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Relational Time Flow from Particles' Internal Cyclic Times: Why Elementary Cycles Theory Works

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Relational Time Flow from Particles' Internal Cyclic Times: Why Elementary Cycles Theory Works

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Abstract

Elementary particles exhibit intrinsic phase recurrences, implicit in the undulatory description, so each can serve as a "virtually perfect" reference relativistic clock. From this perspective, Rovelli's "timeless" viewpoint is best read not as denying time, but as denying the fundamentality of any preferred external time coordinate: time persists as internal cyclic variables carried by particles, covariantly modulated by energy exchange and relativistic transformations. Then, macroscopic flow arises from records and thermodynamic coarse-graining. This Letter shows that cyclic internal times of elementary systems are fully compatible with the ordinary non-compact relativistic time flow observed in nature. In particular, it identifies the fundamental "internal" variables underlying physical relativistic time with the particles' intrinsic cyclic times and their relational covariant modulations. Supported by theoretical and phenomenological results established in previous works, intrinsic temporal periodicity constitutes the fundamental principle of Elementary Cycles Theory and acts as exact quantization condition.

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1. Introduction

Time is both the most basic ingredient of physical description and one of its least understood concepts. Since every physical notion of time is operationally grounded on periodic phenomena, i.e., clocks, and since elementary particles can be regarded as fundamental relativistic clocks, it is natural to ask whether a cyclic nature of time may itself be fundamental. This immediately raises two related objections: the physical world is not globally periodic, and the periodic structures used to define clocks are often formulated in terms of an external time variable, which may therefore seem to be presupposed rather than derived. We show that these objections can be resolved. Intrinsically cyclic internal times at the elementary level are fully compatible with ordinary nonperiodic physics and provide a precise, non-arbitrary identification of the *ontic* temporal variables underlying dynamics, without ad hoc fine-tuning or speculative Planck-scale ingredients. The time axis is derivative not because temporal parameters disappear, but because no preferred external time coordinate is fundamental, Thm.(1,2): physical evolution emerges from covariant correlations among elementary clocks rather than from the isolated recurrences. This makes explicit compatibility between Hamiltonian time-reversal symmetry and the effective entropic irreversibility, Prop.(1-3). Without loss of generality, we restrict the analysis to elementary particles as they are the fundamental constituents of every physical system and to the temporal sector as this is the only sector relevant for a relational description (the spacetime-covariant formalism is given in [4–16]).

1.1. Definition: Relativistic Clock

We experience time as a flow, yet we define it operationally by counting cycles of clocks. Clocks are, by definition, periodic phenomena: *"By a [relativistic] clock we understand anything characterized by a phenomenon passing periodically through identical phases so that we must assume, by the principle of sufficient reason, that all that happens in a given period is identical with all that happens in an arbitrary period"* (Einstein, 1910), [1]. Because we cannot access the past or the future directly, time is necessarily defined by assuming the existence of a physical process that reliably passes "*periodically through identical phases*", so that the duration of a cycle is preserved.

1.2. Definition: Time Axis

Modern metrology implements this idea by defining the *second* as the duration of a prescribed number of periods T_{Cs} of the radiation associated with the ^{133}Cs hyperfine transition, observed in its reference frame:

$$1\ \textit{second} = 9.192.631.770 \times T_{\mathrm{Cs}}\,.$$

We associate to the ^{133}Cs atomic clock a cyclic (angular) variable σ_{Cs} of period T_{Cs} (the clock-hand), named atomic clock's *Internal Cyclic* (IC) proper-time[1],

$$\sigma_{\mathrm{Cs}} \in S^1_{T_{\mathrm{Cs}}} \equiv \mathbb{R}/(T_{\mathrm{Cs}}\mathbb{Z}), \qquad \text{i.e.,:}\ \sigma_{\mathrm{Cs}} \equiv \sigma_{\mathrm{Cs}} \pmod{T_{\mathrm{Cs}}}\,.$$

The ordinary time coordinate $t \in \mathbb{R}$ used by observers is obtained operationally by *counting* recurrences, Figure 1:

$$\sigma_{\mathrm{Cs}} \in S^1_{T_{\mathrm{Cs}}} \qquad \overset{\textit{counting}}{\rightsquigarrow} \qquad t \in \mathbb{R}\,.$$

This operational viewpoint carries a simple message: time is not accessed directly, but through (i) the existence of *periodic phenomena* and (ii) the ability to *count* their cycles via persistent *records*.

1.3. Definition: Elementary Particles as Elementary Clocks

The tight link between time and periodic phenomena is not merely philosophical: it is rooted in fundamental physics. In the undulatory formulation of quantum theory, since de Broglie's introduction of the concept of matter waves in his seminal PhD thesis [2], one associates to any particle of mass m a persistent proper-time recurrence of Compton period in its rest frame[2]:

$$T_C = \frac{h}{mc^2}\,.$$

> *"To each isolated parcel of energy [elementary particle] with a proper mass m one may associate a periodic phenomenon of [Compton] periodicity measured, of course, in the rest frame of the particle."* L. de Broglie (1924), [2].

In the same spirit, Penrose emphasizes:

> *"For there is a clear sense in which any individual stable massive particle plays a role as a virtually perfect clock. [...] Any stable massive particle behaves as a very precise quantum clock, which ticks away with [Compton periodicity]."* R. Penrose (2011), [3].

1.4. Definition: Particle's Internal Cyclic Proper-Time

This suggests that we can associate the particle's linear proper-time $\tau \in \mathbb{R}$ with an internal clock hand (phase), i.e., a cyclic (angular) variable σ of period T_C (e.g., the rest frame wave function has the form $\psi(\tau) \propto \exp[-imc^2\tau/\hbar]$, so that $\psi(\tau)\sim\psi(\sigma)$), named here particle's IC proper-time:

$$\tau \in \mathbb{R} \qquad \rightsquigarrow \qquad \sigma \in S^1_{T_C} \equiv \mathbb{R}/(T_C\mathbb{Z})\,,$$

1.5. Relativistic Transformations

More generally, away from the rest frame, relativistic transformations of the particle's proper time $\tau \in \mathbb{R}$ yields the relativistic time coordinate $t \in \mathbb{R}$:

$$\tau \in \mathbb{R} \qquad \xrightarrow{\text{covariance}} \qquad t \in \mathbb{R},$$

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[1] S^1_T is a shorthand notation for cyclic variable of period T; $\mathbb{S}^1$ is the topology.

[2] Particles' Compton periods are ultrafast compared with both the cesium-clock period and present-day time resolution. *E.g.*, for the electron, $T_{C_e} \simeq 8.09 \times 10^{-21}$s, and, the heavier the particle, the faster its Compton period.

e.g., as the effect of a Lorentz transformation $t = \gamma\tau$ where γ is the Lorentz factor. Correspondingly, the particle's proper-time periodicity T_C yields, in that frame, the *instantaneous* time periodicity T whose rate is locally modulated along the particle's evolution by its energy E, exactly as for a relativistic clock, Figure 1:

$$T_C = \frac{h}{mc^2} \qquad \xrightarrow{\text{covariance}} \qquad T = \frac{h}{E}\,.$$

Elementary particles are relativistic clocks of nature: their ticking rates transform covariantly under changes of reference frame and are dynamically modulated by interactions through energy exchange. The "phase harmony" condition remains always satisfied throughout the evolution, [4–16]:

$$mc^2 T_C = ET = h.$$

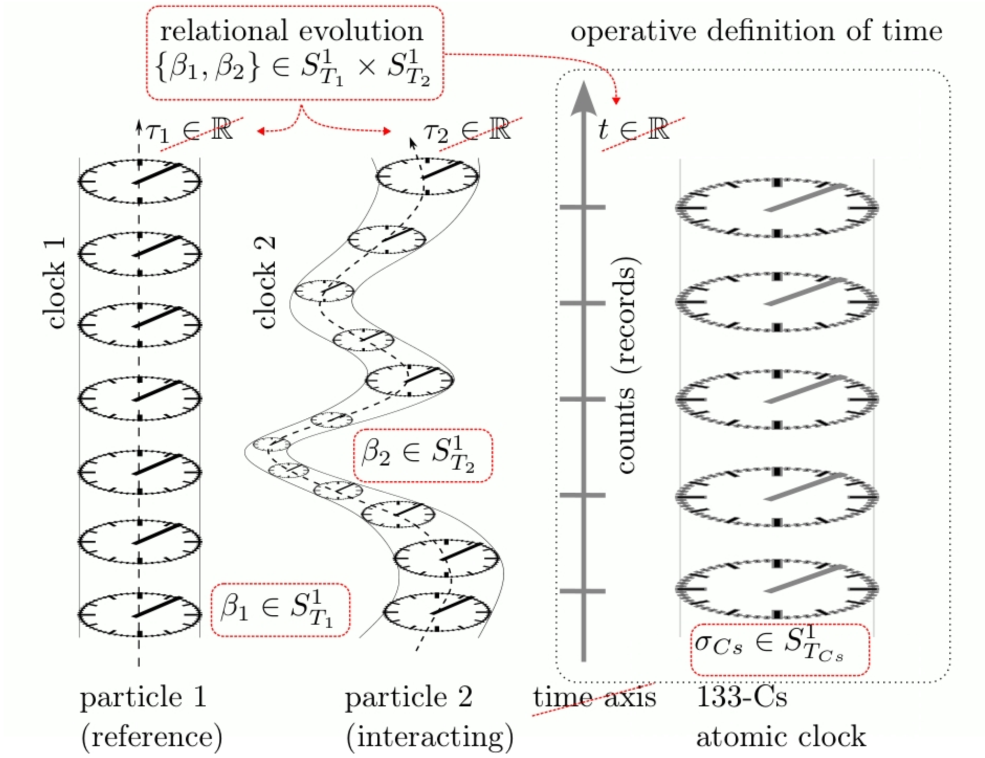

Figure 1. Relational evolution from internal cyclic times. In the quantum description, each particle is an elementary clock with internal time of cyclic character (phase recurrence/clock hand) $\beta_i \in S^1_{T_i}$ (left). The physical evolution can be relationally described by correlations between the internal times $\{\beta_1, \beta_2\} \in S^1_{T_1} \times S^1_{T_2}$, without introducing an independent external time parameter, [21]. Interactions appear as modulations of the internal periodicity (clock 2). The usual time coordinate $t \in \mathbb{R}$ is dispensable and can be operationally defined by counting cycles (right) of the ^{133}Cs atomic clock with period T_{Cs}, or, in principle, of the rest particle of quantum recurrences T_1 (clock 1).

1.6. Definition: Particle's Internal Cyclic Time

Elementary particles thus play a role conceptually analogous to the ^{133}Cs atomic clock: each particle can, in principle, be used to define the relativistic time coordinate $t \in \mathbb{R}$.

In Rovelli's terminology one may speak of an "*internal time*" for each constituent, [17]. Here however we emphasize that these "*internal times*" have a cyclic character. Indeed, in quantum mechanics time enters the dynamics as the argument of a phasor (e.g., $\psi_i(t) \propto \exp[-iE_i t/\hbar]$). Thus, for the i-th particle of local energy E_i, the relativistic angular "clock-hand" variable β_i of instantaneous period $T_i = h/E_i$, locally modulated by the particle's energy E_i, can be introduced, Figure 1:

$$t \in \mathbb{R} \qquad \rightsquigarrow \qquad \beta_i \in S^1_{T_i}\,,$$

which we call particle's IC time (e.g., , $\psi_i(t) \sim \psi_i(\beta_i)$).

The IC time β_i is fully determined by the particle's IC proper-time σ_i through relativistic transformations and interactions, in the same covariant way in which the instantaneous period T_i is determined from the Compton period T_{Ci}:

$$\sigma_i \in S^1_{T_{Ci}} \qquad \xrightarrow{\text{covariance}} \qquad \beta_i \in S^1_{T_i}$$

Therefore, the *universality* of these elementary internal clocks is ultimately fixed by the universality of particles masses through the Compton relation $T_{Ci} = h/(m_i c^2)$.

1.7. *Massless Particles and Gravity*

Massless particles play a special role in this picture. A photon has no rest frame and its Compton time is infinite: *"a photon would take until eternity before its internal 'clock' gets even to its first 'tick'!"*, R. Penrose, [3]. Yet, a photon still carries a well-defined phase evolution in any chosen inertial frame and it can be treated as a relativistic clock with an IC time $\beta_\gamma \in S^1_{T_\gamma}$. *E.g.*, a photon with constant energy E_γ is a periodic phenomenon with persistent $T_\gamma = h/E_\gamma$.

For a massive particle, the upper value of the recurrence T_i is bounded by the Compton period $T_i \leq T_C$, since $E_i \geq m_i c^2$. For massless particles, instead, the time recurrence can be arbitrary large: $T_\gamma \to \infty$ as $E_\gamma \to 0$. Thus, IC times β_γ of low-energy photons provide the closest operational analogue to the "external" time reference $t \in \mathbb{R}$, suggesting a natural reference signal for comparing and mediating mutual modulations of phases of massive clocks [4,8]. Finally, independently of whether gravity is quantized in terms of gravitons, General Relativity teaches that gravitational fields act precisely by redshifting energies, hence by modulating local ticking rates. Gravity induces covariant time-dependent modulations of the elementary recurrences, preserving the "phase harmony" condition, which is the aspect of gravity relevant for our discussion of time flow — [4,8] provide a similar geometrodynamical description, in terms of clocks modulations, for the electromagnetic interaction.

1.8. *Internal Times and General Covariance*

Remarkably, the use of particles' IC times $\sigma_i \in S^1_{T_{Ci}}$ described above, is naturally motivated by General Relativity. As also pointed out by Rovelli, [17], *in generally covariant dynamics there is no preferred coordinate time $t \in \mathbb{R}$* with invariant physical status, see also [18–20]. Consequently, evolution is most naturally formulated relationally, in terms of correlations among observables serving as internal clocks. *This provides additional motivation for our framework, whereby the microscopic clock degrees of freedom are identified with the particles' IC times (e.g., $\beta_i \in S^1_{T_i}$) and their mutual correlations.*

2. Relational Evolution from Particles' Internal Cyclic Times

In the following we do *not* assume the existence of any ontic external time axis. We only assume the existence of elementary particles as *fundamental* elementary clocks, i.e., as periodic phenomena. Then, the central thesis of this paper is that *the ordinary time axis $t \in \mathbb{R}$ (or $\tau \in \mathbb{R}$) is an auxiliary parameter rather than fundamental, while the physically relevant temporal information of dynamics is fully captured by the underlying IC times β_i (or σ_i) and by their relational correlations*. This perspective may also be relevant to the problem of time in quantum gravity, [17,21,22].

We first formulate the result for a simple system of two elementary particles, and then extend the discussion to ensembles of particles. Elementary particles are adopted as the natural foundational starting point because they constitute the irreducible constituents of physical systems, and because their undulatory description directly provides intrinsic cyclic times that are not themselves emergent from a deeper substructure within the present framework.

In general, the Hamilton-Jacobi optical-mechanical analogy, [4,5,7,23–25], states that every Hamiltonian system has a dual undulatory description and therefore a formulation in terms of instantaneous recurrences covariantly modulated by the energy. In this sense, the present analysis is not restricted in principle to elementary particles, but can be generalized to arbitrary correlations of physical systems. [3] In the present framework, the IC times are treated as fundamental microscopic *ontic* variables, namely as physically real variables underlying the dynamical description, rather than as merely auxiliary or epistemic parameters. Rovelli's relational construction [21,22] can be restated in a form that is particularly transparent for fundamental physics:

Theorem 1 (Relational two-particle system)**.** *Consider a relativistic Hamiltonian system of two elementary particles (two relativistic elementary clocks) labeled by* $i = 1, 2$*, with "partial observables" given by the underlying IC times* β_i*, defining an event space* $\mathcal{C} \simeq \mathbb{S}^1 \times \mathbb{S}^1$ *of simultaneous readings* $\{\beta_1, \beta_2\}$*. Then the external relativistic time axis* $t \in \mathbb{R}$ *(or* $\tau \in \mathbb{R}$*) is an auxiliary parameter and the physical content of the dynamics is encoded by the allowed unparametrized correlation curves* γ *in the event space* $\mathcal{C}$*, where* β_i *(or* σ_i*, assuming covariance) are the fundamental physical parameters relevant for the evolution:*

$$\left(\cancel{\tau \in \mathbb{R}} \qquad \rightsquigarrow \right) \quad \boxed{\sigma_i \in S^1_{T_{Ci}}},$$
$$\left(\cancel{t \in \mathbb{R}} \qquad \rightsquigarrow \right) \quad \boxed{\beta_i \in S^1_{T_i}}.$$

Proof. We essentially follow Rovelli's proof, [21,22], with some fundamental distinction and insight. Instead of the macroscopic reference clock and the modulated pendulum of [21] (i.e., two periodic phenomena), we consider two elementary particles (elementary clocks): for convenience we assume particle 1 serves as a reference clock (e.g., a massive particle at rest, so that $\beta_1 = \sigma_1$) while particle 2 is modulated by motion and/or interactions through energy exchange, see Figure 1.

Let $\{\beta_1, \beta_2\}$ denote their phase readings, where each "partial observable" $\beta_i \in S^1_{T_i}$ [4] is the angular variable parametrizing the cyclic evolution of the i-th clock, i.e., the particle's IC time. The physical content of the dynamics ("physical motion") is an unparametrized curve γ in the two-dimensional "event space" $\mathcal{C} \simeq \mathbb{S}^1 \times \mathbb{S}^1$ of simultaneous clock readings $\{\beta_1, \beta_2\} \in S^1_{T_1} \times S^1_{T_2}$. Each curve γ can be read symmetrically as "clock 2 versus clock 1" or *vice versa*; *no preferred background time is required*, Figure 1. The set of all such allowed curves γ defines the "physical phase space" Γ, restricted here to the temporal sector. Each point in Γ ("Heisenberg state") corresponds to one whole "history" γ of correlations among the "partial observables". The cotangent space $\Omega = T^*\mathcal{C}$, coordinatized by the "observables" β^i and their cotangent conjugate variables ω_i ("momenta"), which determine the local instantaneous periodicities T_i, provides the phase-space coordinates of the system.

Such a relational evolution (i.e., physical "correlation" between "partial observables") can be selected by a reparametrization-invariant variational principle on the constraint surface

$$H(\beta^i, \omega_i) = 0\,, \qquad i = 1, 2\,,$$

where "relativistic Hamiltonian constraint" $H(\beta^i, \omega_i) = 0$ defines a constraint surface $\Sigma \subset \Omega$ whose projection on $\mathcal{C}$ determines a "physical motion" exclusively in terms of correlations of "partial observables". This implements the absence of a preferred evolution parameter $t \in \mathbb{R}$, in agreement with Rovelli, [21,22]. ■

The instantaneous periods T_i evolve along the curve γ with the Hamiltonian flow, preserving causality and locality in the description where clocks are covariantly modulated by energy exchange and interactions.

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[3] This also suggests that the thesis of this paper also has a more general validity, directly rooted in classical-relativistic Hamiltonian mechanics.

[4] Here $S^1_{T_i}$ is used as a shorthand to indicate that the phase variable β_i is associated with an instantaneous local periodicity T_i. Since T_i is not itself a partial observable and varies along the motion with the Hamiltonian flow of the system, this notation should not be understood as implying a rigid globally fixed circle, but only the local cyclic character of the clock variable.

Lemma 1 (Gauge orbits)**.** *The external arbitrary parameter* $\lambda \in \mathbb{R}$ *and the Lagrange multiplier* $N(\lambda)$ *(lapse) for the relativistic Hamiltonian constraint* $H(\beta^i, \omega_i) = 0$ *generate gauge reparametrization of the same motion.*

Proof. The relativistic Hamiltonian constraint $H(\beta^i, \omega_i) = 0$ can be written with a Lagrange multiplier $N(\lambda)$ in the corresponding action

$$S = \int d\lambda \left[\omega_i \dot{\beta}^i - N(\lambda) H(\beta^i, \omega_i)\right],$$

with arbitrary parameter λ. The Hamilton equations are therefore $\dot{\beta}^i = N(\lambda)\frac{\partial H}{\partial \omega_i}$, $\dot{\omega}_i = -N(\lambda)\frac{\partial H}{\partial \beta^i}$ and $H(\beta^i, \omega_i) = 0$. A possible gauge-invariant relational law between the two clocks is

$$\frac{d\beta_j}{d\beta_i} = \frac{\partial H/\partial \omega_j}{\partial H/\partial \omega_i} = \frac{T_i(\lambda)}{T_j(\lambda)},$$

since $T_i(\lambda) \propto 1/\dot{\beta}_i$ along the orbit. Indeed, their ratio is independent of the parametrization choice. This defines a gauge-invariant relational law between the two clocks. Thus the β_i are "partial observables", not unconstrained Dirac observables: gauge transformations, such as correlated phase shifts, which are natural in an undulatory description and preserve the relational laws $d\beta_i/d\beta_j$, reparametrize them coherently along the same correlation curve, while the gauge-invariant physical content is carried by their relational phase structure. ■

In this sense, reparametrization invariance removes the external evolution parameter from the physical content of the dynamics, which is entirely encoded in the correlation curve $\gamma \in \mathcal{C}$, [29]. A detailed analysis about the gauge invariance for the cyclic dynamics of elementary particles meant as clocks is given in [4,7,8] (in the context of Geometric Quantization and interactions). Indeed the cyclic nature of particle dynamics where β_i is intrinsically cyclic (compact with periodic boundary conditions) allows a simple geometric interpretation of gauge invariance in terms of holonomies.

A single isolated elementary clock has a perfectly cyclic regime (in a universe composed of a single isolated particle, time would be truly cyclic). The phase of such an isolated clock is not sufficient to define physical time flow in the ordinary sense, because time flow is not the mere repetition of one system in isolation, but the relational ordering of one process with respect to another. This is why, within a reparametrization-invariant description, an individual clock variable is a partial observable, whereas the physically complete content is carried by the correlations among clocks. Furthermore, any direct observation of the clock necessarily involves interaction and energy exchange, which in general perturb its ideal cyclic evolution.

2.1. *From Timeless Construction to Particles' IC Times*

Rovelli's choice of two periodic phenomena (a reference clock and a pendulum) is natural, but it implicitly suggests a cyclic notion of time. At the purely classical level, one may formulate the same relational construction of Thm.(1) by using monotonic variables $\{\bar{\beta}_1, \bar{\beta}_2\} \in \mathbb{R} \times \mathbb{R}$. However, the situation becomes qualitatively different once the dual undulatory description of matter is taken seriously. As already noticed, every Hamiltonian system has a dual undulatory description and therefore a formulation in terms of instantaneous recurrences modulated by the energy. Furthermore, every physical system is *inevitably* decomposed into elementary particles (as in the Standard Model, plus gravity) and thus into elementary clocks. Thus, a relational formulation in terms of elementary "clock" degrees of freedom is not merely an illustrative choice: in the quantum/undulatory description, a formulation in terms of internal clocks is essentially *unavoidable*. Since every system is ultimately composed of elementary particles and every elementary particle in undulatory mechanics is a clock, the conceptual distinction becomes sharp. Rovelli's thesis [17,21,22] is often summarized as "timeless physics" — and sometimes paraphrased (too strongly) as "time does not exist" [26,30,31]. In our reading, however, the formalism supports a milder and more practical statement: the external relativistic time axis $t \in \mathbb{R}$ is an auxiliary parameter according to Rovelli, but time inevitably persists as IC times

$\beta_i \in S^1_{T_i}$ carried by elementary particles. This identifies in a falsifiable and without fine-tuning or speculative Planck-scale arguments the fundamental physical parameters ("internal times") relevant for the system evolution.

We now extend the previous result to generic many-body systems. The universe, as physical system, is ultimately composed of elementary particles (as in the Standard Model, plus gravity). We therefore inhabit a universe of interacting, modulated clocks, which can be, in principle, described relationally in terms of correlations of IC times (and their relativistic modulations due to interactions, including gravitational redshift), *without introducing a preferred external time coordinate*. Importantly, this does *not* imply that the system (or the universe) globally evolves periodically: complex many-body phenomena, including phase mixing and chaos, arise precisely from coupling and modulation of the individual clock phases. *E.g.*, a single isolated clock is perfectly cyclic. With two clocks of incommensurate periods, $T_1/T_2 \notin \mathbb{Q}$, the combined phase point $\{\beta_1, \beta_2\} \in S^1_{T_1} \times S^1_{T_2}$ does not close and instead explores the phase space *ergodically*. In interacting ensembles, energy exchange continuously modulates the local periods (thermal collisions) generically producing non-periodic and potentially chaotic many-clock dynamics.

Theorem 2 (Relational many-particle system)**.** *Consider a generic relativistic Hamiltonian system of many elementary particles (relativistic clocks) labeled by* $i = 1, 2, \dots, N$ *with IC times* β_i *as fundamental "partial observables". Then the external relativistic time axis* $t \in \mathbb{R}$ *(or* $\tau \in \mathbb{R}$*) is an auxiliary parameter and the physical content of the dynamics is equivalently encoded by the allowed unparametrized correlation curves* γ *in the event space* $\mathcal{C} \simeq \prod_{i=1}^{N} \mathbb{S}^1$ *of simultaneous readings of* β_i*:*

$$\left(\cancel{t \in \mathbb{R}} \qquad \rightsquigarrow \right) \qquad \{\beta_1, \beta_2, \beta_3, \dots, \beta_N\} \in \prod_{i=1}^{N} S^1_{T_i} \,,$$

Proof. The proof is the direct generalization of the two-particle case to $i = 1, 2, \dots, N$. The event space of simultaneous clock readings is now $\mathcal{C}$, and $\Omega = T^*\mathcal{C}$ is the cotangent space of the partial observables β_i and their conjugate cotangent variables ω^i. A reparametrization-invariant Hamiltonian constraint $H(\beta^i, \omega_i) = 0$ defines a constraint surface in Ω, whose Hamiltonian orbits project onto $\mathcal{C}$ as physical motions γ. Hence the physical content of the dynamics is again entirely encoded by correlations among the internal cyclic times, rather than by evolution with respect to an external time parameter. ■

The system's evolution can be viewed as described by a very complex "calendar" of coupled cycles, rather than an external time axis, whose fundamental periods are continuously reshaped (modulated) by interactions.

3. Time Flow and Entropic Arrow

What remains to be explained is not "motion" or "change", but the familiar experience of *entropic arrow of time* and the apparent irreversibility of macroscopic processes, together with the possibility to count time cycles of a clock, i.e., to have *records* (degrees of freedom that store information about correlations and can be read out reliably). We limit ourselves here to an operative and statistical discussion, leaving more conceptual aspects to future work.

3.1. Cycles Counting from Thermodynamics and Time Axis

We discuss the operational definition of time axis $t \in \mathbb{R}$ based on cycle counting of a reference elementary clock $\beta_r \in S^1_{T_r}$, which, by itself requires records. Without memory there is no operational notion of "how many cycles have elapsed". As correctly shown by Rovelli, [17,21,22], thermodynamics provides such a counting mechanism:

Lemma 2 (Rovelli's thermodynamical memory)**.** *Records are naturally understood as (i) metastable out-of-equilibrium configurations of separated systems (ii) sustained by thermodynamic imbalance and (iii) long thermalization times.*

Proof. A simple operative model for memory is provided by Rovelli's system of damped pendulums, initially near rest (the low-temperature "memory" subsystem, at temperature $\mathcal{T}_m$), interacting occasionally with a set of balls (or particles) carrying average kinetic energy $K_e = \frac{1}{2}k_B\mathcal{T}_e$ (the higher-temperature "environment", with $\mathcal{T}_e \gg \mathcal{T}_m$), [27,28]. After a collision, the large oscillation of a pendulum is a "trace" of the past interaction: it is a metastable out-of-equilibrium configuration storing information about the event. Slow damping ensures both persistence of the record and, eventually, its reset. The corresponding entropy increase is of order $\Delta S \sim \frac{\Delta E}{\mathcal{T}_m} - \frac{\Delta E}{\mathcal{T}_e}$, where ΔE is the transferred energy, [27,28]. In the present context of elementary internal clocks, the pendulums can be replaced by effective clock subsystems initially close to their unperturbed periodic regime (e.g., Compton periods), so that a past interaction is encoded in a large modulation of their periodic behavior with respect to the original (Compton) recurrence. ■

Proposition 1 (Operative time axis from cycles)**.** *Assume a reference clock with underlying IC times $\sigma_r \in S^1_{T_r}$ and thermodynamical memory systems with different damping factors. Then the number of reference cycles $n_r \in \mathbb{N}$ can be counted and the auxiliary external time axis $t \in \mathbb{R}$ can be defined as $t \sim \mathfrak{t} = n_r T_r$, for a sufficiently fast reference period T_r.*

Proof. In general, Thm.(2), *any physical device, such as a real device effectively used to store records or count cycles, whether mechanical or electronic, is itself a physical system of particles and can therefore be described relationally without introducing any fundamental external time axis.* Lemma.(2) suggests an operative mechanism for counting the cycles of a reference clock, such as a ^{133}Cs atomic clock, or ideally the recurrence of a massive elementary particle. The microscopic recurrence provides the standard, but countable occurrences require dissipative memory devices able to convert that recurrence into stable records. For instance, a first short-term control stage may convert the stabilized ^{133}Cs recurrence into an electronic square-wave signal through a servo-correction device based on fast feedback-memory mechanism. Macroscopically, the square wave is an ordered control signal; microscopically, however, it is supported by a nonequilibrium ensemble of carriers delivering free energy to a subsequent memory device. Its "high" phase can temporarily play the effective role of Rovelli's hot environment. A second flip-flop memory then toggles between the metastable logical states 0 and 1, generating the sequence $0, 1, 0, 1, \dots$, while further layers of memory and counting circuitry transform this alternating pattern into accumulated records[5], and hence into the analogical time reading (seconds, minutes, and hours), without introducing any fundamental external time axis.

Thus, the cycles of a suitable reference clock can become physically countable through physical memory devices storing in such thermodynamic traces, giving an analogical time $\mathfrak{t} = n_{Cs}T_{Cs}$, which can be approximated to a continuum $\mathfrak{t} \sim t \in \mathbb{R}$ for a sufficiently fast reference clock such as the ^{133}Cs atomic clock or, ideally, for a reference particle internal clock $\beta_r \in S^1_{T_r}$:

$$\boxed{\sigma_{Cs} \in S^1_{T_{Cs}}} \qquad \left(\overset{counts}{\rightsquigarrow} \quad \mathfrak{t} = n_{Cs}T_{Cs} \sim t \in \mathbb{R} \right),$$
$$\boxed{\beta_i \in S^1_{T_r}} \qquad \left(\overset{counts}{\rightsquigarrow} \quad \mathfrak{t} = n_r T_r \sim t \in \mathbb{R} \right).$$

This means that one may still choose a reference clock and use it operationally to label evolution by means of an external time axis t (or τ) obtained by counting clock cycles, but again this is *conventional* rather than a fundamental ingredient. ■

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[5] The possibility to order the sequence with reference to the flow of a system is independently discussed in Proposition.(2).

We finally mention Rovelli's **thermal time hypothesis**: *if a thermodynamical system is described by a statistical state ρ on Γ, then a preferred variable is singled out by the state of the system. This is what we call time.* [21]

4. Irreversible Flow from Coarse-Grain and Statistics

From the perspective of elementary clocks, coarse-graining means that most microscopic phase relations of an ensemble become practically inaccessible. Interactions continuously reshuffle energies, and therefore modulate the ticking rates, producing a progressive scrambling of relative phases. For an observer who can only access macroscopic records, this phase mixing manifests as an effectively irreversible evolution toward the most probable macroscopic configurations. In this coarse-grained sense, the effective arrow is the regime in which records and traces can accumulate, consistently with Rovelli's thermodynamical analysis of memory, [27,28].

Proposition 2 (Coarse-grained entropy arrow)**.** *Consider a system of many interacting particles described as modulated relativistic clocks and let ρ be a statistical distribution on the microscopic phase space Γ, evolved from an initial low-entropy ensemble. Let $M : \Gamma \to \mathcal{E}$ be a coarse-graining map onto the space $\mathcal{E}$ of macrostates, and assume a macrostate $X_{eq} \in \mathcal{E}$ such that $\nu\big(M^{-1}(X_{\mathrm{eq}})\big) \geq \nu\big(M^{-1}(X)\big)$, $\forall X \in \mathcal{E}$, where ν is a reference measure on Γ. Then the coarse-grained evolution is overwhelmingly likely to approach X_{eq}, without requiring any fundamental external time coordinate.*

Proof. Consider, without loss of generality, an ensemble $\mathcal{E}$ initially prepared in such a way that all particles have the same energies E_i (the same periodicity T_i) and an isotropic distribution of spatial momenta p_i, and let the particles interact undergoing elastic scattering (as in dilute gas at finite temperature). Microscopically, each particle of energy E_i carries an IC time $\beta_i \in S^1_{T_i}$, while thermal collisions randomly redistribute energy and thus chaotically modulate individual ticking rates T_i. However, macroscopic observations do not resolve the full set of microscopic phase relations: they only access the induced evolution on $\mathcal{E}$ through the coarse-grained map M. The probability of observing the macrostate $X \in \mathcal{E}$ is $P_\rho(X) = \int_{M^{-1}(X)} \rho(\gamma)\, d\nu(\gamma)$, with $\gamma \in \Gamma$.

For instance, from the initial conditions, the ensemble evolves for statistical reasons toward a Maxwell-Boltzmann distribution in energy and, correspondingly, to a chaotic distribution of ticking rates. The approach to equilibrium is overwhelmingly likely because the equilibrium macrostate occupies an astronomically larger region of phase space than the initial low-entropy configurations. In fact, by assumption, the equilibrium macrostate X_{eq} corresponds to an overwhelmingly larger region of Γ, namely a larger ν-measure, than a low-entropy macrostate X. Therefore it carries a larger entropy, $S(X_{\mathrm{eq}}) - S(X) = k_B \log \frac{\nu(M^{-1}(X_{\mathrm{eq}}))}{\nu(M^{-1}(X))} \gg 0$. Hence the macroscopic flow appears effectively oriented toward increasing entropy. This orientation is defined statistically on $\mathcal{E}$, rather than by a fundamental external time variable. ■

This highlights the fundamental distinction at the core of our proposal between the fundamental *IC times* of the particles and the macroscopic *entropic arrow*. Every *IC time* is the fundamental physical microscopic variable β_i of cyclic character carried by each particle. The universality of particle's masses and covariance guarantees its (relativistic) universality, and through the operational definition, the (relativistic) universality of the auxiliary time axis $t \in \mathbb{R}$. The *entropic arrow* is a macroscopic, effectively monotonic, auxiliary property emerging from coarse-graining and from the statistics of many interacting clocks, i.e., from the typical increase of entropy. The *entropic arrow*, for instance, allows a conventional order of events, such as sequences of $0, 1, 0, 1, \ldots$, [27,28]. The auxiliary *time axis* $t \in \mathbb{R} \sim \mathrm{t} = n_r T_r$ doesn't depend on the *entropic arrow* emerging from coarse-graining; $t\mathbb{R}$ is operationally defined by the universal *IC times* constituting the only fundamental physically relevant temporal coordinates, and thus it is related to Hamiltonian (micro)physics. However the potentially arbitrary positive orientation of $t \in \mathbb{R}$ may be conventionally fixed by ordering allowed by the *entropic arrow*. The external time axis can be, in principle, dropped at the fundamental level, while the macroscopic arrow retains a purely statistical origin.

Proposition 3 (Time reversal and entropic flow)**.** *Consider again a system of many interacting particles described as modulated relativistic clocks. The simultaneous inversion $\beta_i \to -\beta_i$ of the microscopic IC times of all particles does not invert the evolution flow toward the compatible macrostate E_{eq} of maximal entropy: the direction of the entropic arrow is not reversed by the general time-reversal invariance of Hamiltonian mechanics.*

Proof. Consider again the ensemble where all particles have the same energies E_i (same periodicity T_i) and an isotropic distribution of spatial momenta p_i, but now assume that the (arbitrary) orientation of the internal phase evolution of each clock is inverted, e.g., from clockwise to anticlockwise. This means that we are reversing the IC times of all the particles constituting the system: $\beta_i \to -\beta_i$, $\forall i$. However, this global inversion of the microscopic internal times does *not*, by itself, invert the evolution flow of the system in the coarse-grained description (i.e., the *entropic arrow*) and recover the initial low-entropy macrostate where all clocks have the same period (same energy). Indeed, we have proven in Lemma.(1) that the relational evolution of the system is encoded by the gauge-invariant correlations among internal clocks, and under the simultaneous inversion of all internal cyclic times one has $\frac{d(-\beta_j)}{d(-\beta_i)} = \frac{d\beta_j}{d\beta_i}$, so the relational laws are unchanged. Therefore, this transformation amounts only to a global reparametrization of the microscopic cyclic orientations (gauge), not to a reversal of the physical many-body evolution. The system, through the chaotic thermal collisions, will evolve anyway toward the maximal entropy state (e.g., Maxwell-Boltzmann distribution in energy): the inversion of the IC time in each particle[6] does not generically reverse the macroscopic *entropic arrow*. ■

The extreme improbability of returning to the initial ordered configuration is not a dynamical prohibition at the level of individual clocks; it is a statistical statement about the relative measure of microstates compatible with the macroscopic constraints. This explains why reversing the microscopic IC times does not, in general, reverse the macroscopic arrow: one may invert the internal phase evolution of the constituents, yet the *entropic arrow* remains effectively unchanged.

We can now address the problem of Hamiltonian mechanics *time reversibility*. *The observed irreversibility, and the practical impossibility of "traveling backward in time", is a consequence of mathematical statistics and coarse-graining, while the underlying dynamical laws, thus the IC-times, the related operational time axis, and more generally the relativistic Hamiltonian mechanics due to Hamilton-Jacobi analogy, remain consistent with time-reversal at the microscopic level*. Even if the auxiliary time axis, being defined by counting the periods of a reference clock as in Prop.(1), is formally inverted by the simultaneous reversal of all internal clocks, its physically relevant positive orientation may still be fixed by the macroscopic evolution toward higher entropy (*entropic arrow*).

5. Conclusions

Building on Rovelli's relational viewpoint, we have shown that dynamics can be formulated entirely in terms of the internal cyclic times carried by elementary particles. These are the ultimate physically meaningful temporal coordinates resulting from undulatory mechanics, while the usual external relativistic time parameter can be regarded as auxiliary. Macroscopic, effectively irreversible *entropic arrow* then emerges statistically, through coarse graining.

The main outcome is therefore not merely a reinterpretation of time, but the resolution of the apparent incompatibility between local cyclic time variables and the nonperiodic world: once time is understood relationally, compact elementary recurrences and open-ended physical evolution become fully consistent. This precisely identifies, in a falsifiable way, the "internal times" conjectured by Rovelli with the internal cyclic coordinates describing the phase advance of elementary particles (or any Hamiltonian system).

This addresses the description of physics in terms of elementary time cycles, whose applications are developed in [4–16], showing systematically how coherent relativistic and causal dynamics arise

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[6] Inverting the time coordinate of a single clock does not imply inverting the others, since every particle has its own IC time. In ECT this inversion can be interpreted as passing from particle to antiparticle description, in the spirit of Feynman's original interpretation of antiparticles, [8–16].

from the intrinsic cyclic behavior of elementary particles. As established in previous work, the constraint of intrinsic time periodicity acts as an exact quantization condition reproducing standard quantum mechanics [5–11,14–16] and related phenomenology [12,13], and supports a unification-oriented interpretation of interactions as geometrical modulations of internal cyclic times [4,8].

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

References

1. Einstein A. Arch. Sci. Phys. Natur.291910.
2. Broglie L. d. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science471924446.
3. Penrose R. *Cycles of Time. An Extraordinary View of The Universe* (Knopf, New York) 2011 Ch. 2.3.
4. Dolce D. *Electromagnetism as $U(1)$ holonomy from phase harmony and Fermi-Walker transport* (Under review, *Nucl. Phys. B*) 2026.
5. Dolce D. Quant. Stud. Math. Found.12202526.
6. Dolce D. Annals of Physics4572023169398.
7. Dolce D. Annals of Physics4482023169182.
8. Dolce D. Annals of Physics32720121562.
9. Dolce D. IJQF82022125.
10. Dolce D. *Introduction to the Quantum Theory of Elementary Cycles* in *Beyond Peaceful Coexistence: The Emergence of Space, Time and Quantum*, edited by Licata I. 2016 pp. 93–135.
11. Dolce D. Electron. J. Theor. Phys.12201629.
12. Dolce D. Perali A. Eur. Phys. J. Plus130201541.
13. Dolce D. Perali A. Found.Phys.442014905.
14. Dolce D. EuroPhys. Lett.102201331002.
15. Dolce D. Annals of Physics32720122354.
16. Dolce D. Found. Phys.412011178.
17. Rovelli C. Class. Quant. Grav.1019931549.
18. Altaie M. B., Hodgson D. Beige A. Frontiers in Physics102022.
19. Page D. N. Wootters W. K. Phys. Rev. D2719832885.
20. Moreva E., Gramegna M., Brida G., Maccone L. Genovese M. Physical Review D962017.
21. Rovelli C. Found.Phys.4120111475.
22. Rovelli C. Physical Review D652002.
23. Arnol'd, V.I. *Mathematical Methods of Classical Mechanics* (Springer New York) 2013.
24. Fasano A., Marmi S., Marmi S. et al. *Analytical mechanics: an introduction* (Oxford University Press on Demand) 2006.
25. Masoliver J.; Ros A. European journal of physics312009171.
26. Barbour J., Foster B. Z. Murchadha N. O. Classical and Quantum Gravity1920023217.
27. Rovelli C. Entropy2420228
28. Rovelli C. *Agency in Physics* (2020).
29. Dittrich B. Gen.Rel.Grav.3920071891
30. Barbour J. *The End of Time: The Next Revolution in Physics* (Oxford University Press) 2001.
31. Barbour J. *The Nature of Time* (2009).
32. Kaluza T. Sitzungsber. Preuss. Akad. Wiss. Berlin (Math. Phys.)19211921966.
33. Klein O. Z. Phys.371926895.
34. Hooft G. *The Cellular Automaton Interpretation of Quantum Mechanics* Fundamental Theories of Physics (Springer International Publishing) 2016.
35. Kapusta J. I. Gale C. *Finite-temperature field theory: Principles and applications* Cambridge Monographs on Mathematical Physics (Cambridge University Press) 2011.
36. Zinn-Justin J. *Quantum Field Theory and Critical Phenomena* (Oxford University Press) 2021.
37. Aspect A., Grangier P. Roger G. Phys. Rev. Lett.49198291.
38. Bell J. S. Physics Physique Fizika11964195.
39. Regge T. E. Il Nuovo Cimento (1955-1965)141959951.
40. Veneziano G. Nuovo Cimento571968190.

41. Cappelli A., Castellani E., Colomo F. Di Vecchia P. (Editors) *The birth of string theory* (Cambridge Univ. Press, Cambridge, UK) 2012.
42. Chodos A., Jaffe R. L., Johnson K., Thorn C. B. Weisskopf V. F. Phys. Rev. D919743471.
43. Afonin S. S. The European Physical Journal C712011.
44. Susskind L. Journal of Mathematical Physics3619956377.