Memoro Ergo Sum

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Abstract: In the framework of Presentism, we introduce a novel interpretation of time as a quantum memory, evolving in atomic instants, and show its compatibility with relativistic time dilations. First, we clarify our postulates on time, causality, and information, and define our ontology in terms of entanglement in a spatial lattice encoded in the Present memory. Then, we introduce our observer as an elementary massive particle, and describe its wave function from the entanglement in the lattice and across the instants. Finally, we derive the proper time of such particle from the information of entanglement in its causal cone. We conclude suggesting a more comprehensive theory of Quantum Gravity and a relation between the concept of memory and the emergence of complexity.

Keywords: presentism; information; entanglement; matter; relativity; gravity; memory; emergence.

1. Introduction

The understanding of the quantum nature of spacetime has gained interest in the recent years, following the search for a theory of Quantum Gravity (QG) able to describe, in a single framework, General Relativity (GR) and Quantum Mechanics (QM). At the core of the problem, as already reminded by Smolin in Ref. [1], there is an old question still unanswered: *what is time?* Recently, in the search for a better understanding of the foundational aspects of our universe and of the emergence of spacetime, entanglement and information have also been promoted as key elements, as shown in Refs. [2] and [3].

In this contribution, we introduce a novel description of the emergence of spacetime inspired by Presentism and Information Theory. Presentism is an ancient interpretation of time for which only the present instant exists, already suggested by Heraclit of Efes and Plato and recently rediscovered by several scholars, including Aharonov *et al.* in Ref. [4].

What seems to be missing, in the literature inspired by Presentism, is a clear indication of how a relativistic description of time intervals could be derived or emerge, given the existence of the Present only and an apparent absolute description of evolution. We believe that answers to this open question might offer a more profound understanding on the quantum nature of our universe.

To show how a model inspired by Presentism is compatible with the emergence of spacetime and a relativistic description of the passage of time, we proceed as follows:

- In section 2, we briefly introduce the rich literature on Presentism in physics, mathematics, and philosophy.
- In section 3, we clarify the main postulates of Presentism on time and causality considered in our description and add an element of novelty to the established framework: an explicit relation with information. Leveraging on the insights of Refs. [5] and [6], we describe the Present as a quantum memory, which encodes the entanglement information in a spatial lattice and evolves in atomic instants. We conclude this section clarifying our ontology in terms of entanglement in space and in time encoded in the memory of the Present.

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- In section 4, we introduce our observer: an elementary massive particle. Extending Refs. [4] and [6], we provide a description of particles in terms of their non-locality and spin, interpreted through entanglement in space and in time. We then connect the emergence of particles in the Present to the persistence of information across instants, as in an extended memory capability.
- In section 5, we overcome the criticism often raised against the models of time inspired by Presentism in terms of compatibility with Special Relativity (SR) and derive the particle's proper time from the entanglement information encoded in the causal cone between events.
- In section 6, we conclude proposing a list of extensions of our framework towards a possible theory of QG, which could be experimentally verified, and suggesting a deeper relation between the concept of memory and the emergence of complexity.

2. The Presentism Framework

Interpretations of time inspired by Presentism have now their tradition, established by several scholars of physics, mathematics, and philosophy. In this section, we report a brief list of the main concepts behind this rich framework. We note that, in the literature, the present instant is often also called the *Becoming*, to highlight the idea of transition from what is *undetermined* and *quantum*, to what is *determined* and *classical*.

Smolin highlights the need for a new understanding of time already in Ref. [1], proposes a description of evolution as a sum of *"views"* of the past in Ref. [7], extended to a *"Quantum Mechanics of the Present"* in Ref. [8]. Gisin, in Refs. [9] and [10], connects Presentism to intuitionist mathematics, where Real numbers are not "*given all at once*" with infinite information, but "*bit by bit*", in an increasing information instant after instant.

Riek, in Refs. [11] and [12], investigates the implications of a discrete evolution and the need for a "thickness" in time to distinguish, in an event, the cause from the effect. Schlatter elaborates on the concept of *synchronization* and of a spacetime emerging from irreversible events in Refs. [13], [14] and [15]. The research of Operational Theories, which starts from Information Theory to interpret Quantum Mechanics (QM) and has been introduced in Ref. [16] and [17], is based on discrete operations and circuits (*foliations*) that evolve in atomic computational instants, similar to atomic present instants.

Eliztur speculates on the *Becoming* as a bridge between QM and SR in Ref. [18], while Kauffmann, in Ref. [19], elaborates on the description of the present instant as connected to the Heisenberg *Res Potentia* of QM, different from the classical *Res Extensa* of the irreversible spacetime, which emerges from the events of collapse.

The absence of a preferred arrow of time within an atomic Present has been proposed by Aharonov, Popescu and Tollaksen in Ref. [4], where each instant is as a "new universe" (inspired by Heraclit of Efes). In Aharonov description, unitarity comes from maximal entanglement between subsequent moments, while events of collapse disentangle adjacent instants. Cohen, Cortez, Elitzur and Smolin focus as well on a time symmetric model of the Present in Ref. [20], extending to *Energetic Causal Set* in the past of the Present in Ref. [21].

Finally, Kauffman in Ref. [22], and Capurso in Refs. [5] and [6], investigate the quantum information potential in the Present and its connection with non-locality and undefined causality.

In Presentism, the discreteness of time is usually extended to space. This is proposed in the context of a physically realizable universe, for which the information density required to describe it must be finite. From a mathematical perspective, a finite information cannot describe the Real continuum, as elaborated by Gisin in Ref. [9], and no existing universes should need infinite or unbounded information to be physically representable.

The finiteness of information density, given that information is generally associated with energy, is supported also by the Bekenstein bound of Ref. [23], and leads to a picture of the universe that is both relativistic and indeterministic in its evolution, very far from the block-universe of Eternalism, as illustrated in Ref. [24].

The finiteness of information suggests a possible indeterminacy of the past as well. Recent *gargantuan simulations* reported in Ref. [25] have shown that time seems irreversible at the most fundamental level, beyond a thermodynamic arrow of time: even a 3-body system "*would require an accuracy of smaller than the Planck length in order to produce a time reversible solution*". The irreversibility of events has also been related in Presentism to the concept of *irretrodicibility*, as illustrated by Del Santo and Gisin in Ref. [26] with a model to calculate *propensities* of past events. In a framework inspired by Presentism, what has already happened can influence the Present but cannot be changed and, beyond fundamental limits, cannot even be known with certainty.

We conclude highlighting the relevance of Presentism as a model of time in modern Philosophy. To support the reader, we list here a few references, which investigate the ontological and logical aspects of this interpretation, such as Refs. [27], [28], [29] [30], [31], [32], [33], [29], [34], [35], [36], [37] and [38].

3. Postulates and Ontology

Postulate on Time

The main assumption of Presentism is summarized in the following postulate:

Only the Present exists, as an atomic instant of evolution ΔT of the whole universe P. 1

Postulate P. 1 implies that evolution in the universe occurs in discrete atomic instants of temporal duration ΔT. This evolution is considered synchronous in all the universe, as a global "update cycle" that marks the progression of instants as a universal clock. Each present instant, that we call a universe *tick*, identifies the evolution of space as a foliation. This foliation has a thickness in time of magnitude ΔT, and it is considered equivalent to a circuit foliation of Operational Probabilistic Theories, introduced in Ref. [16] and [17].

In this discrete evolution, we label the Present as the instant T_k. The instant T_{k-1} is considered the immediate past, while T_{k+1} the immediate future. Postulate P. 1 implies that T_{k+1} does not exist yet, while T_{k-1} does not exist anymore. We call *causal time* the ordered set of instants prior to T_k. This set identifies an oriented and discrete axis of evolution, from a distant past to more recent instants of the universe. The causal time labels the passage of instants as a classical Newtonian time of the universe. Being the present instant T_k the *k^th^ tick* in the discrete evolution of the universe, the concept of "age of the universe" is then intended as a temporal interval $t_U = k\Delta T$ from a hypothetical *first tick* T_1 of our universe.

It is crucial to note that the Present is not an "observers' common now". Observers, as clarified in section 5, can only compare differences in the number of ticks, and an extended causal time axis (to count the passage of time with a "proper number of ticks") is not defined at the fundamental level of abstraction on time given by the present instant only.

Postulate P. 1 implies a shortest time interval ΔT, duration of each atom of evolution. This discrete evolution implies a maximum rate of change. In this sense, ΔT is also proposed as the "temporal resolution" of the occurrence of events. The boundary between T_k and T_{k-1} (defined as the *past boundary* of the Present) separates what has already happened (events) from what is still possible (namely, what has not happened yet, but may happen in the present instant, given the past consequences at the end of T_{k-1}). The Present, as per the referenced literature, encodes the possible *becoming* of information from undetermined and potential to determined and classical.

In this framework, events are irreversible as they do not exist anymore, and something that does not exist cannot be acted upon, nor changed. The irreversibility of the past, as well as its limited *retrodicibility*, has been elaborated in Refs. [24], [25], and [26], and it is foundational in a model of time that considers only the Present as ontologically existing. Even if events do not exist in the Present, from a given event at an instant, a cone of causal information propagates as the universe ticks occur, in a sphere of consequences growing in each instant. These causal cones are the basis for a causal evolution. In this sense, events in the causal time influence the Present.

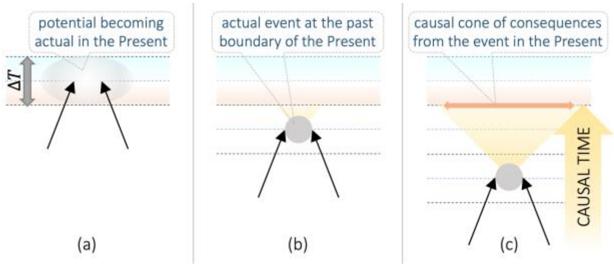


Figure 1. Representation of the *Becoming* in 3 consecutive universe ticks, as 3 "snapshots" (a, b, c). Each snapshot is shown with the Present at the top and the past ticks "sinking" as the causal time grows. In (a), we picture a possible event in the Present from past energy-momenta (*black arrows*), that becomes an actual event (*grey dot*) at the past boundary of the Present in (b), and from which a cone of consequences propagates (as causal information in the Present) as the ticks occur in (c).

In line with Ref. [19], we consider the following definitions:

- *Res Extensa*: what has already happened, intended as the classical domain of events behind the past boundary of the Present, irreversible, and ordered in a causal set along the causal time.
- *Res Potentia*: what could happen in the current instant given the causal past, intended as the evolution from the events' consequences, possible events in the Present and the quantum information encoding what is still undefined.

Given P. 1, the information in the k^{th} instant of evolution ontologically exists in the Present T_k. In this sense, the Present is described as an ontological memory that encodes through entanglement the information of events that can happen but are not happened yet. We clarify our ontology based on information and entanglement after having concluded our investigation of the main postulates of Presentism. Here, we take the opportunity to highlight that the possible relation between quantum information, memory and evolution has been recently investigated in Refs. [5], [6] , and [39] as well.

The ordered causal time extends up to the past boundary of the Present, giving causal order to the set of events, but it is not properly defined within the Present. As discussed in Refs. [4], [5], [6], [1], [7], [8], [13], [14], [15], [18], [19], [20], [21], [22], and as originally suggested by Plato himself (see Ref. [34]), the Present is not part of the causal time, nor of a classical and deterministic spacetime. In the encoding of the *Res Potentia*, we do not consider an explicit arrow of causality within the thickness of the Present, as elaborated in the QM models reported in Refs. [4], [5], [6], [1], [18], [20], and [21]. The absence of a preferred arrow of time has been described, in these models, through a time-symmetric formalism in each instant, with the superposition of the forward and the backward contribution within ΔT. We note that a time-symmetric formalism to model the information within the Present requires a description of the thickness of each instant as $\Delta T = 2T$. From this equivalence, being the Present intended as the k^{th} tick from the birth of our universe, the label $(2k-1)T$ marks the past boundary of the Present, while $(2k+1)T$ marks the future boundary of this atom of time, that we consider of Planckian nature (T = Plank time).

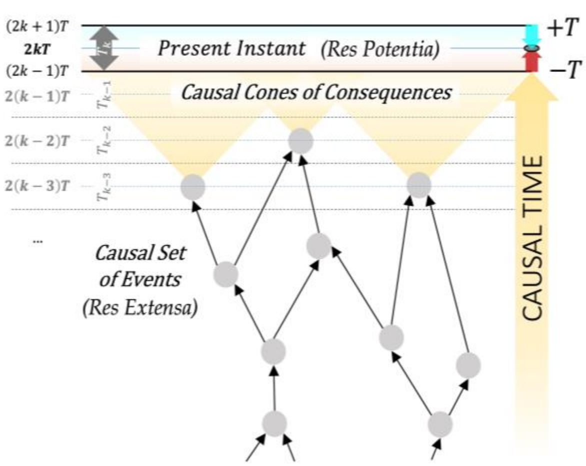


Figure 2. Model of a universe evolving in instants. From the top, we represent the Present T_k, which encodes the *Res Potentia* with a time symmetric formalism (*cyan and red arrows*). It is identified as the k^{th} instant from the first tick, between $(2k-1)T$ and $(2k+1)T$. Below the Present, we show a causal set of events (*grey dots*) connected through energy-momenta (*black arrows*) along an emerging discrete arrow of causal time (*yellow arrow*). These events represent a classical domain of *Res Extensa* that shapes the Present through the consequences in the causal cones.

Postulate on Causality

Descriptions of our universe inspired by Presentism have a strong connection with the concept of causality. An evolution in thick present instants is naturally related to the information in the causal set behind the past boundary of the Present, as already elaborated by several scholars, including Smolin *et. al.* in Refs. [7], [20], and [21]. The relevance of causality is not limited to the information in the past, as it is also a fundamental aspect in the quantum evolution in each instant, as elaborated by Aharonov *et. al.* in Ref. [4], Elitzur and Dolev in Ref. [18], and Del Santo and Gisin in Refs. [24] and [26]. In this paper, we consider a postulate on causality that focuses on its speed, intended as a maximum rate of change of the possible spatial position over the universe ticks.

The speed of causality c is invariant in the whole universe P. 2

In this discrete evolution, we consider a possible event at the present instant, such as the emission of a photon from a particle at a position X at T_k, or simply X_k. From X_k, we describe the other possible events' locations during the same instant through an imaginary time it_X at the speed of causality c (defined in P. 2) to reach these other possible locations, and 2 angular degrees of freedom $\theta_{1,2}$.

The imaginary time it_X is orthogonal to the arrow of causal time, as well as to the time symmetric arrows within the Present, as per space and time orthogonality. In a spacetime diagram, the causal time identifies past time-like separated events, while the imaginary time axis is related to space-like separated possible events in the Present.

Given a discrete temporal evolution from P. 1, the imaginary time it_X is intended as discrete as well, and it is defined through multiples of an atom of imaginary evolution $i\Delta T$. From a given X_k, we map the other atoms of space at $n_X \in \mathbb{N}^+$ *imaginary steps* $ic\Delta T$, in an equivalent imaginary distance $ict_X = icn_X\Delta T$ from X_k. Given that we have posed no conditions on X_k, this mapping is proposed as a relational description of the whole space through the variable in_X (we omit the index X in the future).

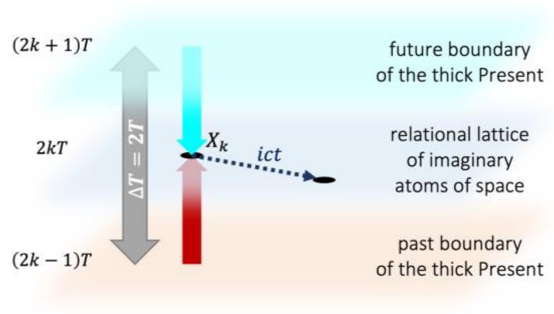


Figure 3. Graphical representation of the hyperplane within the Present instant. We highlight the past and the future boundaries of the Present, the time symmetric model within its thickness (*red* arrow from $-T$ and *cyan* from $+T$) and 2 locations of possible events separated by an imaginary, oriented, and relational distance ict_X from the possible event's location X_k at the instant T_k.

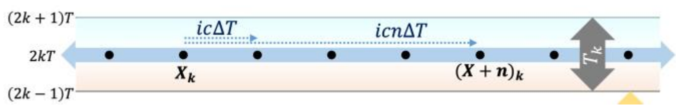


Figure 4. Discrete set $\{in, \theta_{1,2}\}_X$ from an atom of space X (with $\theta_{1,2}$ omitted for clarity). We show the imaginary space in the Present as a lattice (*black dots*). It is defined on an imaginary time counting *steps* at the speed of causality, orthogonal to the causal time, in a relational description of space.

We consider the set $\{in, \theta_{1,2}\}_X$ of all possible spatial locations in the foliation at the present instant from X_k. This set maps to a discrete space from X_k: a *lattice* in 3 dimensions with a resolution of $|ic\Delta T| = c2T = 2L$, being L an elementary unit of distance derived from P. 1 and P. 2 of Planckian nature (L = Planck length). Given the use of an imaginary time at the speed of causality between possible events' location, we call *imaginary space* the set $\{in, \theta_{1,2}\}_X$ of all possible locations from X_k. We conclude that, in a presentism perspective, space at T_k from X_k is imaginary, relational, and discrete. The 4D set $\{in, \theta_{1,2}\}_{X,k}$ from X_k along k ticks is proposed as a relational and discrete imaginary space evolving in instants.

We note that models of our universe which consider a Wick rotation (imaginary time) resolve singularities in black holes (BH) and at the Big Bang through an asymptotically flat region of a "*fuzzy Euclidean space*". This is common in several approaches to QG, from the Hartle-Hawking proposal of Refs. [40] and [41], to models of our universe based on Loop Quantum Gravity (LQG), as described in Ref. [42] (LQG is a framework aiming at unifying QM and GR, see Ref. [43]).We also note that the lattice of imaginary atoms of space in our model resembles the virtual Planck BHs proposed by Hawking in Ref. [44] to describe space. We therefore conjecture that our imaginary atoms, as Hawking virtual atoms, could be replicas of a single BH in a parent universe. In this hypothetical mapping, the fuzzy Euclidean space emerging in the interior of the BH is equivalent to the imaginary space of our model, while the BH itself becomes a physical implementation of the memory of the Present. We further elaborate on this speculative conjecture in section 6.

Postulate on Information

We conclude section 3 adding, to the established framework of Presentism, an explicit relation with information. It is worth to clarify that we attribute to this information a physical nature, as proposed by Landauer in Ref. [45], and discourage the idea that "*we live in a simulation*". In this paper, the physical representation emerges from information thanks to the references of P. 1 and P. 2. The temporal interval ΔT (max rate of change in the time) and the imaginary distance $ic\Delta T$ (max rate of change in space) give physicality to our discrete representation. References for a max rate of change seem needed not only to define any meaningful comparison between independent observers, but also to give a coherent structure between far regions of spacetime, as in a universal encoding. These references define the basis through which the physical representation of time intervals and spatial distances emerge from the abstract entity of discrete information. We also remind that, thanks to the *Nyquist – Shannon sampling theorem* of Ref. [46], a continuous signal with a limited bandwidth can be equivalent to the information contained in its discrete samples. Given a universe evolving in thick present instants ΔT as equivalent to a signal with maximum bandwidth $1/\Delta T$, according to this theorem, a continuous spacetime experience can emerge from its discrete samples.

Clarified these elements of Information Theory in a Presentism framework, we now elaborate on entanglement in space and in time and describe how this fundamental information can be encoded in the thickness of the Present. We first consider entanglement in space. In our proposal, this entanglement is intended as a spatial non-locality, in a description of the imaginary space inspired by the *ER=EPR* conjecture of Refs. [47] and [48]. The emergence of space from entanglement is common to several descriptions of QG, as shown in Refs. [2] and [49]. According to Aharonov in Ref. [4], the non-local potential in the k^{th} instant is encoded in a pair of Hilbert spaces, $\mathcal{H}_k$ and $\mathcal{H}_k^\dagger$, in a dual cover of the imaginary space from the boundaries $(2k-1)T$ and $(2k+1)T$: $T_k = \left\{\mathcal{H}_k|_{2k-1}^{2k}, \mathcal{H}_k^\dagger|_{2k}^{2k+1}\right\}$, with the imaginary space on the boundary at $2kT$. In Aharonov model, $\mathcal{H}_k$ encodes *ket* vectors $|\psi\rangle$, while $\mathcal{H}_k^\dagger$ is mapped to *bra* vectors $\langle\psi|$, with a max correlation $|\psi\rangle\langle\psi|$ between instants and disentanglement in case of an event $\langle\psi|\psi\rangle$ at a given instant.

In this symmetric description, the state of a system at X is determined by 2 waves, closed in the thickness of the Present. The first evolves from *(2k−1)T* to *2kT,* while the second from *(2k+1)T* to *2kT*. Here, we follow Aharonov formalism and consider $|\psi\rangle$ as the *initial* (*forward*) wave, while $\langle\psi|$ as the *final* (*backward*) wave. Even if called *initial* and *final*, as in Refs. [20] and [21], we remind that these waves occur in the same instant and entangle the atom X to other atoms in the imaginary space, where the waves meet.

In the extension of Aharonov description proposed in Refs. [5] and [6], the non-local potential of the wave in the Present is encoded through the superposition of paths from *(2k−1)T* and *(2k+1)T*. These paths meet at *2kT* as closed loops in the thickness of the Present and pierce the imaginary space in atoms that result connected by a tunneling potential.

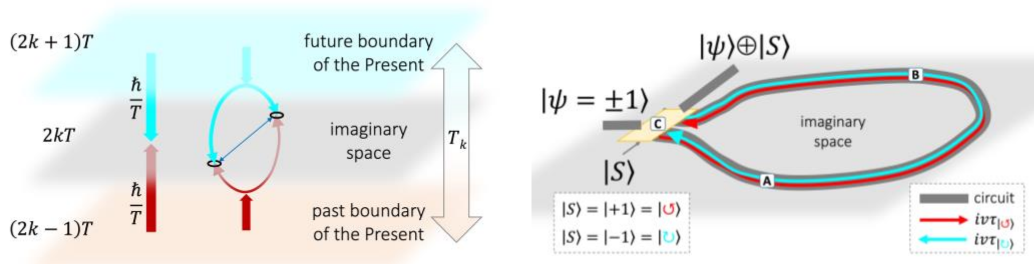
Besides entanglement in space, we consider the entanglement in the time order of possible events, intended as an information of undefined causality. This entanglement has been studied and experimentally verified in Refs. [50], [51], [52], and [53].

To describe undefined causality in our model, we consider the order of events $\{A \rightarrow B\}\, XOR\, \{B \rightarrow A\}$, being A and B two distinct atoms of space belonging to the path of a particle, which crosses them in an undefined order. According to Ref. [5], this information can be encoded in a closed path that develops in the imaginary space. This closed path comes from the superposition of a path in which A is met first and B second, or vice versa. These paths are described, in the time symmetric formalism considered, as a forward $\{A \rightarrow B\}$ and backward $\{B \rightarrow A\}$ imaginary path, superposed thanks to a controller qubit.

Given the relation between causal non-separability and causal structure cyclicity and that no events can occur on a closed path, as clarified in Refs. [54], [55], [56], and [57], considering also that loops are the most basic circuits to implement an information storage, these time-symmetric paths closed in loops seem the ideal quantum circuit to encode the undefined but logically consistent information of entanglement, both in space and in time.

The description of our universe through loops might remind LQG. Beyond this similarity, we depart from its formalism. The loops introduced in our model, that we will call *memory-loops* as in Refs. [5] and [6], are the basic building blocks of matter particles, as elaborated in section 4. The interpretation of entanglement through loops modelled as a superposition of time-symmetric closed paths is, to our knowledge, a novel proposal.

We represent these concepts in the next figure, in which "loops in time" (orthogonal to the imaginary space) encode entanglement in the imaginary space (non-locality), while "loops in space" (orthogonal to the thick Present) encode entanglement in time (undefined causality across instants). Both these kinds of memory-loops are modelled with a forward and a backward contribution, in a time-symmetric description within the Present.



(a) (b)

Figure 5. (a) Entanglement in space as a superposition of a forward (*red*) and a backward (*cyan*) wave closed in a loop in the thickness of the Present. (b) Entanglement in time as a superposition of imaginary paths of a particle $|\psi\rangle$ controlled by $|S\rangle$. The paths $ivt_{|↺\rangle} \oplus ivt_{|↻\rangle}$ (*forward* $\oplus$ *backward wave*) represent an undefined order $\{A \rightarrow B\} \Leftrightarrow |S\rangle = |+1\rangle, \{B \rightarrow A\} \Leftrightarrow |S\rangle = |-1\rangle$ with an imaginary loop in the space $ivt_{|S\rangle}$ closed between the controller C and any two points (A, B) on the circuit.

Beyond these elementary memory-loops, we introduce the concept of *entanglement information in the causal cone*. To identify this information, we consider a bipartite system, a massive particle ψ and the rest of the space of possible imaginary locations. Given N instants from an event of collapse of ψ at X, we define the entanglement information $\varsigma_{e,N}$ in the causal cone from the event at X as equivalent to the number of discrete angular Degrees of Freedom (DoF) on the sphere of radius $cN\Delta T$ from X, in a saturation of the Bekenstein bound of Ref. [23]. This information is decomposed in the information of entanglement in time $\varsigma_{t,N}$ and in space $\varsigma_{s,N}$, both intended in terms of angular DoF from X after N tick:

$$\varsigma_{e,N} = 4\pi N^2 = \varsigma_{t,N} + \varsigma_{s,N} = 4\pi N_t^2 + 4\pi N_s^2 \quad (1)$$

In Eq. (1), $-N_t$ is defined as the *temporal window amplitude* on the surrounding possible incoming causal stimuli. It is connected to a growing entanglement in time of the particle and to a possible causal aging of the particle of N_t ticks at the N^{th} tick. On the other hand, iN_s is defined as the *spatial imaginary amplitude* on the surrounding imaginary space. It is connected to the growing entanglement in space of the particle and to a possible quantum jump of the particle of N_s steps from X at the N^{th} tick.

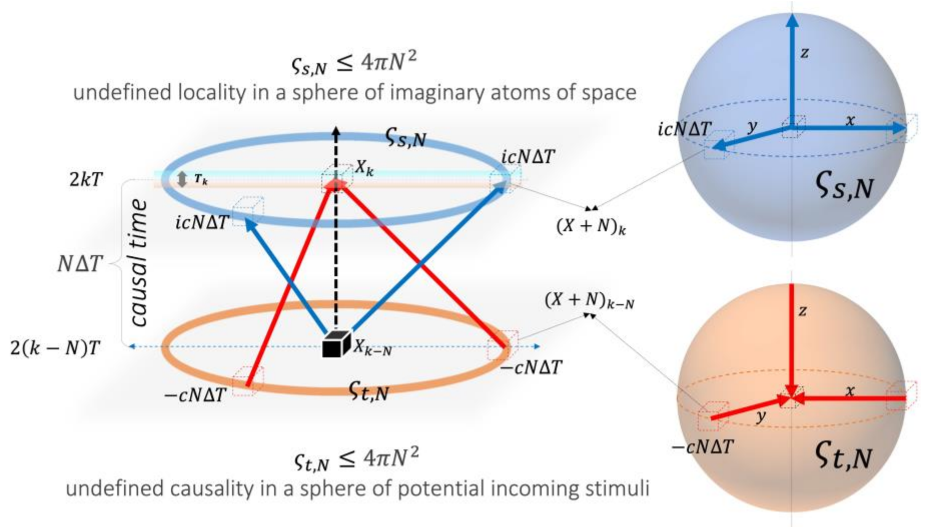


Figure 6. Max entanglement information in space and time in N ticks. On the left, we show the cones, with k marking the ticks on the vertical axis. On the right, we show the 3D lattice, with k implicit. *Blue* figures represent entanglement in space, *red* figures represent entanglement in time.

We summarize these considerations with the last postulate of our model.

The entanglement information in the causal cone of N instants from an event saturates on the surface of a sphere of radius N, as per Eq. (1) P. 3

Introducing "*entanglement*" in P. 3, we refer to the quantum nature of this information, and include in our model the global reference of QM: $\hbar$. We also note that, as elaborated in Ref. [58], the Bekenstein bound is related to the Uncertainty principle, as 2 sides of a common limit on information density and discernability.

4. Matter from Entanglement

Momenta in Space and Time

We propose here a toy-model and an interpretation of elementary massive particles in terms of entanglement in the imaginary space and across the instants, described through the memory-loops of section 3. We start from a description of the particle's non-locality in the lattice inspired by Aharonov, and then extend to a possible relation between the half spin of fermions, their invariant mass, entanglement in time, and the persistence of information across the instants.

To describe a particle in terms of its non-locality, we elaborate on known equations and show how these can be interpreted in our model. We consider the relation between energy and momentum introduced by Dirac: a decomposition of the energy E in orthogonal components (also known as *Einstein triangle*). Being m_T the invariant mass, $m_r = m_T/\sqrt{1-\beta_r{}^2} = \gamma m_T$ the relativistic mass, and $v_S = \beta_r c$ the translational velocity of the particle in space, we define *momentum in time* p_T and the *momentum in space* p_S.

$$\begin{cases} p_T = m_T c \\ p_S = m_r v_S = (\gamma m_T)(\beta_r c) \end{cases} \tag{2}$$

The momentum in space p_S is intended as a vector with 3 imaginary spatial components $\{\boldsymbol{i_1}, \boldsymbol{i_2}, \boldsymbol{i_3}\}$ developing from the Center of Momentum (CoM) of the particle in the imaginary space (imaginary part of quaternions). The momentum in time p_T represents the relativistic invariant information in time and develops in the thickness of the Present, orthogonal to all the 3 imaginary dimensions of space.

From p_S and p_T, we define $p_{ST} = p_T + ip_S$, which is related to the energy of the particle by the following equation (from here on, for simplicity, we consider in our notation a single imaginary direction $\boldsymbol{i_1} = i$, usually intended as the direction of the velocity v_s).

$$E^2 = (\ m_r c^2)^2 = |m_T c^2|^2 + |im_r v_S c|^2 = |p_T c|^2 + |ip_S c|^2 = |p_{ST} c|^2 = (p_{ST} p_{ST}^*) c^2 \tag{3}$$

Given $\alpha_r = 1/\gamma = \sqrt{1 - {\beta_r}^2}$ and $m = \frac{1}{n_c}$ (equivalent to the mass m_T in Planck units):

$$p_{ST} = p_T + ip_S = \frac{\hbar}{cT} \gamma m(\alpha_r + i\beta_r) = \frac{\hbar}{cT} \gamma m \varepsilon_r = |p_{ST}| \varepsilon_r; \qquad |\varepsilon_r| = 1 \tag{4}$$

To show the relation between p_{ST} and the non-locality of the particle in the Present, we consider the wave function ψ from the CoM of the particle at an atom O at T_k:

$$\psi = \frac{R}{cT} e^{\frac{iS}{\hbar}}$$

We define the gradient ∇ from O in the imaginary distance axis $ict = ir$ as $\nabla = \frac{i\partial}{\partial ir} = \frac{\partial}{cT}$ (with ∂ intended as a variation in the imaginary space from O along n). We consider a single imaginary dimension for simplicity but, in general, ∇ is intended as applied to a vector with 3 components of which $|ir|$ is the magnitude of the imaginary distance.

In line with a model of *zitterbewegung* with maximum entropy, we describe R as shaped in a thermal distribution from O, with an energy that depends on the momentum in time and being $\frac{i\hbar}{p_T} = icn_c T$ the reduced Compton wavelength in the imaginary space.

$$R = \frac{p_T c}{\hbar/T} e^{\mp \frac{p_T c}{\hbar/nT}} = \frac{1}{n_c} e^{\mp \frac{n}{n_c}} \tag{5}$$

The possible opposite signs of the momentum in time are related to matter/antimatter, as discussed in Ref. [6]. Here, we only focus on matter particles. The emergence of the particle in the imaginary space following R is in any imaginary direction, and not only along the direction of the translational motion. Beyond p_T, the momentum p_S is equivalent, as usual, to the gradient of the phase S of ψ_E. More specifically, we can express the momentum in space and in time in terms of the wave function ψ as follows:

$$\begin{cases} p_T = m_T c = \mp\hbar \nabla \ln R = \mp \left(\frac{\hbar}{cT}\right) \partial \ln R \\ \quad ip_S = im_r \beta_r c = i\nabla S = \frac{i\partial S}{cT} \end{cases} \tag{6}$$

As a synthesis able to relate the momenta of a free fermion (with CoM at O) with the scale of its non-locality in the Present, we connect p_{ST} and ψ with Eq. (7).

$$\nabla\psi = \nabla \frac{1}{cT} e^{\left(\ln R + \frac{iS}{\hbar}\right)} = \left(\nabla\left(\ln R + i\frac{S}{\hbar}\right)\right) \frac{R}{cT} e^{\frac{iS}{\hbar}} = -\frac{(p_T - ip_S)}{\hbar} \psi = -\frac{{p_{ST}}^*}{\hbar} \psi$$

$$\nabla\psi = \frac{\partial\psi}{cT} = -\frac{{p_{ST}}^*}{\hbar} \psi$$

$$-\frac{\partial\psi}{\psi} = -\partial \ln\psi = \frac{{p_{ST}}^* c}{\hbar/T} = \frac{(p_T - ip_S)c}{\hbar/T} = m - i\gamma m \beta_r = \gamma m(\alpha_r - i\beta_r) \tag{7}$$

How should we interpret Eq. (7) and the non-locality of the particle in a framework inspired by Presentism? We consider 2 insightful perspectives "from the boundaries": the time-symmetric description from $-T$ and $+T$ introduced in section 3 (*ala Aharonov*), and a hyperbolic mapping from *null* and *infinity* in the imaginary space.

Non-Locality from the Boundaries

As per Aharonov description in Ref. [4], extended in Ref. [6], we relate $p_{ST} c$ with the *ket* $|\psi\rangle$ in $\mathcal{H}$, while $-{p_{ST}}^* c$ to the *bra* $\langle\psi|$ in $\mathcal{H}^\dagger$. These states describe the non-locality of the particle as a potential between the atom at the CoM and the surrounding imaginary space, where the particle could emerge (quantum tunnel from the CoM) at a given instant. In this description, the particle is the wave across the Present $|\psi\rangle\langle\psi|$ (ontological information in the *Res Potentia*), while an event of collapse $\langle\psi|\psi\rangle$ (localization of this potential at a given instant at a given atom of space) represents a discontinuity between successive instants, and it is intended as the "point particle" (which belongs to the classical *Res Extensa*).

In terms of memory-loops, the non-locality encoded in $|\psi\rangle\langle\psi|$ is modeled through a bundle of loops crossing the imaginary space. The momentum p_T determines the invariant non-local information from O (reduced Compton wavelength), while p_S determines its relativistic variation across the instants. These loops in the thickness of the Present, which cross the imaginary space at a distance $\pm incT$ from O, have a probability of occurrence as per the usual Born rule.

$$\wp\{collapse@(O+n)_{k+1}|\psi@O_k\} \propto 4\pi n^2|\psi|^2 \tag{8}$$

The momentum p_{ST} can also be described through the language of modular operators, introduced by Aharonov *et al.* in Ref. [59]. Modular operators have been shown to be a more effective language for non-locality in the context of a lattice with fixed spacing, as shown in Refs. [60] and [61].

The indeterminacy relation between position and momentum is interpreted, in modular operators, with an indeterminacy of the modular energy across the atoms of space and the instants of time, in which the modular operators are defined. In our model, $p_{ST}c$ is intended as related to the modular Energy. We leave the mathematical details of this description to a future contribution.

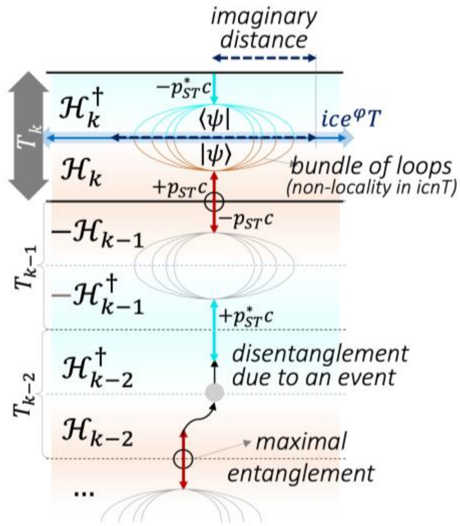


Figure 7. Representation of the evolution of a particle in the last few instants up to the Present. We picture the imaginary space axis in T_k as $ice^{\varphi}T$. The modular energy $p_{ST}c$ and $-p_{ST}{}^*c$ are shown as vectors from the boundaries of the Present, as per Aharonov in Ref. [4] (*red* in $\mathcal{H}$, *cyan* in $\mathcal{H}^\dagger$). They are at the root of the initial and final wave, represented as possible paths closed between $\pm T$ in a bundle of loops. Maximum entanglement among successive instants (*black circle*) is broken in case of an event (e.g., *grey dot* at the instant T_{k-2}).

Beyond a model *ala Aharonov*, we can also map the intrinsic non-locality of a particle with a description of the Present similar to *Celestial Holography*, model of our universe elaborated in Ref. [62]. More specifically, as suggested in Ref. [6], in the encoding of the entanglement in the imaginary space, $\mathcal{H}$ and $\mathcal{H}^\dagger$ can be interpreted as 2 symmetric bulks, rooted at *null* and *infinity* respectively, and with a common boundary at *2kT*.

In this correspondence, the limit at *null* in $icnT$: $ice^{\varphi}T|_{\varphi\to-\infty}$ (ideal center of a given atom of space) is mapped to the past boundary, at $-T$. The limit at *infinity*, with $\varphi \to +\infty$, is not intended as a physical infinity in the imaginary space but as a tangent limit, which is mapped to the future boundary of the Present, at $+T$. The case $\varphi \to 0$ represents the boundary of the given atom.

To represent the intrinsic non-locality of the particle in this mapping, the state $|\psi\rangle$ in $\mathcal{H}$ from $-T$ is causally projected on the boundary at *2kT*. Through this projection, we model the non-locality of a particle with CoM at an atom of space O with an amplitude β_m in each instant ΔT, which is related to the invariant information of p_T as per Eq. (9).

$$\beta_m = \frac{p_T c}{\hbar/T} = m \tag{9}$$

We show this projection in Fig. 8, with the point $\boldsymbol{A}$ and a *red* arrow from $\boldsymbol{O}$ to $\boldsymbol{A}$, graphical representation of the amplitude β_m. From $+T$, the information of $\langle\psi|$ in $\mathcal{H}^\dagger$ is mapped to the stereographic projection of $\boldsymbol{A}$, namely the point $\boldsymbol{A'}$, which identifies an atom of space A' entangled with the atom O. The state $\langle\psi|$ is shown, in Fig. 8, as a *cyan* arrow from *infinity* in the imaginary space. The entanglement between O and A' is intended as a loop in the Present that crosses the imaginary space at $2kT$ in the points $\boldsymbol{A}$ and $\boldsymbol{A'}$.

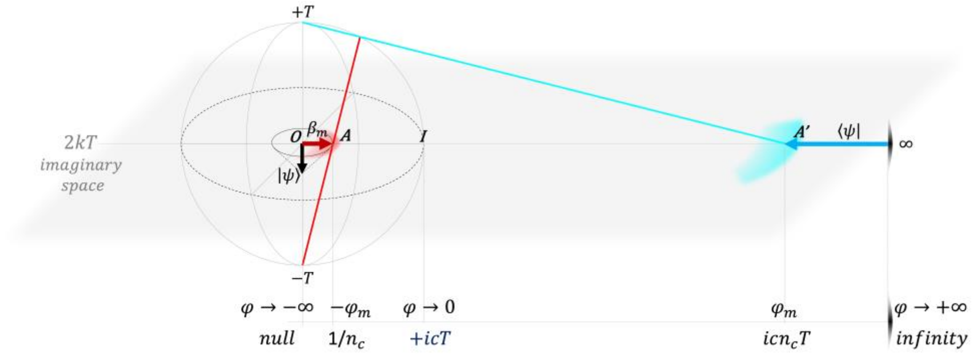


Figure 8. Graphics of a fermion in the imaginary space through a stereographic projection from *null* ($-T$) and *infinity* ($+T$). The atom O is shown as the disk on the 2D plane of the imaginary space, with a thickness within $\pm T$. We illustrate $|\psi\rangle$ (*black arrow* of length m), β_m (*red arrow)* and $\langle\psi|$ (*cyan arrow*), as well as the points ***O*** (*null*) and at *infinity*, ***I*** (boundary of the atom O), ***A*** and ***A'*** (information of β_m at O and its projection from $+T$, at a distance equivalent to the reduced Compton wavelength).

In this hyperbolic map of the imaginary space from *null* and *infinity*, as a synthesis of the magnitude of the non-locality $|AA'|$, we define a log-phase φ_m (to be further investigated in the developments for QG).

$$\varphi_m = \ln \beta_m \; ; \qquad \frac{|AA'|}{c\Delta T} = \frac{e^{\varphi_m} - e^{-\varphi_m}}{2} = \sinh \varphi_m \tag{10}$$

Spin and Entanglement in Time

A description of particles in terms of entanglement in a lattice is not new the literature, as shown in Ref. [2]. A model based on Presentism, besides being naturally related with this kind of description, may offer useful insights towards a description of the invariant mass as “information persisting in time”, related to an entanglement across instants.

To elaborate on this, we consider the particle quantum spin. In Ref. [6], we suggest a connection between the half spin of fermions and an extended period of revolution of magnitude $\frac{\Delta T}{spin} = 2\Delta T = 4T$. This relation has already been considered in theories with a discrete time. In Ref. [63], for example, a fast oscillation between 2 states is given as the basis for a statistical model of spin. In our interpretation, we see the relation between the half spin of fermions and a characteristic period of revolution as a phenomenon to be interpret in terms of entanglement in time.

To show the possible relation between spin and entanglement in time, we map the 4π revolution of spin ½ particles to the 2 sides of an ideal *Möbius strip*, identified with the 2 sides of the boundary at $2kT$, $|+\rangle$ and $|-\rangle$, facing $+T$ and $-T$ respectively. We suggest that a fermion, in an instant $\Delta T = 2T$, explores with a 2π revolution 1 side only of this boundary and, for a logically consistent evolution, complete its cycle with the exploration of the other side at the following instant. To fulfil a global logical consistency, the order of exploration of the 2 sides is not relevant. The *XOR* logic $\{|-\rangle_{k-1}, |+\rangle_k\} \oplus \{|+\rangle_{k-1}, |-\rangle_k\}$ that describes this condition is equivalent to a controlled-NOT (*CNOT*) gate: the state of a fermion at T_k correlates with itself across the boundaries of the Present (which act as CNOT controller).

To explore both sides, the particle can evolve clockwise or counterclockwise but, for a full revolution, a logical consistency between instants is needed. If the revolution is, for example, clockwise at T_{k-1}, then the same direction must be considered at T_k, as a counterclockwise revolution at T_k after a clockwise revolution at T_{k-1} would have explored again the same side of the boundary at $2kT$ in a backwards fashion.

We clarify that these “paths on a strip” are not actual paths of the surface of a classical spinning particle at superluminal speed, but a revolution of the particle’s persisting information in $\mathcal{H}$ and $\mathcal{H}^\dagger$ (in Eq. (9), the amplitude β_m and the momentum p_T). We also note that, in the description of a massive particle through a momentum p_T rooted at $\pm T$ (*ala Aharonov*, as in Fig. 7*)*, which is equivalent to a perspective at $\varphi \to \pm\infty$ in the proposed hyperbolic mapping, we see a possible physical implementation of the of the *belt in the book* metaphor used by Penrose in Ref. [64].

Given a *belt* (p_T) anchored on a *book-particle* at one end (at the *null* of the CoM), and in *our hand* on the other side (at *infinity*), we need not a 2π but twice a 2π rotation for a full revolution able to untangle the *belt* from *infinity*, as for a fermion's cycle in respect to the Present duration and its momentum in time from $\pm T$.

We identify the clockwise revolution with an imaginary path over 2 instants and the counterclockwise with a similar description but with an imaginary time evolving in opposite direction. These orthogonal possibilities are interpreted as a *forward* and *backward* propagation, as per the time-symmetric formalism in the imaginary space introduced in section 3. The superposition of the forward/backward (clockwise/counterclockwise) path traces imaginary closed loops in each instant, which identify an entanglement in time. More explicitly, the particle entangles across the instants in a complete exploration of the imaginary space, on the 2 sides of the boundary at $2kT$ facing $\pm T$. This entanglement in time identifies the CoM of this persisting potential at the center of this undefined order.

We suggest that spin ½ and entanglement in time are strictly related with the nature of fermions as particles with an invariant mass (*rest* mass). We believe that the momentum in time emerges from the entanglement in time of the revolution of the amplitude β_m.

To the best of our knowledge, the connection between spin ½, entanglement in time, and the invariant mass, as a persisting information in time, is a distinctive feature of our framework and, as elaborated in the last section, we believe this relation can be tested in a table-top experiment.

We conclude this section highlighting that fermions have an extended perspective across the boundary of adjacent instants, like an "extended memory of time" in respect to a single present instant. We remind that, in our Presentism model, only the Present ontologically exists, and that this extended memory is intended as the possibility to discriminate the existence of successive instants through entanglement in time, in a proper counting of ticks and proper experience of the passage of a causal time. It does not imply the concurrent existence of several present instants.

5. Spacetime from Information Sampling

The Relativity of Information

In section 4, we have described a particle in the Present through its momentum in time and in space. We have shown that the momentum in time is related to the entanglement across the instants, while the momentum in space, from Eq. (7), represents the variation in the imaginary space of the CoM, and it is interpreted as an increased tunneling amplitude and entanglement in space across the instants. We suggest in this section that these momenta are connected to the information of entanglement introduced in section 3 and that, thanks to P. 3, the concept of a present instant is compatible with SR and the emergence of a relativistic spacetime. Following the "classes of emergence" of Ref. [3], we take the opportunity to clarify that, in our model, the emergence of spacetime from entanglement information is intended as *Hierarchical*, similarly to LQG and several holographic models.

To show how spacetime emerges for the elementary observer of section 4 and how its proper time is derived, we start by considering a fermion that last collapsed at a position X at T_{k-N}, N instants before the Present, with $N \gg \frac{\hbar/T}{p_T c} = n_c$ (red. Compton wavelength).

The surface of the causal cone from the last collapse identifies a bipartite system: the universe, and the particle (its non-locality and undefined causality). The information on this surface, as per Eq. (1), is equal to $\varsigma_{e,N} = 4\pi N^2$, number of angular DoF after N ticks. We propose that a particle "samples" this information as an increasing entanglement in space and in time from the collapse event. The information sampled through entanglement in space $\varsigma_{s,N}$ is related to the increased non-locality of the particle in the imaginary lattice due to its momentum in space. The information sampled through entanglement in time $\varsigma_{t,N}$ is related to the imaginary loops of the momentum in time and the increased undefined causality from the collapse event. We explicitly describe this relation with Eq. (11).

$$\begin{cases} \dfrac{\varsigma_{t,N}}{\varsigma_{e,N}} = \left(\dfrac{N_t}{N}\right)^2 = \dfrac{|p_T|^2}{|p_{ST}|^2} = \alpha_r^{\ 2} \\ \dfrac{\varsigma_{s,N}}{\varsigma_{e,N}} = \left(\dfrac{N_s}{N}\right)^2 = \dfrac{|ip_S|^2}{|p_{ST}|^2} = \beta_r^{\ 2} \end{cases} \tag{11}$$

From Eq. (11), we can explicitly calculate N_t and N_s and rewrite Eq. (1):

$$\varsigma_{e,N} = \varsigma_{t,N} + \varsigma_{s,N} = 4\pi N_t^{\ 2} + 4\pi N_s^{\ 2} = 4\pi(\alpha_r N)^2 + 4\pi(\beta_r N)^2 = 4\pi N^2 \tag{12}$$

In Eq. (12), $\varsigma_{t,N}$ is intended as a sphere of undefined causality of radius $-c\alpha_r N\Delta T$ from X_k. This radius represents the particle proper experience of the passage of time: the temporal window amplitude $-N_t = -\alpha_r N$ from the last collapse, introduced in section 3. Similarly, $\varsigma_{s,N}$ represents the imaginary surface $(X + \beta_r N)_k$ of radius $+ic\beta_r N\Delta T$ (equivalent to an imaginary path amplitude of $i\beta_r N$ steps) and identifies the set of atoms where the particle could quantum jump at the N^{th} instant. In this discrete evolution, time dilations depend on the reduced information sampled through entanglement in time, given that part of the total information from the last collapse is sampled in a non-local potential. The proper time emerges from a subsampling of the universe ticks, and it is calculated as the fraction of the causal time experienced by the particle between its events of collapse.

Given a causal time equal to $\Delta t = N\Delta T$, a particle with a momentum in space p_S entangles with $\varsigma_{s,N} = 4\pi(\beta_r N)^2$ atoms of space in the N ticks and samples $\varsigma_{t,N} = \varsigma_{e,N} - \varsigma_{s,N}$ through entanglement in time. At a collapse at the N^{th} tick, the particle has experienced a proper number of ticks equal to N_t, which is equivalent to a proper time interval $\Delta\tau$ as per Eq. (13), in line with the known result of SR:

$$\Delta\tau = N_t\Delta T = \alpha_r N\Delta T = \sqrt{\frac{\varsigma_{t,N}}{\varsigma_{e,N}}}\Delta t = \sqrt{1 - \frac{\varsigma_{s,N}}{\varsigma_{e,N}}}\Delta t = \sqrt{1 - \beta_r^{\ 2}}\Delta t \tag{13}$$

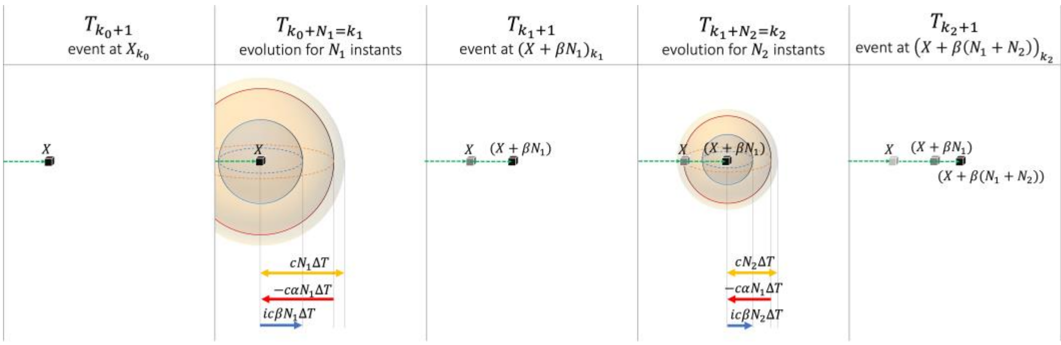


Figure 9. Evolution of a particle between 3 events. Each panel represents a snapshot at a given T_k. We highlight the atom of space where the particle is located at the different collapse events (*cubes*), the particle's world-line (*green dashed arrows*), the information sampled between the event of collapse (*blue and red shaded spheres*), as well as the total information (*yellow shaded spheres*). We note that events and world-lines do not exist in the Present and are shown in the figure for illustrative purpose.

We clarify that, from the last collapse, we are not allowed to consider an "average uniform motion till the Present", as no movement is causally defined until a new event of collapse occurs. In an evolution based on a discrete time and tunneling events, there is no uniform motion, but an average speed emerging from a series of collapse events. If, at the N^{th} tick from the last collapse, there is a new collapse event, the information of undefined causality and non-locality sampled by the particle in its causal cone is released: the particle causally "ages" by $|-\alpha_r N\Delta T|$ ("quantum jump in time" of its "ticks counting") and it is relationally displaced from X by $|ic\beta_r N\Delta T|$ ("quantum jump in space" of its CoM), with an average speed between collapses of magnitude $v_s = \beta_r c$. We also note that the emergence of the dynamics of a system from entanglement in time and the possible symmetry of QM inequalities between entanglement in space and in time has been shown in Ref. [65] through Pseudo-Density Operators. Here, we have provided a physical description of how a relativistic dynamic can emerge from entanglement in time, complementing the picture.

Elementary Observers of Spacetime

To further clarify the proposed model, we elaborate on the most extreme scenarios, related to the sampling of information through entanglement in space or in time only.

We consider the limit scenario $\beta_r \rightarrow 1$. It is straightforward to show that such particle experiences no proper time as it never entangles in time. In this paper, we do not consider such particles as properly defined observers: there is no spacetime emerging from their perspective, but the present instant only. A bath of such particles, as the Cosmic Microwave Background (CMB), can represent a statistical reference to define average velocities, as experimentally verified in Refs. [66] and [67] through the study of the CMB dipole.

We consider the limit scenario $\beta_r \rightarrow 0$. We suppose that the origin of every particle in the universe occurred with some initial kinetic energy. Moreover, even if in a discrete evolution we can consider a potential resting condition in an instant, there is no chance for an observer to be in such state for long. Given that there are no observers deterministically at rest that could serve as "absolute clocks" to measure the whole set of universe ticks, then it is only possible to compare relative differences in respect to other observers and clocks. Observers can only verify proper relativistic experiences of time intervals, comparing their proper counting of ticks. In any case, for every observer, a proper subsampling of the universe ticks is expected even without other observers to confront with.

From Eq. (13), we deduce there is no "common now" nor absolute simultaneity for observers. A single universe tick is the same "common now" only for colliding particles in the instant of the event becoming actual (as in Fig. 1a). From the perspective of a single observer, we can only consider a "local now", related to the proper experience of the surrounding universe, and an "extended proper present", connected to the observer's proper number of ticks experienced between collapses.

From Eq. (13), we can describe the phenomenology of time dilations. According to SR, a clock with an internal period Δt_0 when at rest, has a period $\Delta t_r > \Delta t_0$ when moving at average speed $v_s = \beta_r c$ in respect to its resting position. The same time interval measured as N_0 periods of duration Δt_0 by the stationary clock, will be measured with only N_r "stretched proper periods" of duration Δt_r when part of the total information between collapses is sampled as a non-local potential. Mathematically: $N_r \Delta t_r = N_0 \Delta t_0$, $N_0 > N_r$.

The non-locality between collapses of the moving clock is balanced by a reduced sampling of information through entanglement in time. This leads to a reduced proper rate of change. The dilated period Δt_r (slower frequency) depends on the smaller number of universe ticks counted by the moving clock over the ones causally passing in the universe. If a full cycle at rest needs N universe ticks ($\Delta t_0 = N\Delta T$), according to Eq. (13), in the same N ticks, the moving clock has experienced $\alpha_r N$ proper ticks. To complete its cycle, the moving clock needs N proper ticks, and this happens only after N/α_r universe ticks. The extended or "dilated period" Δt_r can then be calculated with Eq. (14), in line with SR result.

$$\Delta t_r = \frac{N}{\alpha_r}\Delta T = \frac{1}{\sqrt{1-{\beta_r}^2}}\Delta t_0 = \gamma \Delta t_0 \tag{14}$$

In our derivation of SR phenomenology, we have posed no conditions on the initial and final positions of the observer, but simply defined the max rate of change in time and in space (with P. 1 and P. 2) and the rate of entanglement information in the causal cone between collapses (with P. 3). Our deductions are then valid in every reference frame, with no dependencies on the spatial or temporal location.

6. Conclusion

Discussion on Presentism

We have proposed a framework inspired by Presentism and Information Theory and shown its compatibility with SR. The Present has been described as a quantum memory, which evolves in atomic instants and encodes the entanglement in an imaginary set of possible locations.

In this imaginary space, we have modeled elementary massive particles through momenta in space and time, which encode the relativistic and the invariant information respectively. We have mapped the momentum in space to a gradient of entanglement in the foliation and the momentum in time to an entanglement in time, connected with the half spin and the invariant mass. In our interpretation of the Present as a memory, matter particles emerge as a greater form of complexity from the entanglement in time of the entanglement in space existing in single present instants. Finally, we have considered such an elementary particle as an elementary observer and derived its proper time in terms of the information of entanglement in time sampled between its events of collapse.

In our model, eventually, not only matter particles emerge. The classical spacetime does not exist either but emerges as a subjective experience of the past events. From a proper number of ticks between collapses, the causal set of events appears to each observer as a relational and relativistic manifold. The globally consistent causal structure is experienced by different observers with a relative order of events, that depends on the magnitude of entanglement in space and time. Relative is the dimension in which an observer samples information, counting universe ticks (through entanglement in time) or exploring an imaginary space of possible locations (through entanglement in space).

Concluding on Presentism, if a relativistic experience of time can emerge from a single instant, given as the only one existing, why should we consider the past as existing as well? We note that a more complex observer than a fermion might encode an extended interval of causal time thanks to the complexity of its interconnected parts, and model in its internal components "more spacetime" than just the intervals between collapses. However, at the most fundamental level, more memory of time than a thick instant seems not needed.

Outlook on Quantum Gravity

We have suggested, in the context of Presentism, several novel interpretations for foundational concepts in physics. Time is described as a quantum memory encoding the Present potential. Entanglement in space (time) is modeled with loops in time (space), specifically, time-symmetric closed paths in the thick Present (in the imaginary space). The limits at *null-infinity* in space are mapped to the boundaries of the Present. The metaphoric "*belt from infinity*" used to describe the 4π period of spin ½ particles is identified in the momentum in time, connected to the invariant mass and an entanglement across instants. Beyond these insightful correspondences, we believe that this framework can be a first step towards a novel understanding of the quantum nature of gravity. We suggest here some possible developments, to be elaborated in coming contributions.

To describe curvature in our model, we consider an intriguing perspective, elaborated in Refs. [68] and [69] as well. We suggest connecting curvature to non-hermicity, intended as an asymmetric tunneling β_X at an atom of space X towards the source of gravitational potential. The amplitude β_X at X, N steps from a mass m, could be intended as an average between φ_m of Eq. (10) and of the phase $\varphi_N = -\ln N$, specifically $\beta_X = e^{(\varphi_m+\varphi_N)/2} = \sqrt{m/N}$, being $V_X = \left(\frac{i}{\sqrt{2}}\beta_X c\right)^2$ equivalent to the Newtonian potential at X. In this description, we can also interpret the relation between β_m and p_T in Eq. (9) as an *equivalence principle* between the gravitational mass (amplitude β_m) and the inertial mass (expressed as p_T, persisting information across the instants).

In the context of the proposed relation between entanglement in time and rest mass, we also believe that a circuit implementing such entanglement could act as an antenna able to generate a local curvature. To increase the gravitational effect, several smaller circuits can be used in parallel, as an array. The generated curvature could be verified through the analysis of the variation of the random walks in a lattice, or with other experimental setups capable of measuring gravitational interactions between small masses.

Given the relation between the spin and the period of revolution in terms of instants introduced in section 4, it also seems worth to investigate a possible description of spin 1 and spin 2 bosons in such context. Here, we briefly suggest that spin 1 particles could be intended as loops closed in 1 instant (existing only in the Present), with no entanglement in time nor the experience of the passage of a causal time.

Spin 2 particles, on the same line of reasoning, could be modeled as "2 loops per instant", in a dual cover of the imaginary space in $\mathcal{H}_k$ and $\mathcal{H}_k^\dagger$. These loops closing in a time $\Delta T/2 = T$ (Planck time) could represent the "circuitry" of the memory of the Present and an equivalent sampling frequency of twice the bandwidth of the universe evolution, as per the Nyquist-Shannon theorem in Ref. [46].

Beyond these possible extensions of our framework towards QG, we list here some wilder speculations that elaborate on the mapping of the imaginary space with the fuzzy Euclidean space that emerges, in the models based on an imaginary time, in the interior of a BH (see Refs. [40], [41], and [42], as introduced in section 3).

In this speculative conjecture, we map the radius of the "parent BH" to the thickness of the Present, while the horizon to the boundaries at $\pm T$ (equivalent to $\varphi \to \pm\infty$ from a perspective in the inner fuzzy Euclidean space). In this context, the definition of the fundamental constants of the imaginary space (e.g., $\hbar/c$) could be related to the parent BH, in a possible "cosmological selection" (Smolin in Ref. [70]). Moreover, Dark Energy (growth of the inner space at infinity) can be related to the growth of the parent BH radius. Finally, in the mapping of the Present to a BH in a parent universe, we can interpret the momenta in time as modes in the parent BH radius, and generators of the particles' fields. The mapping of elementary fields to these modes in the parent BH reminds the *one-electron* conjecture, as these modes would be an ontologically real representation, with several replicas in the imaginary space.

The Relevance of Memory

We conclude this contribution highlighting the relevance of the concept of *memory* in our framework and, possibly, in the emergence of complexity.

Beside the toy model suggested, in which the Present ontologically exists as a *memory* and particles emerged as *extended memories*, the author of Ref. [71] maps the evolution of the universe to the learning process of a Neural Network, which can be seen as a global memory-network.

In terms of neural networks and emergent behaviors, we note that the creation of novel content in Generative AI models depends on *Transformers*, which allow to keep a longer coherence in patterns recognition and creation increasing the network *attention*. As clarified in the foundational paper on the topic, see Ref. [72], Generative AI networks are Transformers that have been trained on terabytes of data, making sense in their extended and interconnected memory of the patterns in the online knowledge base.

Beyond the relevance of memory in the possible description of our universe and in the emergent behaviors of neural networks, DNA, in Biology, has often been described as a memory encoding the basic information for life. Moreover, besides the connection between memory and the human perception of the passage of time and of a "self-identity" (as proposed in Ref. [73] by Locke), in recent studies of cognitive neurology (see Ref. [74]), also awareness and consciousness have been connected to the access to a *real time memory*. The relation between consciousness and memory in the context of quantum information has been investigated in Refs. [75] and [76] as well.

The emergence of more complex types of *memory* to encode the relevant information seems to be a leitmotiv of evolution, and a key element to understand the emergence of complexity, from the most fundamental *physical layer* of our universe, such as the Present, up to the most abstract entity we could discuss about, such as human consciousness.

In an effort of synthesis of the relation between memory, existence, and emergence, from the existence of our universe to the awareness of our existence, we therefore dare to formulate:

$$memoro\ ergo\ sum$$

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