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Article

The matter of time

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Abstract: About a century ago, in the spirit of ancient atomism, the quantum of light was renamed the photon to suggest its primacy as the fundamental element of everything. Since the photon carries energy in its period of time, a flux of photons inexorably embodies a flow of time. Time comprises periods as a trek comprises legs. The flows of quanta naturally select optimal paths, i.e., geodesics, to level out energy differences in the least time. While the flow equation can be written, it cannot be solved because the flows affect their driving forces, affecting the flows, and so on. As the forces, i.e., causes, and changes in motions, i.e., consequences, cannot be separated, the future remains unpredictable, however not all arbitrary but bounded by free energy. Eventually, when the system has attained a stationary state, where forces tally, there are no causes and no consequences. Then time does not advance as the quanta only orbit on and on.

Keywords: arrow of time; causality; change; force; free energy; natural selection; nondeterminism; quantum; period; photon

1. Introduction

We experience time passing, but the experience itself lacks a theoretical formulation. Thus, time is a big problem for physicists [1-3]. Although every process involves a passage of time, the laws of physics for particles, as we know them today, do not make a difference whether time flows from the past to the future or from the future to the past. However, it is a thin line between the microscopic and the macroscopic. So where does the arrow of time [4] come from?

In modern physics, there is no point even in asking why things happen. In general relativity, the flow of time is without cause, so there are no consequences either. Bodies move along their optimal paths; the planets orbit the sun one cycle after the other; comets come and go. In turn, quantum mechanics does not outline alternative events but rather all possible events superposed [5]. Logically, there are parallel cosmoses since this quantum entanglement does not confine to the microcosm of particles [6].

Be that as it may, we have a hard time comprehending these theories that match but do not explain data, for an explanation calls for causation [7]. Einstein's famous criticism of quantum theory, "God does not play dice," captures the foolishness of a belief that any consequence could be the result of mere chance without any proximate cause [8]. A phenomenon may appear random, but there is no guarantee that this is truly the case. Science does not have criteria for proving a phenomenon to be arbitrary. Instead, every single phenomenon in the universe should have a natural cause [9]. So, could it be that time does not point anywhere so long as nothing is happening? Have we simply defined the laws of physics to be independent of time, i.e., applicable only to stationary states, to achieve maximum precision? When quantities stay put, the measurement is indeed precise. Symmetry associates with stationarity, but unmistakably the world is in flux.

Since the flow of time is a natural phenomenon, it seems reasonable that it, too, should be shown to have a natural cause, i.e., driven by forces. Thus, the flow of time should be written as an equation of motion to understand where the arrow of time comes, why the future is unpredictable, and what gives rise to history. To this end, let us employ the old empirical method.

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2. Materials and Methods

Galileo structured observations as mathematical laws by drawing understanding from experience [10-12]. Today, the profound, pragmatic method is still on hand. The first physics may well be a profitable approach, now that we do not even know how to tackle the problem of time. So, let us first express our own experience of time and then translate the expression into the language of physics.

A clear, frosty night under a starry sky is a great experience – except that with time it feels cold. Heat does not escape by itself but together with time. The observation is obvious, but that is precisely why it is precious. Can we thus infer that the passing of time always associates with a flow of energy? What is it that moves when energy and time flow?

Under the starry sky, one feels cold because heat escapes from the warm skin to cold space. The experience exhibits causality. The temperature difference is the cause, i.e., force, and the loss of heat is the effect, i.e., a change in motion. The photon carries energy. But does the photon carry time too?

In the history of science, the right question has often pointed to the answer. As Max Planck exposed in 1900, energy and period are inseparable, complementary properties of the photon [13]. However, instead of calculating the photon energy, $E = hf$, from the frequency of oscillation, f, Planck's constant, h, the quantum of action, is understood here as the photon's measure [14]. The mathematically equivalent but rearranged form, $h = Et$, renders time as real as energy. Energy and time are properties of the photon. So, as the photon wavelet propagates, time and energy move at the speed of light, $c = \lambda/t$, for all wavelengths, λ, and periods, t [15].

By this logic, time comprises periods as a trek comprises legs. This is a new viewpoint, not a new finding. In fact, the second is defined as 9 192 631 770 multiples of the photon period, whose energy makes the cesium-133 atom oscillate. Time, comprehended this way through the experience, is tangible, even visible; a red photon period is longer than that of a blue one.

From the adopted empirical perspective, Planck's constant is not a constant of proportionality but an invariant measure of the fundamental element, the quantum of action [16]. This axiomatic basis [17] would be proven false if, for example, the massless photon were to decay. The tenet would also turn out false if a photon were to split up and if energy were to stay constant in an event.

Galileo founded physics as a method for mathematizing first-hand knowledge into a universal law [10]. This is what we have followed. The experience of heat escaping from the warm skin to cold space with time identifies the constituent of time to the photon period. Rather than through such an experience, Planck found the constant by interlacing two equations together. While covering the whole spectrum of light, Planck's law of radiation does not explain light. Planck was, therefore, blind to the essence of light, the photon as the carrier of time and energy.

3. Results

The reasoning that the fundamental element of time is the period of a quantum is perhaps surprising in its simplicity but logical. It would be confusing to consider this period and time as different concepts. They have the same unit of measure as well. Paraphrasing Leibniz: if we do not have the means to distinguish between two things, we must regard them as identical [18]. There is thus no more of a mystery hidden in time than in energy. The agent of causality is the quantum, as it carries both energy and time. The cause, i.e., the motive force of occurrence, is an imbalance, and the consequence, i.e., the change in motion, is leveling out that imbalance.

Since time and energy, as well as momentum and wavelength, are complementary properties of a quantum [19], the steps in a sequence of events are not interchangeable. Mathematically speaking, they are noncommutative. The result depends on the order in which the measurements are made because no observation will leave its object intact by either extracting out of it or granting it at least one quantum. The order of time [20] thus follows from the order in which the quanta move.

Passage of time renders the universe asymmetrical in its details [2,3], whereas truly symmetrical distributions of random processes are found nowhere in Nature [21,22]. Even so, the steady state is the norm of physics. That is why stationarity is known in precisely defined terms, such as equilibrium, conserved, commutative, computable, linear, Euclidean, and deterministic. By contrast, the full range of processes is referred to by vaguely understood antonyms, such as nonequilibrium, nonconserved, noncommutative, noncomputable, nonlinear, non-Euclidean, and nondeterministic. Thus, there is a need for a general equation of motion for nonstationary systems.

Such an equation of time can be derived from statistical mechanics. The many-body theory is posited on the axiom that everything comprises the same basic building blocks. The atomistic underpinnings of statistical mechanics date back to Ludwig Boltzmann, who understood that not only a gas through collisions but everything through various interactions evolves toward thermodynamic balance. Similarly, Willard Gibbs theorized that compounds reach chemical equilibrium through reactions [23]. Also, a photon gas, through interactions, attains thermal equilibrium with matter. Accordingly, the evolution of any substance, i.e., any occurrence in a sequence, can be understood so that the quanta, the fundamental elements of everything, redistribute through all kinds of events ever more favorably in energy.

3.1. The State Equation

Assuming that the quanta embody everything, any system can be formalized in the same way. This scale-free account in a mathematical form can be inferred from the energy level diagram (Figure 1).

Let us examine an entity indexed with j. Its existence can be quantified by probability, ${}_1P_j = \phi_1\phi_2\phi_3\ldots = \Pi_k\phi_k$, in the form of product, Π_k, over ingredients, indexed with k, to ensure that if any one component k is missing altogether, $\phi_k = 0$, then also ${}_1P_j = 0$. For example, an enzyme in a cell could not possibly exist if any one of its ingredients were missing altogether. We can express the probability ${}_1P_j$, even if we do not know what components k are in the product, Π_k, provided that all entities are made of quanta.

When the system houses several indistinguishable entities, for example, a cell houses multiple copies of an enzyme, the probability of that population $P_j = [{}_1P_j][{}_1P_j][{}_1P_j]\ldots/N_j! = [{}_1P_j]^{N_j}/N_j!$ is a product of ${}_1P_j$ over the size of the population, N_j. Again, the product form ensures that if any one entity is missing altogether, ${}_1P_j = 0$, then also $P_j = 0$. When the entities are identical, their mutual order makes no difference. Hence, the expression is divided by the number of ways, $N_j!$, the entities can be arranged into a sequence.

The total probability P of the system is the product Π_j over P_j

$$P = \prod_j P_j = \prod_j \left[\prod_k \phi_k\right]^{N_j} / N_j! \, , \tag{1}$$

where each factor $\phi_k = N_k\exp[(-\Delta G_{jk} + i\Delta Q_{jk})/k_BT]$ denotes the population of starting materials, N_k, and the energy differences, i.e., free energy $-\Delta G_{jk} + i\Delta Q_{jk}$, relative to the average energy of the system, k_BT. Since temperature, a meaningful notion for a statistical system, was taken in use long before the concept of energy, T is multiplied by Boltzmann's constant, k_B, to make it commensurate with the other terms of energy. When any one event, either absorption or emission, shifts k_BT only slightly, the system evolves smoothly, as if continuously. In such a statistical system, an energy difference can be approximated by an exponential function (exp) [23,24]. The base of the natural logarithm, the limit of continuous compounding, is a natural of choice, as the function $f(x) = e^x$ is self-similar under a change, $de^x/dt = e^x$. The gap in energy, ΔG_{jk}, between the starting material, indexed with k, and the product, indexed with j, can be bridged with the flux of energy between the system and its surroundings, $\Delta Q_{jk} = nhf_{jk}$, carried by quanta with a characteristic frequency, f_{jk}, that couple to a jk-transformation from the starting material into the product. The label, i, in front of the energy term, means that the system is open to the surroundings for the flows of quanta. For example, the influx of photons from the sun makes photosynthesis happen, and the efflux of photons from a body makes metabolism happen. The expression of free energy, $-\Delta G_{jk} + i\Delta Q_{jk}$, with complex notation, describes formally an open system evolving approximately along a logarithmic spiral and eventually settling at a closed stationary orbit where $\Delta Q_{jk} = 0$ [25].

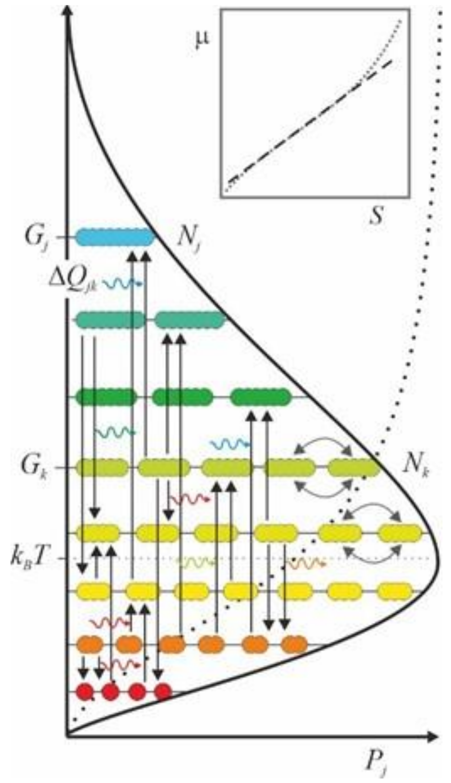

Figure 1. When everything comprises quanta, any system can be formalized by an energy level diagram. The entities of a system, in numbers N_k, that have the same energy G_k are on the same level. The bow arrows portray their mutual exchange, which changes nothing and hence causes no change in the average energy of the system, k_BT, either. By contrast, the vertical arrows indicate events in which the entities move from one level to another. For example, in a chemical reaction, starting materials, N_k, transform into products, N_j. The horizontal wave arrows denote the quanta of light that enter the system from the environment or vice versa. Since the quanta carry energy, ΔQ_{jk}, all events, as flows of quanta, move the system and its surroundings toward thermodynamic balance. When the energy of the surroundings is higher than that of the system, the system evolves toward higher average energy and the surrounding systems toward lower average energy, and vice versa. The cumulative probability distribution curve (dotted line) is a sigmoid. When its logarithm, entropy, S, is plotted as a function of (chemical) potential energy, μ, it mainly follows a power law, i.e., a straight line on the logarithm-logarithm scale (inset).

The state equation (Eq. 1) is the main result of the thermodynamic theory for open quantized systems; its straightforward mathematical derivation yields the equation of motion in various forms.

The state of the system is customarily given by an additive Σ measure obtained as the logarithm (ln) of the state equation (Eq. 1). For historical reasons, the logarithm of probability, when multiplied by k_B, is known as entropy

$$S = k_B \ln P = k_B \sum_j \ln P_j \approx \frac{1}{T} \sum_{jk} N_j \left(-\Delta\mu_{jk} + i\Delta Q_{jk} + k_B T\right), \quad (2)$$

where $\Delta\mu_{jk} = \mu_j - \mu_k$ means the potential energy difference between the populations N_k and N_j. The population of k-entities embodies the potential, $\mu_k = k_BT\ln\phi_k$, and that of j-entities the potential, μ_j. While the functional form of μ_k is the familiar chemical potential, it is valid for any potential, assuming that everything comprises quanta. For example, an electric field potential comprises photons. The entry ≈ in Eq. 2 stands for the statistical approximation, $\ln N_j! \approx N_j \ln N_j - N_j$, which is excellent for $N_j > 10$.

It is worth emphasizing that entropy (Eq. 2), as the logarithm of probability (Eq. 1), adds nothing to the description beyond the concept of energy. The total energy of the system, TS, temperature, T, times entropy, S, comprises the system-bound energy, $\Sigma N_j k_B T$, and free energy, $\Sigma N_j(-\Delta\mu_{jk} + i\Delta Q_{jk})$ [26]. Thus, the system is subject to evolution so long as there is free energy. Conversely, at balance, all energy is bound.

3.2. The Equation of Motion

In a statistical system, the quantum-by-quantum changes in populations, N_j, can be conveniently denoted by differentials, dN_j, to see that free energy terms, $-\Delta\mu_{jk} + i\Delta Q_{jk}$, drive forward transformations, where N_j increases, and the opposite forces drive the reverse reaction, where N_j decreases. As a result of jk-transformations, the total energy of the system, TS, comprising all quanta, changes with time, t,

$$T\frac{dS}{dt} = T\sum_j \frac{dS}{dN_j}\frac{dN_j}{dt} = \sum_{jk}\frac{dN_j}{dt}\left(-\Delta\mu_{jk} + i\Delta Q_{jk}\right). \tag{3}$$

As the quanta redistribute along the gradients, dS/dN_j, temperature, T, changes as well. Since variation in the average energy follows from variation in S, T is not explicitly differentiated with respect to time.

The equation of motion cannot be solved because the changes in each population, N_j,

$$\frac{dN_j}{dt} = \frac{1}{k_B T}\sum_k \sigma_{jk}\left(-\Delta\mu_{jk} + i\Delta Q_{jk}\right), \tag{4}$$

proportional to the free energy terms by mechanism-dependent factors, $\sigma_{jk} > 0$, cannot be separated from their driving forces, i.e., $\Delta\mu_{jk}$ is a function of N_j. In the scale-free description, a mechanism σ_{jk}, such as an enzyme, is a system of its own that facilitates the consumption of free energy by speeding up the jk-conversion of N_k into N_j or vice versa. To attain thermodynamic balance in the least time, the flows of quanta *naturally select* the most efficient mechanisms [27]. It is thus the forces, i.e., free energy, at present that point to the future and transform the present into the past through various mechanisms.

When influxes of free energy fuel the growth, $dN_j/dt > 0$, and conversely when effluxes consume N_j, $dN_j/dt < 0$. Thus, at any given time, entropy cannot decrease, $dS \geq 0$, as can be seen by squaring the free energy terms that are orthogonal in the jk-basis of equations 3 and 4, i.e., every motion follows its line of force, not others. Since no quanta can come out of nothingness or vanish into nothingness, a quantum that leaves the system will end up in the environment or vice versa [25]. There is thus no exception to the second law of thermodynamics. The conclusion complies with diverse data. Both animate and inanimate systems display ubiquitous patterns [21,22] that result from the least-time free energy consumption [13].

Along an evolutionary path from one state to another, free energy may only decrease and entropy may only increase. It is the whole energy landscape, including all entities, that is in motion rather than any one entity moving on an invariant landscape. Thus there are no energy barriers to be crossed; thermodynamics and kinetics are consistent with each other. For example, water starts to flow when the water level rises over the spillway crest. Likewise, a chemical reaction proceeds from starting materials to products when the energy of the starting materials, including chemical and kinetic energy, as well as absorbed photons, exceeds the energy of the products. Accordingly, a catalyst does not change the energy level diagram or landscape but only speeds up converting the starting materials into the products or vice versa. Likewise, water levels even out the faster, the larger channel. As the quanta flow along the lines of force, i.e., geodesics, energy differences diminish in the least time, and hence entropy does not just increase; it does so in the least time.

While the course of events, i.e., evolution, growth, or any other change, cannot be predicted as everything depends on everything elese, it can still be simulated a step at a time according to equation 4 to demonstrate that standards, skewed divisions, growth curves, oscillations, and chaotic courses emerge from the least-time processes [28].

3.3. The Continuous Equation of Motion

Although any system evolves from one state to another quantum-by-quantum, many phenomena, such as the flow of water, appear as if they were continuous motions. We obtain the continuous equation of motion from equation 3, in terms of continuous potentials U and Q using the definitions $\mu_j = (\partial U/\partial N_j)$ and $Q_j = (\partial Q/\partial N_j)$

$$T\frac{dS}{dt} = \sum_{jk}\frac{dN_j}{dt}\left(-\frac{\partial U}{\partial N_j}+\frac{\partial U}{\partial N_k}+i\frac{\partial Q}{\partial N_j}-i\frac{\partial Q}{\partial N_k}\right) = -\frac{\partial U}{\partial t}+i\frac{\partial Q}{\partial t} = \frac{d}{dt}2K, \tag{5}$$

because in the orthogonal jk-basis, the change dN_j does not affect the gradient $\partial/\partial N_k$. The change in entropy, $TdS = d2K$, that translates to the change in kinetic energy, means that the absorption or emission of photons, carrying Q, causes concomitant changes in U and K. In other words, the system's quanta assume new paths that differ from the old ones by energy and period, equivalently by momentum and wavelength. The potential energy changes per time, $\partial/\partial t$, can also be written per position, $\partial/\partial x_j$, multiplied by velocity, v_j, i.e., $\partial U/\partial t = \sum_{j=x,y,z} v_j\partial U/\partial x_j$ and $\partial Q/\partial t = \sum_{j=x,y,z} v_j\partial Q/\partial x_j$.

The differential equation Eq. 5 corresponds to the integral form known as Maupertuis' principle of least action, $\int\mathbf{p}\cdot d\mathbf{x} = \int 2Kdt$, that sums up momenta $\mathbf{p}$ of the quanta on their paths $\mathbf{x}$, or equivalently kinetic energy, $2K$, on their periods, t [29]. However, unlike the later Lagrangian, the original form is open for evolution, i.e., dissipation. This means that the limit of integration moves during the integration as the driving forces affect the motion, affecting the forces, and so on. For this reason, the future cannot be known beforehand but remains nondeterministic. Yet, the transformation is not random, indeterministic but follows the least-time paths, the lines of force in the words of Faraday [12], until all forms of free energy have been consumed.

We can also obtain Eq. 5 by multiplying with $\mathbf{v}$ the original form of Newton's second law of motion by writing the change in kinetic energy, $2K = \mathbf{v}\cdot\mathbf{p} = \sum v_j m v_k$, in the Cartesian base where the inner product vanishes for $j \neq k$ and $d\mathbf{v}/dt\cdot\mathbf{p} = 0$ as $d\mathbf{v}/dt \perp \mathbf{v}$, i.e.,

$$\begin{aligned}\mathbf{F} &= \frac{d}{dt}\mathbf{p} = m\mathbf{a} + \mathbf{v}\frac{dm}{dt} \;\Big|\; \mathbf{v} \\ \mathbf{v}\cdot\mathbf{F} = \mathbf{v}\cdot\frac{d}{dt}\mathbf{p} &= \frac{d\mathbf{x}}{dt}\cdot m\mathbf{a} + \mathbf{v}\cdot\mathbf{v}\frac{dm}{dt} = -\frac{dU}{dt} + i\frac{v^2}{c^2}\frac{dE}{dt} = -\frac{dU}{dt} + i\frac{dQ}{dt}.\end{aligned} \tag{6}$$

Geometrically speaking, the change in mass, $dm/dt = dE/c^2dt = dQ/v^2dt$, denotes changes in curvatures of the quantized trajectories opening up by dissipating quanta into the surroundings. In this context, $E = mc^2$, customarily understood as a relativistic formula, is motivated by extending it to the action $Et = mc^2t = px$.

Thus, the second law of thermodynamics, Maupertuis' principle of least action, and Newton's second law of motion are one and the same law, refereed here as the equation of time [28]. Poynting's theorem is also the same law given in electromagnetic terms [25]; the work exerted by the electromagnetic forces on charges equals the change in the density of electromagnetic energy. It is noteworthy that the force, $\mathbf{F}$, also contains absorbed or emitted energy, idQ, at the event where the system is displaced by $d\mathbf{x}$. The concomitant change in mass, dm, is big in nuclear reactions, small in chemical reactions, and always finite. In other words, mass, i.e., the geodesic curvature of quanta, changes until the system becomes stationary [30].

Once the net flow of energy between the system and the surroundings has vanished, the system has attained balance in its surroundings. In balance, dissipation ceases $dQ = 0$, and the equation of motion (Eq. 6) reduces to $2K + U = 0$, known as the virial theorem. The content of a steady-state system, in the form of Noether's theorem, $2Kt = nh$, totals n quanta with kinetic energy, $2K$. In any given stationary system, the quanta complete their full

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orbits within their characteristic periods, *t*; may that system be an electron torus [31-33] or a planet orbiting the sun. Such stationary-state trajectories are computable [34] and customarily formalized by Lagrangian rather than by the more general Maupertuis principle of least action. As Noether's first theorem states, every continuous, i.e., differentiable symmetry of the action, corresponds to a conservation law. Time invariance corresponds to constant energy, translational invariance to fixed momentum, rotational invariance to fixed angular momentum. Accordingly, invariant charge, magnetic moment, and mass correspond to stationary paths.

3.4. The Equation of Time

In hindsight, associating the flow of time with the flow of energy is self-evident, for energy is constant only in a stationary system. Planck's constant, $h = Et$, suggests by differentiation, $dh = 0$, that energy differences decrease with time, i.e., $dE/dt = -E/t$. Since the quanta carry both energy and time, the flow of time cannot but be the flow of quanta. This dissipative motion is the essence of the second law of thermodynamics (Eq. 3 – 6).

The equation of motion reveals that the future is fundamentally unpredictable not because of complexity but because everything depends on everything else. The free energy variables are inseparable from the motional variables (Eq. 4). Already a three-body system displays chaos when free energy becomes comparable to the bound energy [28]. In other words, the statistical approximation fails. Even so, the future is not all arbitrary but bounded by free energy. Chaos and dramatic effects are thus understood not to follow deterministically from subtle differences at the onset but nondeterministically from the tremendous forces engaged along the way, i.e., history. The flap of a butterfly's wings in Brazil does not cause a tornado in Texas [35] but the temperature difference between the warm ocean and the cold upper atmosphere does. From this perspective, the tornado is a mechanism to dissipate the energy difference, not a consequence of an initial condition.

The equation of motion (Eq. 4) makes it explicit that forces set the arrow of time. The rate at which the quanta flow depends on free energy, i.e., energy differences and mechanisms that channel the flows. From this thermodynamics perspective, the rate of a clock depends on the surrounding potential, such as the gravitational potential, in agreement with general relativity [36,37]. For instance, a clock runs faster in the attic than in the basement. By the same token, the speed at which the clock is moving affects its rate. As the speed approaches the speed of light, the difference to the surrounding vacuum narrows down to nothing, and hence the rate of ticking dwindles down to zero in agreement with special relativity. For example, when a spontaneously decaying particle moves very fast, almost at the speed of light, its lifespan increases greatly [38]. However, no particle can attain the speed of light and become uncuttable, *atomos*. Only the photon is indivisible and eternal [17]. This means. for example, that light does not age in a constant vacuum, but in expanding space, its period lengthens [37]. Thus, relativity is seen as an effective theory, i.e., a mathematical model, for flows of quanta [1]. Likewise, quantum mechanics, say Schrödinger's equation, is a model for stationary circulations of quanta. It cannot deal with a change, breaking of symmetry, due to influx or efflux of quanta, e.g., at the event of measurement.

Moreover, the optimum expressed in terms of time and energy is the same because time and energy are inseparable properties of the quantum. For example, the rotating earth's slightly flattened form is energetically optimal, having the least-time shape. Therefore a clock runs as fast at the North Pole as at the Equator. On the one hand, the clock would run faster at the Equator than at the pole because the distance to the center of the earth is longer, and hence gravity is weaker. On the other hand, the clock would be running slower at the Equator due to the earth's rotation. These two opposing effects precisely cancel each other [39]. Likewise, Schrödinger's equation, a model of a stationary system, can be transformed into a rotating frame where time is no longer a variable.

While the calculation of a stationary system, such as a closed orbit, can be precise, it is not a prediction about the future. It is a disclosure of the unknown trajectory. In such a

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system, time does not advance but circulates on and on. The outcome is a paradox: the steady-state equation of motion has the elements of the explanation, but at the point of balance, where nothing happens, there are no causes or consequences to be explained [40]. The inevitable conclusion is that the future is genuinely unpredictable yet bounded by free energy. In other words, not just anything can happen, only something for which there are forces, say, resources.

4. Discussion

For ages, the vexed question of time has preoccupied scientists and philosophers. The idea that time is the property of a quantum, like energy, might be surprising in its simplicity and concreteness. However, we would not talk about time if it had no substance at all. And we would not talk about the arrow of time if the substance had no sense of direction as the photon has. Thus, a theory lacking the notion of time is empirically untenable [41].

At first glance, one might suppose that if one only knew a system's initial state exactly, say that of a traveling salesman, then also the future could be worked out precisely. However, an event, such as the salesman arriving in a city, will alter the driving forces, say, travel costs, which in turn will change the future course, and so forth. Hence there is no effective algorithm for figuring out the least-expensive travel plan. At worst, every possible path must be evaluated to the end. Such a computational task is intractable, i.e., noncomputable [34]. Noncomputability is thus not about complexity because even problems involving only three bodies are unsolvable. The motion of one body, say, the earth affects the forces that act on the other two, say, the moon and the sun and vice versa. The source of intractability is not either the inherent indeterminism in knowing things, as maintained by Heisenberg's uncertainty relation. Instead, nondeterminism follows from both the system and its observer (background) changing upon interacting, i.e., through flows of quanta. For example, when a rock rolls down from a hilltop to a valley, the height difference decreases simultaneously. This motion of a landscape is perhaps not obvious in the case of one rock but apparent when the whole hill has eroded to plateau; rocks do not roll anymore. Thus a nondeterministic course of events is driven by forces, i.e., causes, rather than being random, i.e., indeterministic without involving any forces, or being deterministic without alternatives or being deterministic in probabilistic terms among alternatives. The least-time principle in its original form contrasts with background-depended theories that offer exact solutions assuming fixed boundary conditions but thereby are not accurate accounts of reality.

Also, the physical rationale behind the halting problem, or an undecidable problem in general, is that everything hinges on everything else. It is impossible to know a priori without executing, i.e., unleashing a flow of quanta, whether a process, such as a program with input, will finish up with output or get caught up in circulating forever.

The preconceived idea that ever-increasing disorder is what directs the arrow of time is deeply rooted in contemporary physics [42,43]. Our own experience is that also ordering takes time. For example, we see that order increases when water freezes, and we see that disorder increases when the ice melts. Order, just as disorder, emerges as the energy difference between the environment and the system evens out [44]. It is, therefore, not an increasing disorder but an imbalance that directs the arrow of time [45].

When a film is played backward, the course of events looks unreal. Shards of glass on the floor just cannot merge into a solid vase and rise back onto the table. For that to happen, work needs to be done, but we see no one doing it. Time does not step all by itself but by forces, i.e., free energy. In other words, we can only be in the present and neither in the past nor the future [46]. This tenet, compatible with our experience, contrasts eternalism, theoretically speaking, the block universe where space and time are on equal footing [47]. The realistic stance also differs from presentism since the present is understood to result from the forces present in the past. History is on display everywhere. As much as the forces, i.e., causes, are apparent, the future can be foreseen. In every case, the future will be energetically more favorable, i.e., more probable than the present, which in turn is more probable than the past [26]. Therefore, it is only natural that the universe expands everywhere in every direction, a stone falls straight down, a plant grows toward light, and you go for the best price. In this way, balance is pursued in the shortest time. The maxim is, in a sense, a truism.

When this quest for balance in the least time is understood as natural selection, that is, Nature selects, then evolution encompasses not just the living but everything. Temperature difference forces hot tea to cool down, just as food powers the growth of a population [48]. Be it in temperature, chemical energy, or any other difference, they all diminish by flows of quanta in the least time.

Long ago, the biosphere, as a mechanism in its entirety, emerged to consume the energy imbalance between matter on the globe and the hot sunlight [49]. Nowadays, solar panels gain ground for the same reason; they collect photons even more effectively than do plants [50]. These transformations involve different mechanisms, σ_{jk}, but the same underlying principle (Eqs. 3 – 6). That is why the data, irrespective of scale and scope, display the same patterns [21,22]: skewed distributions, sigmoid growth curves, power laws, oscillations, and even chaos [28].

Maupertuis was taken by this holistic comprehension [51] – and apparently, also Leonhard Euler. Even though Euler had formulated the principle of least action at about the same time (1744), he defended Maupertuis against claims that Gottfried Leibniz' formulation had preceded theirs by some 40 years [52]. "This great geometer has not only established the principle more firmly than I had done but his method, more ubiquitous and penetrating than mine, has discovered consequences that I had not obtained. After so many vested interests in the principle itself, he has shown, with the same evidence, that I was the only one to whom the discovery could be attributed" [53]. In retrospect, it might well be that Euler acknowledged Maupertuis for recognizing the principle's nondeterministic character. He certainly refuted such a principle, attributed to Leibniz, that regards not only the minimum but also the maximum as the optimum. Despite, or rather because of the general nondeterministic nature, applicable to nonholonomic, i.e., path-dependent systems, the Maupertuisian action was superseded by the specific deterministic Lagrangian action.

Boltzmann sought after the equation of time, i.e., Maupertuis' principle of least action [29], now derived from the statistical mechanics of open evolving systems [13]. While he was impressed by Darwin's proposal for evolution by natural selection, he did not see the need to make a fundamental distinction between the living and the non-living and hence envisioned evolution of any kind to follow the same principle. Paradoxically Boltzmann failed to discern the dynamic as he knew the end state from deriving the expression for the balance of gas molecules. However, that stationary-state equation does not have any trace of the forces that brought about the thermodynamic balance because, at the balance, nothing happens as the sum of forces is zero.

The root of the problem with the H-theorem [54] was noted by Boltzmann's friend Josef Loschmidt. The professor of physical chemistry wondered how an equation that is symmetric with respect to time could possibly describe the flow of time. The symmetry stems from Boltzmann modeling collisions as random processes. In the vicinity of a stationary state, it is an excellent but fundamentally flawed acausal approximation. Furthermore, the German mathematician Ernst Zermelo remarked that, according to Boltzmann's equation, a system that has once been in a state of imbalance would return to the same state of imbalance. Such things do not happen. The issues raised by Loschmidt and Zermelo concern likewise other equations in which energy is constant. Such equations do not explain the leveling of imbalance, the flow of energy and time but only model the condition of balance.

To claim that the photon's period is time itself is a mere trifle. Despite this evident logic, someone might still insist that time is not a physical entity but only an abstract concept, even an illusion. After all, the explanation of the arrow of time, as the flow of quanta, does not seem to invalidate the quantitative results of modern physics. However, the object here is not to contest mathematical modeling but to explain time and causality in empirical terms. Even if calculations were to remain as they are, the worldview does change when time is understood as concretely as energy to be the photon's property. Similarly, the Copernican model did not immediately make it easier to calculate the orbits of planets compared with the Ptolemaic system, but the belief system was nonetheless revised.

It is difficult to break the habit of thinking that time is not a dimension. Still, there is no universal axis along which to organize all events because events occur in relation to an observer. Time is relative: the passage of time that I experience matters to me, the one you sense matters to you. Greenwich Mean Time (GMT) serves to synchronize events globally, but in the universe, it is just a local convention. For example, what took place on our neighboring star, Proxima Centauri, about four years ago, is visible only here today. Time is not just what can be timed, so to speak, operational comparison. The running of a clock is also a series of events; the flow of quanta embodies the flow of time.

It is pivotal that the photon is open to change because the universe could not be expanding unless the photon period was increasing and energy was decreasing. The light that departed from the blazing early universe and arrived at the cold present of our time has extended so much that our eyes cannot detect it. But as our body can still feel it, even the earliest events in the universe are not altogether beyond our range of experience. We live amidst all the history that exists. To date, the photon periods sum up to about 14 billion years from the present to the past.

Assuming that the photons are all there is, the expansion of the universe could not possibly exceed the speed of light, that is, to go beyond the unity of everything. When space stems from matter, there is no fuel to power ever-faster expansion [37]. So, we may abandon the assumption that the universe could billow out ever more rapidly by dark energy. Instead, the rate of expansion, the Hubble parameter, $H = 1/t$, is decreasing $d_tH = -1/t^2$, as time, t, is increasing [36,55]. The atomistic idea of the eternal element of everything [56] limits thus interpretations of the data on the universe's evolution more sharply than many a contemporary model of the cosmos.

Time occupied the minds of both Newton and Einstein. Today the issue is neither absolute nor relative time but tangible time – the quantum is the matter of time. Maupertuis inferred that everything complies with his principle of least action. Could not the very least action, the quantum of action, be the ultimate basis of existence? Questions and answers intertwine. Einstein summed up the power of a worldview: it is the theory that decides what we can observe.

To see what lies in the shadows, let us illuminate reality from another angle. Let us look at the whole in terms of details and the details in terms of the whole. Let us ask what the proposed thermodynamic theory of time does and does not explain. The aim is not to justify the tenet but to find out whether we understand what we see.

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