but understood as the density of field quanta that span space through their wavelengths and time through their periods [17]. As quanta carry time, time flows along the least-time gradients in energy, ultimately closing into stationary circulation at the most probable state of maximum entropy [28, 42, 43].

From this physical perspective, a cause is understood as a force and its consequence as a change in momentum down along a gradient in energy. In this natural process, the conservation of quanta imposes continuity,

$$\frac{\partial \rho(x, t)}{\partial t} + \frac{\partial j(x, t)}{\partial x} = 0, \tag{6}$$

**Fig. 1** Wave function,  $\psi$ , evolves along the orthogonal spatial,  $x$ , and temporal,  $t$ , gradients in scalar potential,  $U$ , and dissipation,  $Q$ , from one stable state, e.g., an orbit (dashed line) modular in quanta, to another of a different modulus. Concurrently, the phase,  $\phi$ , develops from that difference along the path from one state to another



so that a change in density tallies a change in the flow of density,  $j = \rho v$ , with velocity,  $v = dx/dt$ . Accordingly, in the middle of a transition, the density changes,

$$\begin{aligned} \frac{\partial}{\partial t} \rho &= \frac{\partial \psi^*}{\partial t} \psi + \psi^* \frac{\partial \psi}{\partial t} \\ &= \frac{1}{2K} \left( \frac{\partial}{\partial t} 2K - \frac{dx}{dt} \frac{\partial U}{\partial x} + \frac{\partial Q}{\partial t} \right) \rho + \frac{1}{2K} (U - Q) \frac{\partial \psi^*}{\partial t} \psi \\ &\quad - \frac{1}{2K} \left( \frac{\partial}{\partial t} 2K + \frac{dx}{dt} \frac{\partial U}{\partial x} - \frac{\partial Q}{\partial t} \right) \rho - \frac{1}{2K} (U - Q) \psi^* \frac{\partial \psi}{\partial t} \\ &= \frac{2}{2K} \left( -\frac{dx}{dt} \frac{\partial U}{\partial x} + \frac{\partial Q}{\partial t} \right) \rho - i \frac{2}{2K} (U - Q) \frac{\partial \phi}{\partial t}, \end{aligned} \tag{7}$$

as much as the energy gradients, normalized by  $2K$ , force the density to flow,  $\rho v$ . In addition, the difference between  $\psi \propto e^{i\phi}$  and  $\psi^* \propto e^{-i\phi}$  amounts to the change in phase,  $2i \partial \phi / \partial t$  (Fig. 1).

Along an open trajectory, the phase develops freely. Still, in the end, for a new state to be stable, the action must enclose complete quanta with their full periods, which, including the surrounding field of quanta, imposes periodicity on the phase. This quantum condition of  $2\pi$  multiplicity underlies Bohr’s model of the atom, Dirac’s argument for the unit charge, and Londons’ idea of flux quantization. Also, a single photon has its field [44, 45], as on display in interference effects, for example, observable by Mach–Zehnder and Hong–Ou–Mandel interferometry [46].

Electromagnetic and gravitational fields stretch out in balance with their sources, ultimately with all matter. As per Planck’s law, the cosmic microwave background radiation displays the Bose–Einstein statistics of photons constituting the universal vacuum in balance with all matter. Similarly, each electron is enveloped by its field, i.e., gradients in the vacuum density and, more significantly, dispersions in phase that force two electrons to align antiparallel, as the Pauli exclusion principle states. Accordingly, the Fermi–Dirac statistics describes the collective behavior of numerous electrons due to their fields.

To obtain the dynamics of quanta among quanta, i.e., thermodynamics, the evolving density (Eq. 7) is integrated over space to the probability current,

$$\begin{aligned} \frac{d}{dt} P &= \frac{\partial}{\partial t} \int \rho(x, t) dx \\ &= \frac{1}{2K} \left( -\frac{dx}{dt} \frac{\partial U}{\partial x} + \frac{\partial Q}{\partial t} \right) P + i \frac{\partial}{\partial t} \Delta \phi. \end{aligned} \tag{8}$$

The process,  $dP/dt > 0$ , continues so long as there is free energy. The paths lengthen or shorten, and the corresponding phase changes integrate into a shift,  $\Delta \phi$ . Even in dynamic balance where the path-independent dynamical shifts, contained in  $\Delta \phi$ , cancel out over a cycle,  $dP/dt = 0$ , the path dependent geometric phase shifts develop as much as periods between emission and absorption vary. Thus, unless all transitions are kept in step by coupling to surrounding cycles, the system loses its coherence [9, 47, 48]. In other words, besides consuming free energy, the probable process redistributes the system’s phases to either lock in with surrounding coherences or disperse along with incoherent surroundings [7].

Finally, the probable process of decreasing free energy (Eq. 8), normalized by the expectation value of the average energy,  $k_B T$ , and given in terms of increasing entropy,  $S = k_B \ln P$ , delivers the 2nd law of thermodynamics,

$$k_B T \frac{1}{P} \frac{dP}{dt} = k_B T \frac{d \ln P}{dt} = T \frac{dS}{dt} = -\mathbf{v} \cdot \nabla U + \frac{\vec{d}Q}{dt}, \tag{9}$$

where  $\vec{d}$  accentuates that the path-dependent process takes place quantum by quantum rather than in a continuous manner. The development in phase shift,  $i \partial \Delta \phi / \partial t$ , has been disregarded, assuming thermalization in incoherent surroundings. Identifying the

right-hand side free energy terms with the path dependent, inexact differential,  $\delta Q$ , yields the familiar form of the 2nd law,  $dS = \delta Q/T$ , summing microscopic motions to macroscopic evolution toward balance. Entropy increases as free energy decreases, however not in whichever way, but in the least time.

#### 4 Discussion

In 1899, at the decennial of Clark University, Boltzmann expressed his longing for correspondence between the second law of thermodynamics and the principle of least action [49]. In hindsight, all the figures for proving this sameness were already waiting in the wings, though some were not welcome. Maupertuis' non-deterministic open form of the least action principle was there to comprehend the evolution toward balance, but Lagrange's deterministic principle met the immediate desire to define the steady-state partition by fixing the total energy and particle number. Also, as early as the 1870 s, Loschmidt pointed out that Boltzmann's time-symmetric equation cannot account for the irreversible flow of time. Lacking dissipation, it conserves mass, charge, momentum, and energy, the hallmarks of a steady state [50]. In 1896, Zermelo reasoned from Poincaré's recurrence theorem that Boltzmann's equation implies a system that, once in a state of imbalance, returns to the very same state of imbalance [51]. That does not happen; instead, free energy is irreversibly consumed. For microscopic and macroscopic systems alike, recurrence refers to the reversible revolution in configurational phase space at constant energy, distinct from irreversible evolution in state space toward free energy minimum.

Unlike thermodynamic entropy,  $S = k_B \ln P$ , which integrates both bound and free energy [26, 27], Boltzmann entropy,  $S = k_B \ln W$ , enumerates microstates,  $W$ . These configurations, indistinguishable in energy, occupy the phase space of stationary state motions; whereas, states, distinguishable in energy, appear along a path toward free energy minimum. For example, when a Bose–Einstein condensate forms upon cooling, the partition of energies limits toward the ground state and dispersion of phases narrows to display interference phenomena [52]. Correspondingly, energies spread and phases disperse to match the warming surroundings. Either way, thermodynamic entropy increases as free energy decreases. In the respective conditions, order or disorder are consequences, not causes. Accordingly, the derived thermodynamic entropy as an additive probability measure of an open evolving system contrasts Jaynes entropy, which expands Boltzmann entropy by assigning uneven probabilities for the microstates, and von Neumann entropy as its quantum version. Similarly, Shannon entropy and its generalization, Tsallis entropy, are immaterial measures of information content; whereas, thermodynamic information is material embodied in quanta. [53, 54].

Ontology has long been overlooked but has become essential as instrumentalism proves insufficient. As outlined in the introduction, the complexity of non-equilibrium thermodynamics arises from expanding the reversible, path-independent stationary state dynamics with perturbations to approximate irreversible, path dependent state-to-state evolution. In turn, simplicity comes from formulating the state of imbalance as exact to start with and letting the system find balance with its surrounding systems on its own rather than predefining it. This understanding derives from the quantum of action, regarded as the concrete building block of particles and fields rather than an abstract modulus of the total action in the wave function phase.

It is worth emphasizing that the offered comprehension does not disprove practical approximations of thermalization; it only makes sense of them. For instance, in nuclear magnetic resonance (NMR) correlation spectroscopy [55], decay of coherences is worked out from the Liouville–von Neumann equation for the density operator. First, the equation of motion is transformed into the rotating frame to eliminate the static Hamiltonian. Then, the remaining thermalizing interactions are assumed to be stochastic perturbations, thus leading nowhere and therefore, the system is bound to a predefined thermal equilibrium. Finally, the secular approximation for spectral densities works well because molecules tumble rapidly in nanoseconds; while, nuclear spins thermalize slowly in milliseconds to seconds. In this way, the relaxation superoperator drives the density operator of the spin Hamiltonian toward equilibrium in excellent agreement with the data. However useful, such approximations and assumptions obscure that the system relaxes because quanta move down along energy gradients. Increasing disorder is thus not a law of nature itself but a consequence of the law to attain balance with incoherent surroundings in the least time.

In 1905, Einstein inferred from the photoelectric effect that light streams as quanta,  $h$ . Two decades later, Schrödinger identified from atomic spectra the same elemental action,  $\hbar$ , as the modulus of the wave function phase. Regrettably, de Broglie's matter-wave hypothesis, while inspiring, led to misassigning the wave function to the bare particle itself rather than assigning its essence to the surrounding particle perturbed quantum vacuum, which Bose, at the same time, realized to measure the elementary volume of  $h^3$  [56]. As a result of mistaking the vacuum immaterial, despite apparent inertial effects, the double-slit interference pattern emerging from specks of individual particles, albeit computable, remains incomprehensible, even today when particles are imagined as excitations of corresponding fields.

However, when we take a particle as the source of fields, it becomes easy to understand that the interference pattern arises not from the particle interfering with itself but from the particle interfering with the vacuum's undulations that the particle itself generated. These motions are non-deterministic since the motions themselves affect their driving forces and thus differ from deterministic motions, e.g., piloted by a hypothetical wave [57, 58]. Similarly, the Aharonov–Bohm effect [59] is understood to display interference due to the vector potential of transparent and relativistic essence complying with the continuity of the Lorenz gauge. It only remains to substantiate the vacuum with rays of photons paired with opposite phases to make sense of both classic and modern experiments that invalidated the *light-carrying* luminiferous aether while validating the *light-comprising* quantized

quintessence in perfect agreement with Bose–Einstein statistics of massless, transparent, and relativistic photon gas characterized with wave speed,  $c$  [17].

In short, the wave function is an excellent mathematical model of the physical vacuum undulating around the particles. However, constraining  $d\rho/dt$  by Eq. 1 to preserve trace,  $Tr(\rho) = 1$ , implies  $dP/dt = 0$  inconsistent with  $dS/dt = k_B d \ln P/dt > 0$  (Eq. 9). In other words, as a system evolves from state to state, its surrounding systems coevolve because the quanta that exit the system enter them, and vice versa. In these natural processes, conjugate variables,  $E$  and  $t$ , covary, while the quantum itself measures the renowned invariant,  $h = Et$ .

As is well known, Einstein rejected Bohr's instrumentalism, arguing together with Podolsky and Rosen that quantum mechanics is incomplete because two physical quantities corresponding to non-commuting operators, such as momentum,  $\mathbf{p}$ , and position,  $\mathbf{x}$ , cannot be simultaneously determined or predicted [60]. In this sense of reality, Einstein found it illogical to claim that the wave function completely describes reality. However, today, we recognize that it takes to extract at least one quantum from the system to know something about it [54, 61]. Therefore, Einstein's idea of an objective view, describing everything without interacting with anything, is an illusion. Perhaps more pertinently, determinism is a delusion as much as one thing depends on another. Thus, even when the ceteris paribus principle adequately approximates a system thermalizing in superior surroundings, the assumed invariance diverts understanding astray.

Einstein's mistrust in quantum mechanics revived in the early 1950s when Bohm rephrased the EPR experiment in terms of two particles emerging from a decay process with opposite spins, conserving total intrinsic angular momentum [62]. But a decade later, Bell ruled out that hidden variables could restore quantum mechanics' completeness via longed-for local determinism [63]. The celebrated experiments by Aspect and others [64–66] certified the conclusion—as it seemed—however, the founders were confused about correlation.

Namely, unlike the linear correlation Bell attributed to hidden variables, the conventional Pearson correlation produces the observed cosine form, hitherto attributed exclusively to quantum entanglement [67–69]. In other words, classical correlation, due to the common cause of the conserved total spin, explains the EPR experiment exhaustively. Correlation, by definition, means that one state is related to the other; technically, one quantum state cannot be described independently of the other. However, this does not imply non-local quantum entanglement [70]; the two-particle wave function does not embody but merely represents the correlation arising from the conservation of total spin. Since no substance mediates and maintains the correlation, utmost care is taken to preserve the correlation across space and time against perturbing surroundings.

Moreover, the confounding collapse of the wave function from a coherent superposition of states is best understood as an effective concept in place of the measurement, the irreversible interaction with the observer [71], that imposes a reference frame on the antiparallel spins, thereby disclosing their directions to the observer [69]. In other words, a phase, like the direction of a vector, is meaningless, i.e., indeterminate, without a coordinate system. The hands of a clock show the time first when numbers are drawn on a dial plate. It is unreal to interpret a not-yet-set frame of reference to imply many worlds [69, 72].

In this way, by deriving comprehensible dynamics of quanta from the atomistic axiom, phenomena are understood by common sense. Such exercises bring quantum mechanics back into line with plain instrumentalism, where it is unmotivated, even unwarranted, to interpret equations as describing something real simply because they generate the right numbers. In contrast, scientific realism starts off with something real, thus, detectable and, therefore, falsifiable [73].

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## Declarations

**Conflict of interest** The author declares that he has no Conflict of interest.

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