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On the Emergence of Spacetime from the Sampling of Holographically Bounded Discrete Information

Time is There even when Nobody is Looking

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Abstract: This paper introduces a framework for a quantum description of spacetime inspired by Presentism and Information Theory. We start from a fundamental thick present instant as the only element of reality in time and map space to a relational lattice evolving in atomic instants. Then, we mathematically derive the emergence of a flat spacetime from the sampling of discrete information in each instant, holographically bounded by the number of instants considered. We elaborate on the probabilistic nature of time dilations in the proposed framework and conclude suggesting next steps towards a quantum description of curved spacetime. Our proposal connects, through the language of information, two seemingly opposite claims: "only the Present exists" and "the proper experience of time is relativistic". This leads Heraclit, Plato, and Einstein, eventually, on the same page.

Keywords: time; discrete; presentism; lattice; relativity; information; holography; gravity.

Introduction

Scope

The nature of time has always intrigued philosophers, physicists, and neuroscientists. Several descriptions have been formulated, spanning from a static "4D block universe" (*Eternalism*) to the idea that only the present instant exists (*Presentism*), with all the spectrum in between. Each description focuses on a measurable or perceived aspect of time, according to the context of interest or of validity.

The Theory of Relativity is considered our best model of time in Physics. In this classical framework, time is intertwined with space in a continuous spacetime manifold. Relativity clearly identifies spatial and temporal separations but seems incompatible with a perspective based on Presentism. The passage of time is all but absolute in Relativity and there should be no preferred reference frames to identify a "common now".

Even if Relativity is our best theory on time, we should consider its insights with caution: as a classical theory, it should be seen as incomplete. Quantum Gravity (QG) approaches are investigating time-less scenarios, towards a description of a relativistic experience of time emerging from more fundamental principles.

In our proposal, we will consider a framework based on Presentism, and elaborate on a discrete space lattice evolving in atomic instants. We will show how the phenomenology predicted by Special Relativity (SR) can be derived in the proposed framework thanks to principles inspired by Information Theory.

More specifically, in this contribution, after a brief introduction on the rich literature on Presentism, we will elaborate our proposal in 2 main chapters, collecting our ideas in a list of deductions (*D.1, D.2*, …) and equations, derived from 3 postulates (*P.1*, …).

First, we will define a discrete space evolving on atomic instants from 2 postulates. Then, we will elaborate on observers in terms of the evaluation of differences in space and time in this discrete universe and, with a third postulate on information, we will set the basis for the emergence of a relativistic spacetime. In the second chapter, we will mathematically derive SR phenomenology from the sampling of information in the Present and elaborate on the emergence of a relativistic spacetime from quantum probabilities. We will conclude introducing possible next steps, such as an extension of the framework towards a model for gravity, and an argument in favor of a logical deduction of Presentism.

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Background

Interpretations of time inspired by Presentism are not new in the scientific literature, and have been proposed by several authors, with roots in Physics, Mathematics, and Philosophy, often referring to the Present as the *Becoming* or *Now*. In this chapter, we will report a brief list of the main ideas behind this rich framework, as a support and reference for the postulates and deductions of the coming chapters.

Smolin highlights the relevance of the concept of the Present already in Ref. [1] and proposes, in Ref. [2] and [3], a description of evolution as a *"dynamic of difference"* between present and past instants. Gisin, in Ref. [4] and [5], connects Presentism to intuitionist mathematics, where Real numbers are not "*given all at once*" with infinite information, but "bit after bit", in an increasing discrete information instant after instant.

Schlatter investigates the concept of *synchronization* and of a spacetime emerging from irreversible events in Ref. [6], [7] and [8]. The research of Operational Theories, which starts from Information Theory to interpret Quantum Mechanics (QM) and has been introduced in Ref. [9] and [10], is based on discrete operations and circuits (*foliations*) that evolve in atomic computational instants, similar to atomic present instants.

Lubashevsky studies the compatibility of Presentism with Newtonian mechanics in Ref. [11]. Riek, in Ref. [12] and [13], investigates the implications of a discrete evolution and the need for a "thickness" in time to distinguish the cause from the effect in an event.

Eliztur speculates on the *Becoming* as a bridge between QM and SR in Ref. [14], while Kauffmann, in Ref. [15], elaborates on the description of the present instant as connected to the *Res Potentia* of QM, different from the *Res Extensa* of a classical past spacetime.

The absence of a preferred arrow of time within an atomic Present has been proposed by Aharonov, Popescu and Tollaksen in Ref. [16], where each instant is as a "new universe" (inspired by Heraclit of Efes). In their model, 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. [17], extending to *Energetic Causal Set* in the past of the Present in Ref. [18].

Finally, Kauffman in Ref. [19] and Capurso in Ref. [20] and [21], investigate the quantum potential in the Present and its connection with non-locality and entanglement in space, towards a holographic model of the information in the Present looking at QG.

In Presentism, the discreteness of time is also extended to space. This is proposed in the context of a physically realizable universe, for which the information 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. [4], 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's bound of Ref. [22], 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. [23].

The finiteness of information suggests a possible indeterminacy of the past as well. Recent *gargantuan simulations* reported in Ref. [24] have shown that time seems irreversible at the most fundamental level, beyond thermodynamic reasons, and even a simple 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 in Ref. [25], where a model to calculate *propensities* of past events is proposed. Eventually, in a framework inspired by Presentism, what has already happened can causally influence the Present, but cannot be changed and, beyond fundamental limits, cannot even be known with certainty.

We also note here that the discreteness of space and time, intended as a lattice of atoms of space evolving synched on atomic instants, may offer a model of space similar to a coherent state of oscillators and a Bose condensate. This discretization of space could be intended as well as similar to Hawking's interpretation, elaborated in Ref. [26] and [27], in which space is pictured as a *"sea of virtual Planck-mass black hole"*.

The literature investigating an evolution occurring in atomic instants and the nature of a thick Present is rich and multifaced on the side of Philosophy as well. De Bianchi, in Ref. [28], investigates Plato's idea of an absolute time emerging from a present instant that is *out of time*. Mariani and Torrengo, in Ref. [29], elaborate on the philosophical description of an indeterminate Present as the basis for an open future, while Tallant and Ingram, in Ref. [30], face the critics to Presentism. Finally, in Ref. [31], Capurso proposes a "*philosophy of efficiency*" inspired by Presentism and telecommunication networks.

We have reported several contributions, from Physics, Mathematics, and Philosophy supporting an interpretation of time as existing in atomic present instants only. Beyond the compatibility of Presentism with QM and the description of the past as a causal set of events (elaborated in the referenced papers), what seems still missing in the scientific literature is a clear indication of how a relativistic description of time intervals could be intended, given a thick present instant, with a corresponding space foliation and an apparent absolute description of the passage of time. We believe that answers to this open question might offer a more profound understanding of the nature of time.

To address this open question and derive time dilations and lengths contraction in Presentism, in the following chapters we will elaborate on the discrete spacetime emerging from the present instants and propose a relativistic sampling of this information.

Our model might seem, at first sight, far from the usual understanding of SR and even preposterous. However, being compatible with the same phenomenology, we believe it could offer interesting stimuli from which a new perspective on spacetime might be developed. As a final reference, we also take the opportunity to remind the 2 postulates or SR, mandatory milestones to confront with:

- *The laws of physics are invariant in all inertial frames (SR1)*
- *The speed of light in vacuum is invariant in all inertial frames (SR2)*

Spacetime and Observers

Postulate 1 – Time

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

Our model starts from a postulate which seems in contradiction with the concept of relativity as per the usual understanding, and even more absolute than SR2. Still, as it will be clarified, the apparent "absoluteness" of P. 1 is compatible with time dilations, lengths contraction, and a relativistic description of the passage of time.

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, like a global "update cycle" marking the evolution as a "universal clock". Each new present instant, often referred as a universe "*tick*", identifies a thick space-foliation of spacetime.

In the last chapter we will suggest how a global synchronicity might be derived from a lighter version of P. 1 that just requires a local discreteness of time. However, in the following deductions, we will consider P. 1 in its full form.

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 will call *causal time* the ordered set of instants prior to T_k. This set identifies an extended, oriented, and discrete axis of temporal evolution, from a distant past to more recent instants of the universe. The causal time always "goes forward", a priori of events. In this discrete evolution, being the present instant T_k proposed as the k^{th} "tick" in the 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" $T_{k=1}$ of our universe.

It is crucial to note that the Present is not intended as an "observers' common now". Observers, as it will be clarified, can only compare differences in time intervals and spatial distances between events in spacetime, 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 possible time interval ΔT, temporal duration of each atom of evolution. The discrete evolution implies a maximum rate of change. In this sense, ΔT is also proposed as the "temporal resolution" of the occurrence of events in spacetime.

If ΔT is a temporal resolution of events, then the boundary between T_k and T_{k-1} (defined as the *past boundary* of the *Present*) identifies the boundary between what has already happened (events) and 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}).

Following this line of reasoning from P. 1, events are irreversible as they do not exist anymore, and something that does not exist cannot be acted upon, nor changed. Even if events do not exist in the Present, the information of events propagates in each instant. 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 space in each instant. These causal cones of information at the past boundary of the Present are the basis for a causal evolution.

We can summarize the line of reasoning so far with the following deductions.

If P. 1, then ΔT is the resolution of events in spacetime (max rate of change in time) D. 1

If P. 1 and D. 1, then events are irreversible as they do not exist anymore.
Only their consequences persist at T_k through the causal cones at the boundary from T_{k-1} D. 2

If D. 1 and D. 2, then events can be ordered in a causal set
along an oriented discrete axis of causal time from far past instants up to T_{k-1} D. 3

Following the definitions suggested in Ref. [15], we will call:

- *Res Extensa* what has already happened, intended as the classical domain of events behind the past boundary of the Present, irreversible and organized as a causal set along the causal time.
- *Res Potentia* what could happen in the current instant given the causal past, intended as the evolution of 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} atomic instant of evolution of space exists in the thick Present T_k. In this sense, we consider the Present as an ontological "memory buffer" that encodes the quantum information connected to events that could happen but are not happened yet (otherwise they would have been behind the past boundary of the Present).

In the encoding of this *Res Potentia*, we do not consider an explicit arrow of causality within the thickness of the Present. The ordered causal time defined previously extends up to the past boundary of the Present, giving causal order to the set of events, but it is not defined within the Present. The Present, in this sense, is out of the causal time, as per Plato.

The absence of a preferred arrow of time in each atomic instant has been elaborated in the QM models of the Present of Ref. [16], [17], [18], [20] and [21]. In these models, the Present is described through a time-symmetric formalism, with the superposition of the past and the future contributions within ΔT in an undefined causality.

We will not elaborate in this contribution on the QM description of the Present and leave the details to the referenced literature. We simply note that a time-symmetric framework to model the undefined causality within the Present suggests a description of the thickness of each atomic instant ΔT as $\Delta T = 2T$. Being the Present intended as the k^{th} instant from the birth of the universe in an absolute causal evolution, 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. The value of the interval of time T is beyond the scope of this contribution and it is not needed for the following reasonings. It can be considered of Planckian nature.

We summarize these further concepts introduced from P. 1 with the following deduction and figure.

If P. 1 and D. 2, then the present instant is based on the consequences
of events that already happened (as causal cones from the classical Res Extensa) D. 4
and encodes the information of events that could happen (as a quantum Res Potentia)

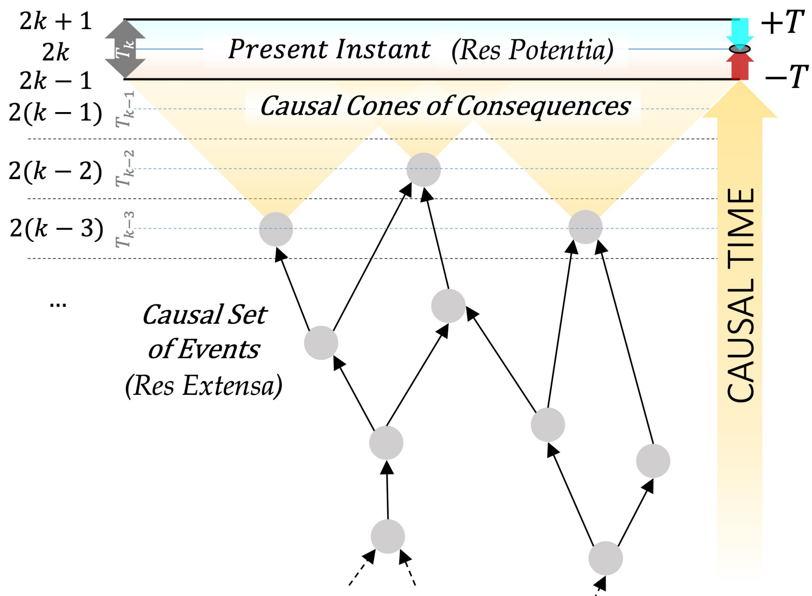

Figure 1. Model of a universe evolving in instants. Each instant identifies a space-foliation. From the top, we represent the time symmetric Present T_k, which encodes the *Res Potentia*. It is identified as the k^{th} instant, between *(2k–1)T* and *(2k+1)T* from the first universe *tick*. Below the Present, a causal set of irreversible events (*grey dots*) is shown along an emerging arrow of causal time. They represent a classical domain of *Res Extensa* and are perceived in the Present through their causal cones.

Postulate 2 – Causality

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

Postulate P. 2 is similar to SR2 but focuses on causality and stresses the absoluteness of its speed a priori of observers. This universal constant is intended as a maximum rate of change in the spatial position and allows the description of space distances coherently with the discrete evolution postulated in P. 1.

From P. 1 and P. 2 given as true in the whole universe, we can consider a definition of "universe" in our model as a "coherent and continuous region of spacetime", intending with "coherent and continuous" the synchronicity of evolution and the continuity of the propagation of the causal information. In the choice of P. 1 and P. 2 as starting postulates, we promote an unbroken wholeness of the entire universe.

In this discrete evolution, we consider a possible event at the present instant T_k, such as the emission of a photon from a particle at a possible position X_k. From X_k, we describe the other possible events' positions in the same foliation (during the same instant) through an imaginary time of motion 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 considered orthogonal to the arrow of causal time, as well as to the time symmetric arrows within the Present, as per the usual space and time orthogonality.

In the description of spatial distances (space-separated possible events in the same instant) through an imaginary time, space is intended as a *hyper-plane* within the time symmetric thick foliation of the Present, as elaborated in Ref. [16], [19], [20], [21] as well.

Given a discrete temporal evolution, the imaginary time of motion is intended as discrete as well and defined through multiples of an atom of imaginary evolution $i\Delta T$.

Thanks to P. 2, we have shown how we can describe the whole space from a position X_k (possible event location) with a coherent causal mapping of imaginary steps at the speed of causality. We note as well that, in this contribution, we are not considering any condition on the size nor on the growth of space, but just on its uniformity in terms of P. 1 and P. 2.

In the following picture, we represent the space hyperplane (2 dimensions of the 3 spatial ones), and the temporal dimension, identifying the thick present instant (with time symmetric evolution) and the oriented arrow of causal time (beyond its past boundary).

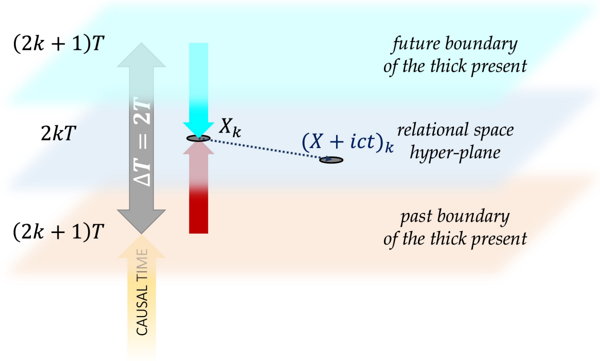

Figure 2. Graphical representation of the space hyperplane within the Present instant. We highlight the past and the future boundaries of the Present, the time symmetric description within the Present (*red* arrow from $-T$ and *cyan* from $+T$) and 2 locations of possible events separated by an imaginary, oriented, and relational distance ict_X from a possible location X_k at the instant T_k.

Given a discreteness of time from P. 1, each possible event's location is identified by an atom of space of extension $|ic\Delta T|$. Each possible atom X_k is pictured as at the origin of a discrete axis of imaginary spatial distance, developing in the directions defined by $\theta_{1,2}$.

From a given X_k, we map the other atoms of space as 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 the position X_k, this mapping is proposed as a relational description of the whole space through the discrete variable n_X (we will omit the index X in n_X the future).

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 defines a discrete space from X_k: a *space lattice* extending in 3 dimensions and with a resolution of $c\Delta T = c2T = 2L$ (being L an elementary unit of distance derived from P. 1 and P. 2, and supposed of Planckian nature).

Given the use of an imaginary time of motion to describe the space-hyperplane in the Present, we will call *imaginary space* the set $\{in, \theta_{1,2}\}_X$ of all possible atoms of space. The 4D structure $\{in, \theta_{1,2}\}_{X,k}$ defined from X_k along the values of k (marking the universe ticks) is proposed as a relational and discrete imaginary space evolving in atomic present instants. In the coming chapters, we will investigate the possible emergence of a relativistic spacetime with metric signature $(+,-,-,-)$ from the "sampling of information" in this discrete structure.

The following deduction and picture summarize the concepts introduced and derived from P. 1 and P. 2.

If P. 1 and P. 2, then space can be mapped to a set of independent imaginary atoms relationally defined from any atom: space at T_k is relational and discrete D. 5

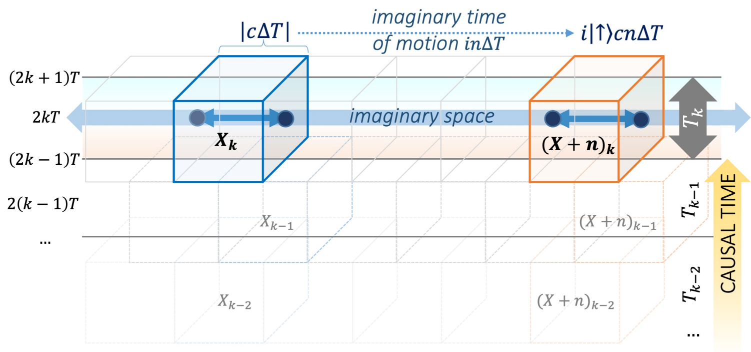

Figure 3. Discrete 4D set $\{in, \theta_{1,2}\}_{X,k}$ along the universe ticks k from an atom of space X (with $\theta_{1,2}$ omitted for clarity). We highlight the imaginary space distance axis inside the Present. It is defined from an imaginary time of motion counting the *steps* at the speed of causality orthogonal to the causal time of the past atomic evolution cycles, in a relational description of the space hyper-plane.

We have presented, from an atom of temporal evolution in P. 1 and a reference for causality in P. 2, a possible discretization of space and time in a seemingly rigid structure. In this set of atoms of space evolving in atomic instants, how can a free massive particle at constant relativistic speed "experience less time" compared to when at rest? How can a free particle experience that its decay time is closer, as "some time" is causally passing, even when no events occur in between? How can a free elementary particle in the universe experience its internal temporal evolution with *ticks* counting a proper time?

In the following chapters, starting from the introduced framework, we will elaborate on this thought experiment through concepts inspired by Information Theory.

The Perspective of a Particle in an Instant

We will now elaborate on the evolution of a free elementary particle, intended as an elementary observer of this discrete universe. The deductions proposed in this chapter are given as a guidance in the interpretation of our framework but are not considered mathematical derivations. Given their relevance, we will propose a synthesis of these ideas in a third postulate. Thanks to this postulate, we will build the mathematical framework to describe relativistic time dilations through the concept of "information sampling".

We are interested in the perspective of a particle in terms of changes from the past to the present instant. This perspective is intended, in our model, as the evolution of the atom of space enclosing the particle's Center of Momentum (CoM) in terms of potential locations in the space lattice and experienced causal changes in the surrounding universe.

We consider a particle at an atom of space X_{k-1} at T_{k-1}. The position X_{k-1} can be the last event's location in spacetime (*e.g.* emission of a photon at the previous instant) as well as a *Quantum Reference Frame* (introduced in Ref. [32]). In this relational description of space, X_{k-1} is defined as an atom of space at *null* distance from the particle's CoM at the end of the instant T_{k-1}, namely the *here* of the observer at the past boundary of the Present.

In the following descriptions, we often refer to a position in the past related to an event but, as clarified, being this position relationally defined from particle's CoM in the previous instant, an event is not strictly needed.

Given a discrete temporal evolution ΔT (universe *tick*) and a discrete space, a particle at a position X_{k-1} at T_{k-1} could move in the Present its CoM in respect to its previous position at maximum by an imaginary distance $ic\Delta T$, equivalent to 1 *step* in 1 *tick*. This movement is not intended as a collapse event but as a potential evolution of the position of the CoM in the space lattice in the instant T_k from the position at T_{k-1}. This movement is intended, in our framework, as an extension of imaginary paths, interpreted as a quantum tunneling potential, which sum in a path integral, as the universe evolves.

From a possible position X_{k-1} at the instant T_{k-1}, the particle can extend its imaginary paths to a position $X_k = (X + ic\Delta T, \theta_{1,2})_k$, with 2 degrees of freedom $\theta_{1,2}$, as no further references are given beyond ΔT and $ic\Delta T$. With the same set formalism introduced, the possible position of the particle is defined as a set of atoms of space at distance $ic\Delta T$ from X_k at the instant T_k, namely: $\{i, \theta_{1,2}\}_{X,k}$.

When a particle, in a universe tick, does not change the position of its CoM (compared to the previous instant), it is considered "at rest" in that instant. Given a discrete space and a position at an atom of space at the instant T_{k-1}, there are no other cases at T_k: either the particle relationally extends its imaginary paths by a potential $ic\Delta T$, or it is at rest.

From the perspective of the CoM, how can an elementary observer experience a potential imaginary step in the lattice? In the Present, the particle receives at its position incoming information at the speed of causality from the events in the causal time. These causal messengers are coming, in every instant, from all possible directions of space $\theta_{1,2}$, in a spherically symmetric fashion around the CoM. The thermal bath of stimuli (photons or other messengers of causal information) is synched in each instant (given P. 1 and D. 2). We assume that a particle at rest symmetrically experiences incoming stimuli and causal changes in the surrounding universe, while a particle extending the tunneling potential from the CoM loses incoming causal stimuli and changes in the causal time.

As said, this model of movement will be better clarified through a third postulate on information. Here, we just want to reassure the reader that our framework does not promote observers at rest acting as absolute clocks and allows a relational and relativistic comparison of intervals only.

We can summarize these elaborations with the following deductions.

If D. 4, and D. 5, then an imaginary movement in space at T_k can be relationally defined in respect to X_{k-1} and the symmetry of the surrounding incoming stimuli at T_k D. 6

If D. 5, and D. 6, then the imaginary movement in the relational space is discrete: in an instant an observer potentially moves of either $ic\Delta T$ or nothing in respect to X_{k-1} D. 7

We have proposed some initial deductions in terms of what could happen in the present instant to a particle, elementary observer of this discrete universe. In the coming chapter, we will consider how the causal and the imaginary information can be "sampled" by an observer in a more extended interval of temporal evolution.

Before further deductions, it is worth to clarify that, in the experience of a spacetime emerging from the "sampling of information", we consider this information physical. Citing Landauer from Ref. [33], "*information is not a disembodied abstract entity; it is always tied to a physical representation*". In our model, following Ref. [21], this representation is defined from the references provided in P. 1 and P. 2. The temporal interval ΔT (max rate of change in the *causal time*) and the imaginary distance $ic\Delta T$ (max rate of change in the *imaginary space*) will be the basis for the definition of a spacetime information, discrete in both space and time. These references 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 protocol.

The Perspective of a Particle after N Instants

We are interested in the perspective on the universe of an elementary observer in the Present, after an evolution from a more distant past than T_{k-1}. This perspective is intended as the evolution of the CoM, in terms of paths in the lattice (with potential imaginary steps) and experienced causal changes in the surrounding universe.

We assume a small number of instants N such that no events occur to the particle in this time interval. This will allow a description of a relativistic evolution of the observer a priori of its collapse events. As shown in the experiments on the Quantum Zeno Effect reported in Ref. [34], a continuous collapse seems to "freeze" a particle temporal evolution.

From the previous deductions, given a particle at position X_{k-N} at an instant T_{k-N} (occurring N universe ticks before the present instant T_k), we can identify 3 possible scenarios. Given a fraction of N, defined as βN, with $\beta \in [0,1]$, we consider:

1. The CoM could move N times over the N universe ticks, with $\beta = 1$
2. The CoM could move $n = \beta N$ times over the N universe ticks, with $0 < \beta < 1$
3. The CoM could move 0 times over the N universe ticks, with $\beta = 0$

Scenario 1 represents a particle constantly moving in every instant. This kind of particle cannot be considered properly an "observer", but a limit case. In the last chapter we will see how only massless particles moves in the lattice constantly.

Scenario 2 represents a particle moving in the space lattice with an average translation of its CoM in the imaginary space equal to $iv_s = ic\beta$, as its CoM moved by an imaginary spatial distance of $ic\beta N\Delta T$ in a time interval of duration $N\Delta T$. We refer to this kind of particle as "body". Bodies are the only proper observers of the universe. This scenario will be detailed in the chapter focused on SR, after having clarified the extreme cases.

Scenario 3 is even more subtle. We can suppose that the origin of every particle in the universe occurred with some initial kinetic energy. This is also in line with the idea that, even if in a discrete evolution we can consider a resting condition in a given instant, there is no possibility for observers to be in such conditions for long. Quantum fluctuations as well as other incoming particles will eventually imprint some kinetic energy to any elementary observer.

Even if not an observer, we can consider each atom of the space lattice as at rest in the thermal bath in respect to the surrounding ones. The evolution of the information in every atom of space, synched in every instant, marks the temporal evolution of the universe itself.

Given a small number of instants N, such that no events occur to the particle in this time interval, we can consider a particle at rest in all the N ticks of the universe. Which could be its description of the surrounding universe as an observer of spacetime information in these instants?

The particle potentially at rest for N instants will receive, synched in each instant, incoming information from all possible directions, from events happened in the past cycles of the universe. We consider this experience of the events in the causal set as a "sampling" in the Present of information in the causal time, in which those events happened.

We note that the proposed information sampling is not intended as a measurement nor assumes the ability of observers to encode the past instants. The only past information we consider available at the present instant is the one at the past boundary of the Present, from which the Present is defined by difference.

We assume that, in the sampling of causal information from incoming causal stimuli, an observer could "count" the universe *ticks,* as causal changes from the previous instant. In this experience of the surrounding evolution along the cycles of the Present, the observer can symmetrically "count" its proper ticks and, in a coherent way, causally evolve.

We note that, given that there can be no observers (bodies) deterministically at rest in respect to the surrounding thermal bath and that could serve as "absolute clocks" to measure the whole set of universe ticks, then it is only possible to measure a "relative rest" in respect to other observers and clocks. Similarly, no observers are always moving. Observers can only verify proper relativistic measures of time intervals and relational distances, in terms of incoming stimuli, comparing their proper counting of universe ticks. Still, time dilations in respect to the universe ticking are expected even without events or other clocks or observers to confront with.

If D. 6, then the experience of a causal time (as changes as our universe ticks) can be counted in proper ticks through the sampling of incoming causal stimuli D. 8

If D. 6 and D. 8, then an observer at rest in respect to its position at X_{k-N} samples at T_k all incoming causal stimuli and should count N proper ticks of causal evolution D. 9

Even If D. 9, there are no observers (bodies) at rest or moving in every instant D. 10

We would like to better quantify the causal information sampled by the observer at the Present after N ticks at rest. We consider no requirements on any memory of the past beyond the previous instant from which an elementary observer compare the differences, and in these differences consider information in the causality of events and counts its ticks.

After N ticks of the universe at the position X_{k-N}, an observer at rest should have a perfect description of the surrounding space at a causal distance $-cN\Delta T$ at the instant T_{k-N}. This information, with no additional postulates on the ability of the observer (such as an elementary particle) to encode the information of the past beyond the difference from the Present, seems the max information available in the causal time at the present instant.

More specifically, the information in the causal time sampled at the present instant from the perspective of the static observer seems equivalent to the causal stimuli that were, at the instant T_{k-N}, at a causal distance $-cN\Delta T$ from the CoM at X_{k-N}, and directed towards the CoM from all directions defined by the 2 degrees of freedom $\theta_{1,2}$. It seems logic to consider the causal information that an observer not moving from the position X_{k-N} samples at the present instant T_k (after N universe ticks) to be proportional to the sphere from X_k of radius $cN\Delta T$ in the causal time. In this sense, the information sampled in the causality of events seems holographic.

If D. 6, then an observer at rest in respect to its position X_{k-N} samples at T_k an information defined on a causal sphere of radius $cN\Delta T$ from X_{k-N} D. 11

We will now consider Scenario 1. A particle moving for the last *N* ticks of the universe till the Present is, at the present instant T_k, at a position defined as $X_k = (X + icN\Delta T, \theta_{1,2})_k$ (with 2 degrees of freedom $\theta_{1,2}$) from X_{k-N} or, shortly, $(X + icN\Delta T, \theta_{1,2})_k \stackrel{\text{def}}{=} (X + N)_k$.

This possible position is defined as a set of atoms of space at distance $icN\Delta T$ from X_k at the instant T_k, namely the set of atoms $\{iN, \theta_{1,2}\}_{X,k}$. The set of possible positions in the space lattice defined by $\{iN, \theta_{1,2}\}_{X,k}$ represents the thick surface of a sphere of radius $icN\Delta T$ from X_k at T_k, being X_k the same spatial position X_{k-N} after *N* instants (defined from *N* iterations of D. 6). This spatial surface is as thick as 1 atom of space.

This extended imaginary movement, as in the single instant case, is not intended as a collapse event but as a potential extension of imaginary paths from the initial position at X_{k-N} to a final position at $(X + N)_k$. Events, when occur, actualize just a single path of the several possible ones, in an actual quantum tunneling event in an instant to a specific atom of space of the sphere $(X + N)_k$. As the instant passes, this irreversible discontinuity in the CoM location between successive instants, defines a causal spacetime element in the causal set of events ordered along the causal time, from which consequences will propagate.

The imaginary paths of the CoM from X_{k-N} are proposed as a "sampling" of the information in the space lattice from the perspective of the particle. The set of atoms of space identified by the sphere $(X + N)_k$ defines, in our interpretation of movement, the spacetime information "sampled" in the imaginary time of motion by a particle always extending its imaginary paths for *N* instants from its position X_{k-N} at T_{k-N} (*e.g.* emission).

The sphere $(X + N)_k$ represents the evolution of the particle along the universe ticks as paths of *N* imaginary steps with a spherical symmetry. The information sampled in the lattice is considered the spatial position "at the tip" of the oriented imaginary paths. These paths, as tunnels of increasing potential, represent the possible positions reached in the Present with a tunneling event at T_k (which would still respect causality, given that the maximum extension of these paths/tunnels in *N* instants is limited by $icN\Delta T$).

The connection of non-locality in the space foliation with the quantum information encoded in the Present has been elaborated in Ref. [19], [20] and [21]. In these models, as in our description of space from an imaginary discrete time, non-locality is fundamental. It is intended as a tunneling potential between atoms of space, in a path integral that evolves in the imaginary time of motion as the universe ticks. These models promote a holographic interpretation of non-locality, considered equivalent to entanglement between atoms of space, as per the famous conceptual equation *ER=EPR* of Ref. [35] and [36].

If D. 6, then an observer always extending its paths in respect to its position at X_{k-N} samples at T_k an info defined on an imaginary sphere of radius $icN\Delta T$ from X_k D. 12

If only the Present exists, it seems that spacetime information after *N* universe ticks (defined as the information of the imaginary positions that can be reached with possible tunnels or of which we can causally know when we stand still) is finite and proportional to the surface of a sphere of radius *N*, in a holographic saturation of the Bekenstein bound.

We summarize with the following deduction.

If D. 6 – D. 12, then spacetime information in the causal time and the imaginary space in N instants seems holographic (proportional to the surface of a sphere of radius N)*
**defined through incoming causal stimuli (carrying info from the causal time) or imaginary paths from the CoM (possible quantum tunnels in the space lattice)* D. 13

Postulate 3 – Information

Inspired by Presentism, we have proposed a discretization of spacetime considering a space lattice evolving in atomic instants. We have then deduced that an observer, such as an elementary particle, could only "count the differences" encountered along its evolution, through incoming causal stimuli synched in the bath of each instant or potential imaginary explorations of other new atoms of space.

We have described the perspective of an elementary particle on the causal evolution of the universe and of itself in terms of "information sampling" in 2 dimensions: the causal time of events and the imaginary time of motion in the lattice.

The information of causal evolution is defined through the observation of differences in the incoming causal stimuli synched in each instant. The imaginary information is defined through the possible locations that the particle might reach in a tunneling event.

We have evaluated movement considering βN imaginary steps in the space lattice over N instants of evolution of the universe and identified 3 scenarios: extending its imaginary paths in every instant (given $\beta = 1$), or with an average speed in the lattice $i\beta c$ (given $0 < \beta < 1$), or at rest in respect to X_{k-N} (given $\beta = 0$).

In this discrete evolution, given N universe ticks, we have evaluated the information sampled in the causal time and in the imaginary space in 2 scenarios, $\beta = 1$ and $\beta = 0$, and deduced a holographic nature of this information in the 2 orthogonal dimensions. Given N universe ticks in these 2 opposite scenarios, the following table and graphical illustrations summarize our description of "information sampling" in:

- the imaginary space, as a set of possible imaginary positions after the N ticks of the universe (defined through a relational number of imaginary steps)
- the causality of events (through incoming causal stimuli, as photons), with a consequent number of proper ticks counted over the N of the universe.

Variables and Symbols		**Case $\beta = 0$**	**Case $\beta = 1$**
imaginary space information	$\varsigma_{i,N}$	-	$4\pi\|icN\Delta T\|^2$
imaginary steps counted	n	-	$n = N$
paths length (relational distance)	$i\Delta s_p = icn\Delta T$	-	$i\Delta s_p = icN\Delta T$
causal time information	$\varsigma_{c,N}$	$4\pi\|cN\Delta T\|^2$	-
proper ticks counted	m	$m = N$	-
proper causal evolution (proper time)	$\Delta t_p = m\Delta T$	$\Delta t_p = N\Delta T$	-

Table 1. Information sampled, imaginary steps and proper ticks counted in N ticks of the universe from an elementary observer, in the limit case of always at rest ($\beta = 0$) or always moving ($\beta = 1$).

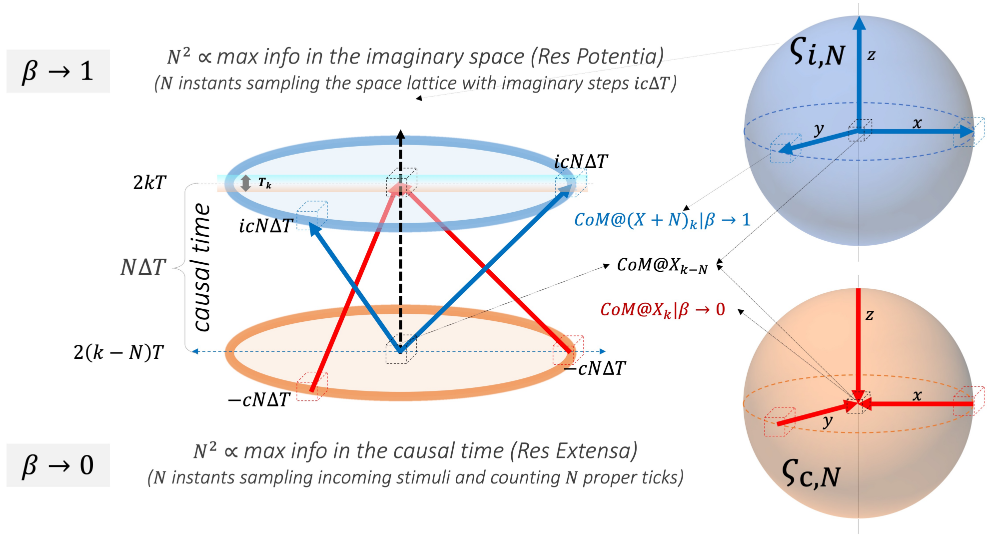

Figure 4. Information in the Present from the perspective of an elementary observer at atom X_{k-N}, N ticks ago. the dimensions $\{in, \theta_1\}_{X,k}$ are represented, with k marking the causal *ticks* on the vertical axis and $\{in, \theta_1\}_X$ as a plane. On the right, the space lattice $\{in, \theta_{1,2}\}_X$ is presented, with k implicit and the boundary of information available highlighted. The *blue* figures represent the imaginary info explored after N ticks when always moving, as a relational position at a new location, N imaginary steps away from X_k. The *red* figures represent the causal info collected at the atom X after N ticks by an observer at rest for all N ticks.

Being $\varsigma_{c,N} = 4\pi|cm\Delta T|^2$ the causal time information sampled by an observer in N instants, and $\varsigma_{i,N} = 4\pi|icn\Delta T|^2$ the imaginary space information sampled in the same N instants (with $n = \beta N$), we define the total spacetime information as $\varsigma_{e,N} = \varsigma_{c,N} + \varsigma_{i,N}$. Among the several possible combinations that Table 1 could inspire, it is tempting to consider the following deduction and equation.

If D. 13, then the total spacetime information in N instants $\varsigma_{e,N}$ is holographic D. 14

$$\varsigma_{e,N} = \varsigma_{c,N} + \varsigma_{i,N} = 4\pi|cm\Delta T|^2 + 4\pi|icn\Delta T|^2 = 4\pi|cN\Delta T|^2 \tag{1}$$

The finiteness of information density in spacetime is supported by the Bekenstein's bound introduced in Ref. [22]. Moreover, the holographic nature of information has been discussed in several models, inspired by the research of Hawking, Susskind, Maldacena (as in Ref. [26], [27], [35] and [36]), and many others.

In an interpretation inspired by Presentism, the holographic nature of spacetime information can be intended in the fact that, in a given instant ΔT, only a boundary with a thickness of 1 atom of space is available as a possible information that can be "sampled", in the causal time (*what was happening N instants ago at N steps away from here?*) or in the imaginary space (*what would happen if I tunnel N steps away from here given N instants?*).

In the QM description of the Present proposed in Ref. [20] and [21], this information (derived from non-locality and entanglement in the lattice) is encoded in the thickness of each instant. This encoding focuses on the differences between a perspective at *null* distance (from the past boundary of the Present) and at *infinity* in the lattice (just beyond the current state, from the future boundary of the Present, and not a physical infinity).

Even if a holographic interpretation of the total spacetime information is encouraged by several arguments, in the description of spacetime proposed in this contribution we do not want to consider D. 14 as a deduction supported by a sufficient elaboration. We suggest a new postulate and consider it to be an assumption of our framework.

The total spacetime information $\varsigma_{e,N}$ sampled at T_k from T_{k-N} is holographic P. 3

$$\varsigma_{e,N} = \varsigma_{c,N} + \varsigma_{i,N} = 4\pi|cN\Delta T|^2$$

Relativity and Probability

The Relativity of Information Sampling

We have described a discrete space evolving in atomic instants and connected the perspective of an elementary observer on time intervals and movement with the sampling of causal stimuli from the past or potential imaginary steps in the space lattice. We have then postulated a holographic nature of the total information that can be sampled by an observer in N instants. In the coming chapters, we will derive the phenomenology of SR in the introduced framework and propose an extension of the same concepts towards a quantum description of spacetime.

We consider, from Eq. (1), the case with $0 < \beta < 1$. A particle that, over N universe ticks, allocates $n = \beta N$ ticks to explore the space lattice with imaginary steps, covers an imaginary distance of $i\Delta s_p = ic\beta N\Delta T$, with an average speed equal to $i\beta c$. From Eq. (1), the imaginary space information sampled at T_k is then equivalent to:

$$\varsigma_{i,N} = 4\pi|icn\Delta T|^2 = 4\pi|ic\beta N\Delta T|^2 \tag{2}$$

If the total spacetime information is holographically bounded from P. 3 and Eq. (1), we can derive that the information that the particle samples at T_k in the causal time, when extending of βN steps its imaginary paths in respect to X_{k-N}, is equivalent to:

$$\varsigma_{c,N} = 4\pi|cm\Delta T|^2 = \varsigma_{e,N} - \varsigma_{i,N} = (1-\beta^2)4\pi|cN\Delta T|^2 = (1-\beta^2)\varsigma_{e,N} = (m/N)^2\varsigma_{e,N} \tag{3}$$

Given Eq. (3), the proper time Δt_p and the proper ticks m counted can be calculated as:

$$(T_k - T_{k-N})_p = \Delta t_p = m\Delta T = \left(\sqrt{1-\beta^2}N\right)\Delta T \tag{4}$$

If P. 3 and Eq.(4), then an observer extending its imaginary paths of βN steps in N universe ticks counts a proper number of ticks $m = \sqrt{1-\beta^2}N$ D. 15

In our discrete interpretation of evolution, time dilations can be intended as a statistical effect from the integration of a reduced sphere of incoming causal stimuli, since part of the total spacetime information is sampled in the imaginary space with an extension of the imaginary paths. The proper time is the fraction of the interval of universe's causal time of which the observer becomes aware, having sampled a reduced percentage of the causal information.

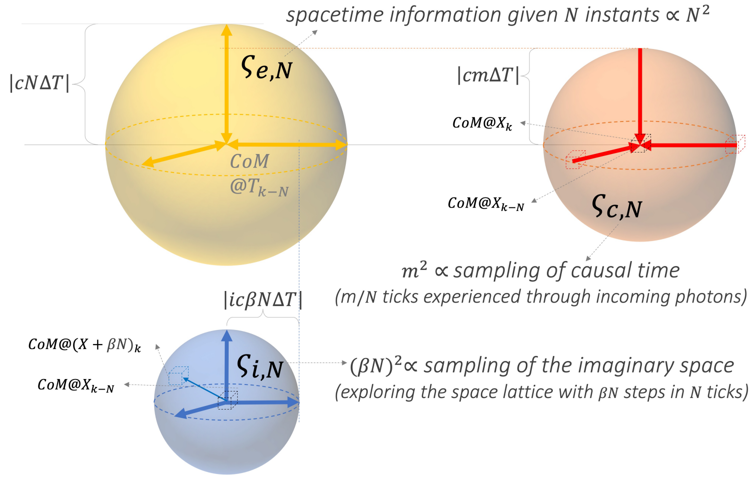

Figure 5. Spacetime information sampled after N universe *ticks* by a particle extending its imaginary paths from X_{k-N} of βN steps. The info sampled is shown as spheres centered at the atom X at the instant *k-N*. We show the total (*yellow*), the causal (*red*) and the imaginary (*blu*) info sampled.

In the experience of the causal evolution of the surrounding universe, the observer coherently evolves in time. Between an event of emission and an event of decay, no events need to happen to the observer to be aware of the surrounding causal evolution in the succession of the universe ticks, and consequently experience a proper causal evolution.

From Equation (4) and D. 10 (*no absolute observers/clocks*) we can also deduce that there is no "common now" nor absolute simultaneity for observers. We can define only a proper local now, and an extended proper present, connected to a proper number of sampled ticks. There is only a "local now" for observers of this discrete universe.

If D. 10 and Eq.(4), then there is no "common now" for observers but just a "local now" and a relativistic simultaneity that depends on the proper sampling of causal stimuli D. 16

We have shown how the concept of an atom of time may open the door to information as a universal language, useful also in the interpretation of observed spacetime differences. A model of the universe based on a discrete space evolving in atomic instants is naturally connected to Information Theory and to the study of continuous-discrete signals.

We remind that the information in a continuous signal with a limited bandwidth is equivalent to the info contained in its discrete samples. Thanks to the *Nyquist–Shannon sampling theorem* and D. 1 (*bandwidth* $1/\Delta T$), given D. 15, we can experience a continuous manifold from just discrete samples of information: imaginary steps in a lattice or incoming stimuli from the surrounding universe, to count proper ticks and consequently evolve.

Time Dilations and Lenghts Contraction

According to SR, an observer such as a clock with an internal period Δt_0 when at rest, has a period of evolution $\Delta t_s > \Delta t_0$ when moving at a speed iv_s 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_s "stretched proper periods" of duration Δt_s when part of the spacetime momentum is allocated to imaginary steps. Mathematically, we can express this relation as: $N_s\Delta t_s = N_0\Delta t_0$, with $N_0 > N_s$.

In a universe existing in present instants only, an increased probability of tunneling in space is balanced by a reduced sampling of information in the causal time. This leads to a reduced info from the causal stimuli, and a reduced proper rate of change. The dilated period Δt_s (slower frequency) is related to a statistically smaller number of universe *ticks* counted over the ones actually passing in the universe.

If a full cycle at rest needs N universe ticks ($\Delta t_0 = N\Delta T$) then, from Eq. (4), in the same N ticks, the moving clock has only sampled $m = \sqrt{1-\beta^2}N$ ticks. To complete its cycle, the moving clock needs N proper ticks, and this happens only after $N/\sqrt{1-\beta^2}$ universe ticks. The extended or "dilated period" Δt_s is then equal to (in universe ticks, times ΔT):

$$\Delta t_s = \frac{N}{\sqrt{1-\beta^2}}\Delta T = \frac{\Delta t_0}{\sqrt{1-\beta^2}} = \frac{N}{m}\Delta t_0 \tag{5}$$

From Equation (4) we can also consider the phenomenology of lengths contraction in a moving condition. We note that the stationary observer measures the length of an external object (intended as the distance between 2 different locations) through all incoming causal stimuli (*e.g.* photons) along its evolution, while an observer extending its imaginary paths in the lattice samples only a portion of them.

The observer not at rest measures a reduced length as it statistically samples fewer incoming photons. When measuring the length of an external object through incoming photons, the observer not at rest will only sample a portion in comparison to the stationary scenario, in a relativistic contraction of the measured length proportional to the proper time. Given Δx_0 as the length measured in the rest frame, the length measured in the moving frame is, from Equation (4), statistically equal to:

$$\Delta x_s = \sqrt{1-\beta^2}\Delta x_0 \tag{6}$$

In this contracted perspective on spatial distances, we can also verify that an observer in a ship at constant speed will measure the light bouncing between 2 mirrors (2-way trip, also known as round-trip) at a speed equal to the one observed when at rest, as per SR2.

Being $\Delta x_0 = cN\Delta T$ the 2-way distance between the mirrors measured in the rest frame, the same distance measured while moving is, from Eq. (6), equal to $\Delta x_s = c\sqrt{1-\beta^2}N\Delta T$. The proper time measured will be, from Eq. (4), equal to $\Delta t_p = \sqrt{1-\beta^2}N\Delta T$.

The measured 2-way speed of light in the moving frame, as the one in the rest frame, will then be:

$$\frac{\Delta x_s}{\Delta t_p} = \frac{c\sqrt{1-\beta^2}N\Delta T}{\sqrt{1-\beta^2}N\Delta T} = \frac{cN\Delta T}{N\Delta T} = \frac{\Delta x_0}{\Delta t_0} = c \tag{7}$$

Given that we have posed no condition on this measurement across different spatial locations or instants in time, nor on β, we can deduce that this relativistic phenomenology is invariant and expected in every inertial frame of reference (SR1 and SR2).

If D. 15, Eq. (4), (6), and (7) then every spacetime location and frame of reference is equivalent (alike SR1) D. 17

If D. 17 and Eq. (7), then every inertial observer measures the same 2-way speed of light, independently of movement (alike SR2) D. 18

In the next chapters, we will elaborate on the possible connection between a relativistic perspective and a quantum description of a discrete evolution in spacetime.

Momenta in Space and Time

We would like to elaborate on an interpretation of the same phenomena from a different perspective: the probability of evolution in spacetime. From the information sampled in the Present after N instants (in the causal time and the imaginary time of motion) we define 2 probabilities of evolution:

- $\wp_e^S = \varsigma_{i,N}/\varsigma_{e,N}$ is the probability of evolution in the imaginary space
- $\wp_e^T = \varsigma_{c,N}/\varsigma_{e,N}$ is the probability of evolution in the causal time

We note that these probabilities can be seen as characteristic of the observer in a single instant as well (case *N=1*). We consider the total probability of evolution in spacetime, defined as $\wp_e^{ST} = \wp_e^S + \wp_e^T$, and express Equation (1) through the new variables:

$$\frac{\varsigma_{i,N}}{\varsigma_{e,N}} + \frac{\varsigma_{c,N}}{\varsigma_{e,N}} = \wp_e^S + \wp_e^T = \wp_e^{ST} = 1 \tag{8}$$

From this perspective, the third postulate can be intended as a *principle of invariance* from 2 perspectives: the *invariance of total spacetime information* $\varsigma_{e,N}$ (sampled by any elementary observer given N instants) and the *invariance of the total probability of evolution* in spacetime $\wp_e^{ST}$ (defined from the probabilities of evolving in the imaginary space and the causal time). This last interpretation of the third postulate suggests that, in a universe defined from the differences between the present and the past instant, every observer is always evolving in space or in time, independently of events.

The same mathematical description can be understood in terms of a famous quote from Heraclit: "*No man ever steps in the same river twice, for it's not the same river and he's not the same man*" (we are never twice in the same instant along the flow of the universe ticks) or, with more ancient words, πάντα ῥεῖ (panta rei), *everything flows*.

If P. 3 and Eq.(8), then the total probability of evolution in spacetime is unitary or, equivalently, everything changes in the Present (πάντα ῥεῖ) D. 19

We will now connect this probability to a momentum in spacetime, as a possible step towards a quantum formalism for a relativistic evolution in the Present.

Given an observer of total energy E that extends its imaginary paths of βN steps per N universe ticks in an undefined constant direction from X_{k-N}, we consider $\beta = \sin(\tau_s)$, with $0 \leq \tau_s \leq \pi/2$. We define a *spacetime momentum* $p_{ST} = |p_T + ip_S|e^{i\tau_s}$ from its temporal and spatial components: the *momentum in space* ip_S and the *momentum in time* p_T. Their amplitude can be calculated from the energy E as in the following equations.

$$\begin{cases} |p_S| = |E/c|\sin(\tau_s) = |p_{ST}|\beta \\ |p_T| = |E/c|\cos(\tau_s) = |p_{ST}|\sqrt{1-\beta^2} \end{cases} \tag{9}$$

The spacetime momentum is connected to the energy of the particle E as in:

$$E^2 = |p_{ST}c|^2 = |p_T c|^2 + |ip_S c|^2 = (p_{ST}p_{ST}^*)c^2 \tag{10}$$

If we consider the component p_S in a 3D imaginary space defined by 3 orthogonal imaginary vectors from the CoM, the momentum in time p_T (connected to the persisting information of the particle in the Present, as in Ref. [21]) develops on the real axis, parallel to the causal time and orthogonal to the imaginary spatial dimensions, as in quaternions.

These momenta can be related to the amount of energy allocated to the sampling of information in the imaginary space and in the causal time. They are proposed as the basis of an observer's perspective in the counting of *ticks* and *steps* in its evolution in spacetime.

More specifically, we can express the variables defined in Equation (1) and (8) through the components of the spacetime momentum defined in Equation (9), and consider:

$$\begin{cases} \dfrac{|p_S|}{|p_{ST}|} = \sin(\tau_s) = \beta = \dfrac{n\ imaginary\ steps}{N\ universe\ ticks} \\ \dfrac{|p_T|}{|p_{ST}|} = \cos(\tau_s) = \dfrac{m\ proper\ ticks}{N\ universe\ ticks} \end{cases} \tag{11}$$

$$\frac{|p_S|^2}{|p_{ST}|^2} + \frac{|p_T|^2}{|p_{ST}|^2} = \frac{\varsigma_{i,N}}{\varsigma_{e,N}} + \frac{\varsigma_{c,N}}{\varsigma_{e,N}} = \wp_e^S + \wp_e^T = 1 \tag{12}$$

If P. 3 and Eq.(12), then the probability of evolution in space and time depends on the momentum allocated in these 2 orthogonal dimensions D. 20

We note that, we can define the rest mass m_T as connected to the amount of energy at rest in respect to the incoming causal information. In Ref. [21], we have proposed a connection between the rest mass and the non-local information potential encoded in the wave-function. We have described an elementary particle from a bundle of "*atoms of space entangled on a common momentum in time*". Here, with Eq. (1), (9) - (12), we can also describe the rest mass of a body as at the root of the component of the momentum of the particle at rest in the Present in respect to the previous instants.

$$(m_T c)^2 = (E/c)^2 \frac{\varsigma_{c,N}}{\varsigma_{e,N}} = (E/c)^2 \wp_E^T = (E/c)^2 \frac{|p_T|^2}{|p_{ST}|^2} = {p_T}^2 \tag{13}$$

From Equation (13), we can verify that an elementary particle moving in every instant, having zero causal information sampled per Eq. (3), has zero mass at rest and vice versa. For a massive observer of rest mass m_T, defined the relativistic mass $m_E = m_T/\sqrt{1-\beta^2}$, we can also verify that $E = m_E c^2$. More formally:

$$\begin{cases} p_T = m_T c \\ ip_S = im_E \beta c = ip_T \tan(\tau_s) \end{cases} \tag{14}$$

We synthetize our deductions on the rest mass with:

If P. 3 and Eq.(13), then the rest mass is connected to a momentum in time and the energy at rest in respect to the surrounding incoming causal stimuli D. 21

Superposition of Relativistic Amplitudes

We have investigated the evolution of an observer along the ticks of the universe and derived a relativistic perspective on the experienced time intervals. In this chapter, we would like to elaborate on a possible description of the same concepts through a formalism similar to the one used in QM. This will allow us to suggest, as a possible next step, a quantum description of GR phenomenology, to be developed in future contributions.

In each present instant, we are interested in the evolution of the position of the CoM of a particle in the space lattice (as a *tunneling potential*) and its proper causal evolution (intended as an *internal aging* from the experience of the surrounding causal evolution). These alternatives will be intended as connected to possible quantum states.

We consider 2 *states of evolution* in the Present. They represent the evolution of the particle along the causal time and the orthogonal imaginary time of motion:

- $|\circlearrowleft_e\rangle$ is a state of evolution associated to the internal clock counting +1 tick in the proper causal evolution (sampling the surrounding causal stimuli)
- $|\rightsquigarrow_e\rangle$ is a state of evolution associated to the paths from the CoM extending of +1 step in the relational imaginary time of motion (sampling the space lattice in an undefined direction $\theta_{1,2}$ given the absence of further spatial references)

From this orthogonal basis and the spacetime momentum introduced, we consider a quantum state $|e_{ST}\rangle$ defined at a given instant as:

$$|e_{ST}\rangle = \alpha|\circlearrowleft_e\rangle + \beta|\rightsquigarrow_e\rangle = |p_{ST}\rangle/|p_{ST}| \tag{15}$$

The state $|p_{ST}\rangle$ is intended as a column vector with p_T and ip_S as orthogonal components of a possible Hilbert space of spacetime momenta, connected to the energy of the particle. We suggest an interpretation of Equation (15) considering:

- α as a *causal window amplitude* on the surrounding causal changes (connected to the "window of opportunity" to experience changes in the surrounding universe through the sampling of incoming stimuli in the causal time)
- β as an *imaginary paths amplitude* in the surrounding space (connected to the extension of the quantum tunneling potential from the CoM to other possible positions, in a relational imaginary sampling of atoms in the space lattice)

It is also straightforward to verify that, from Eq. (8) and (15), we can write:

$$\begin{cases} \wp_e^T = |\langle\circlearrowleft_e|e_{ST}\rangle|^2 = \alpha^2 \\ \wp_e^S = |\langle\rightsquigarrow_e|e_{ST}\rangle|^2 = \beta^2 \end{cases} \tag{16}$$

This "quantum description" of the probability of evolution suggests a holographic interpretation of the *Born rule* as well. Born's "probability amplitudes" can be intended as "normalized distances" in a space of imaginary possibilities from a barycentric perspective. The sum of the amplitudes squared, connected by Born to probabilities, can be described, according to our model, as the sum of "normalized surfaces", saturated on a unitary total probability, equivalent to a normalized maximum information.

We note that the normalization factor in our model of spacetime is the maximum surface derived from the total number of universe ticks considered, as a limit on the max information that can be encoded in a given number of instants.

If Eq.(8) and (16), then the Born rule can be interpreted as the sum of normalized surfaces of information in the Present (holographic perspective) D. 22

Clarifications on the Emergence of Spacetime

Thanks to an interpretation of spacetime inspired by Presentism, we have proposed a description of the same phenomenology of SR starting from different postulates, focused on absolute references for a temporal and a spatial evolution. The quantum formalism introduced describes evolution in terms of amplitudes from the normalized components of the momentum in spacetime, relationally defined in respect to the previous instants. Even if it might seem that we have not achieved much beyond a change of variables, our framework offers a very different perspective on the fundamental aspects of our universe.

In the last chapter, as possible next steps to be further investigated, we will evaluate an extension of the framework towards GR and propose some additional deductions on why Presentism is not only compatible with SR, but it should also be considered the most efficient way to represent the same phenomenology. Before these last steps, we would like to summarize the emergence of spacetime from the perspective of an evolving particle.

An elementary particle, from its last event, is at the present instant in a superposition. In each instant with no events of collapse it evolves outside the classical spacetime of the *Res Extensa*. As also proposed in Ref. [21], the particle exists in superposition as a wave of imaginary locations in the Present. It is a non-local information potential encoded in the thickness of the Present, intended as a *Res Potentia* in an ontological quantum memory.

When a collapse of the imaginary paths occurs, at a specific present instant, the particle tunnels from its last event position to the new specific atom of space, in an event. At the next instant, a new spacetime point is left behind the past boundary of the Present, as a discontinuity between the boundary of 2 instants. From this discontinuity, a cone of consequences causally propagates in all directions of space in the coming universe ticks.

The particle then, from a CoM in space causally updated at the new location, continues its evolution, evolving as the universe evolves, sampling in superposition causal and imaginary information, according to the momentum and amplitude in these 2 orthogonal dimensions. In every instant, from a proper counting of *ticks* and from the information of distances collected through incoming stimuli, the causal set in the *Res Extensa* behind the Present appears to the elementary observer as a relational and relativistic manifold.

From a globally consistent causal structure of irreversible spacetime points (events), different observers read different stories, with a proper order of events that depends on their relative probability of exploring space with imaginary steps or sampling stimuli in the causality of events. Relative is the dimension in which we allocate our momentum, as counted *ticks* or imaginary *steps* in the surrounding universe.

We hope it could be now easier to picture, from the proposed sampling of information and probabilities of evolution, a spacetime manifold with signature $(+,-,-,-)$ emerging as a proper relativistic reading of the surrounding universe in the Present.

In synthesis, we believe that spacetime emerges from the consequences of irreversible events (*Res Extensa*) experienced through a causal window amplitude in each instant, but it does not exist, and so it is irreversible. Events' consequences surround the observer as incoming stimuli in each instant and are collected with a relativistic perspective that depends on the evolution of the causal window and the sampling of causal info.

During the same instants, in a superposition of evolutions, the observer explores the surrounding lattice with imaginary steps, in paths of growing amplitude. In each present instant, the whole space of imaginary locations (that could be reached as the universe ticks) growths as a surface of quantum information. The maximum information that an observer can experience in N universe ticks holographically bounds both the understanding of the past *Res Extensa* and the exploration of the present *Res Potentia*.

Possible Next Steps

Towards a Framework for Gravity

In every deduction proposed so far, we have considered a flat space, in line with the phenomenology described by SR. The description of the quantum nature of spacetime should also consider a possible curvature in each atom of space. What can the introduced model suggest on such scenario? We will dare to propose some further speculations, to be elaborated in a dedicated contribution.

We have based most of our deductions (in terms of spatial and temporal evolution) on the spherical symmetry of the incoming causal stimuli, synched in thermal bath in each instant around every atom of space. In the thermal bath of the Present, each atom of space X_k can be pictured as a *virtual atomic sphere* at relative rest in respect to the surrounding ones, as in the description of the gravitational vacuum introduced in Ref. [21], or as in the "*sea of virtual Plank-mass black holes*" proposed by Hawing in Ref. [26].

We suggest connecting curvature to a possible breaking of this spherical symmetry in the Present, in a sort of local bias and "lensing of information" at an atom of space X_k. This "distortion" can be seen as both a local asymmetric tunneling probability (non-hermicity towards an imaginary direction in the lattice), as well as a "filtering" of the incoming causal information (a reduction of the causal window amplitude at X_k).

The connection between asymmetric tunneling probability in a lattice, non-hermicity, and curvature has been suggested in Ref. [21], in accordance with the derivation proposed in Ref. [37] and [38]. Here we will not propose a mathematical derivation of GR but simply suggest a possible connection between gravity and our probabilistic framework.

In our discrete model, we suggest connecting the escape velocity $iv_g = i\beta_g c$ at an atom of space X_k to an increased tunneling probability towards the source of gravitational potential. We can then express gravitational time dilations with a formalism similar to the one proposed for SR. We define the gravitational state $|X_{g,k}\rangle$ of an atom of space, connected to the local gravitational information, through the orthonormal basis $|\circlearrowleft_g\rangle$ and $|\rightsquigarrow_g\rangle$:

$$|X_{g,k}\rangle = \alpha_{g,k}|\circlearrowleft_g\rangle + \beta_{g,k}|\rightsquigarrow_g\rangle \quad (17)$$

In this formalism, a flat atom of space would be characterized by a gravitational state $|X_{g,k}\rangle \rightarrow |\circlearrowleft_g\rangle$ and, on the opposite side of the spectrum, an atom of space at the horizon of a black hole would be described as $|X_{g,k}\rangle \rightarrow |\rightsquigarrow_g\rangle$ towards the direction of the singularity.

Equation (17) is not providing an interpretation of the quantum nature of spacetime, but simply a representation of the local gravitational lensing being at a specific location in the lattice (intended as a biased probability of sampling information in the imaginary space rather than in the causal time, in respect to a flat scenario).

In Ref. [21], we have proposed a possible physical interpretation of this phenomenon. We have described the thickness of the Present as a quantum memory (bulk) encoding the persisting information potential (momenta) and suggested a possible connection between gravitational time dilations and a locally reduced causal window amplitude, being part of the Present *window* (memory) already allocated to the gravitational info of a nearby mass.

We have already proposed several preposterous perspectives on spacetime and will not speculate further on its possible quantum nature. We hope to leave the curious reader with the present of a doubt, given an atom of time. In the final chapter, in a last attempt to suggest a change of paradigm, we will discuss why we believe Presentism is not only a possible model of a discrete spacetime, but also the best candidate.

Towards a Derivation of Presentism

It is our belief that the concept of a discrete evolution, even if assumed in instants just "locally synchronous", when considered together with a global speed of causality from postulate P. 2, implies a synchronous evolution of the whole space.

If this were not the case, we would have several "space bubbles" of synchronous atomic evolution, with discontinuities on their boundaries. Independent spheres of causal information from events happened in different bubbles might lose their global coherence in these discontinuities, and the universe would appear as disconnected or with "glitches".

It seems reasonable to consider as well that, even if there were several bubbles with different proper synchronization, over time eventually the universe would have probably converged to a synchronous state, as synchronicity usually leads to lower energy states. We can then evaluate a less absolute version of P. 1, namely P. 1′, and from P. 1′ and P. 2 consider a new more fundamental deduction D. 0.

Evolution locally occurs in atomic instant of duration ΔT
(time is discrete) P. 1′

If P. 1′ and P. 2, then evolution should be synchronous in the whole space
in an unbroken wholeness of the entire universe D. 0

If postulate P. 1′ implies a discrete local evolution, and a global synchronicity is suggested in D. 0 by P. 1′ and P. 2, then an Occam's razor would suggest as well to consider the minimum information required to describe the same phenomenology.

If the experience of a relativistic spacetime can emerge from a single atomic instant of evolution, given as the only one ontologically existing, why should we consider the past as existing as well? Why would Nature need to "allocate resources" in the encoding and memory of this information, given that information is linked with energy, usually minimized in Nature?

We note that complex observers might retain an extended interval of causal time info (thanks to the complexity of their internal parts evolving in the lattice) and reconstruct in their extended memory a more "extended classical spacetime interval" than just the thick boundary of a sphere. However, more memory than just the Present seems not needed for a relativistic experience of spacetime.

Postulates on time or information might seem superfluous to describe the same phenomena of SR in terms of "parsimony of postulates" but allow a much greater "parsimony of information" needed to describe what seems a similar emerging universe. In our perspective, the latter parsimony should be preferred.

If D. 0 and Nature prefers minimum information, then P. 1 seems a logical deduction:
Only the Present exists as an atomic instant of evolution ΔT of the whole universe D. 0′

In synthesis, from P. 1′ (*time is discrete*) and P. 2 (*global speed of causality*), we suggest D. 0 (*synchronous evolution*). Given D. 0, then D. 0′ (*only the present exists*) seems natural. From D. 0′, we can continue with the already defined deductions: D. 1, D. 2, and so on.

Concluding, we believe that, in the Present, *"Time is there even when nobody is looking"*. It exists a priory of events, fundamentally and ontologically. An atom of time seems to us a *common beat* of the entire universe and the most fundamental abstraction on evolution and change.

These elaborations may not have provided enough evidence for a lighter version of postulate P. 1. We will leave a more detailed analysis on the matter to future contributions and consider the Present, beyond a postulate, simply a gift to evolve in each new instant. From this gift, and a global speed of causality, we have shown how it is possible to describe our universe as a *causal, relational, relativistic, and unbroken lattice evolving on a common beat*.

Synthesis

On Spacetime and Observers

We have proposed an interpretation of time and space, inspired by Presentism and Information Theory, and coherent with the phenomenology of SR. We believe it could represent a possible step towards a more complete quantum description of our universe.

More specifically, after having introduced the rich literature supporting Presentism, we have postulated the existence of 2 references: an atomic present instant, universe *tick* of a global evolution (P. 1), and an universal speed of the causal information in space (P. 2).

The Present is given as the only element of reality in an emerging axis of causal time. Its duration identifies an *events' resolution* in the causal evolution (D. 1). Being the Present the only element of reality in time, events are irreversible (D. 2) and collected in a causal set behind the past boundary of the Present. In each instant, only their consequences propagate, through their causal cones (D. 3), in a resulting thermal bath of incoming information, everywhere in space at the Present (D. 4).

From P. 1 and P. 2, space has been described through an imaginary time of motion at the speed of causality between atoms of space, in a relational lattice of possible events' location. From this mapping, we have deduced a relational and discrete space (D. 5).

We have then elaborated on the perspective of a free particle in this discrete universe. First, we have described movement as an extension of a tunneling potential along the imaginary time of motion, relationally defined in respect to the position in the previous instant and the spherical symmetry of the surrounding thermal bath of incoming causal stimuli (D. 6). Then, we have deduced a discrete movement: in each instant, either a particle relationally moves of 1 imaginary *step* in respect to the previous instant or does not move at all (D. 7). We have defined resting condition from the spherical symmetry of the causal surrounding information in the Present. This condition has been connected to a complete sampling of the incoming causal stimuli, with a complete reconstruction of the causal time and a possible deduction of the occurrence of a causal evolution in the universe.

We have then considered the evolution of a particle during the last few N instants of the universe, such that no events occur to the particle. We have suggested that the causal information from the surrounding universe can be symmetrically counted by the observer as proper ticks of causal evolution (D. 8, D. 9), and noted that observers moving or at rest in every instant, acting as absolute clocks, are impossible (D. 10). We have investigated the max info sampled in the causal time (causal consequences of events occurred in the past, showing the evolution of the surrounding universe) or in the imaginary time of motion (possible positions reached in a tunneling event). This information, after N universe ticks, saturates on the Bekenstein bound, being proportional to N^2 (D. 11, D. 12, D. 13, D. 14).

The holographic nature of spacetime information has been connected to a general invariance, valid for the total sum of samples in each instant, and it has been proposed as a new postulate (P. 3).

On Relativity and Probability

In the second main chapter, we have investigated the 2 expressions of postulate P. 3.

First, we have derived the proper time from a principle of invariance of the spacetime information in N universe instants. With Eq. (4), the proper time has been mathematically described as a statistically reduced number of universe *ticks* sampled by an observer, given that some info sampling is allocated to the lattice with imaginary steps (D. 15). In this framework, we have deduced that there is no "common now" for observers, but a relativity of simultaneity (D. 16) and, with Eq. (5), (6) and (7), we have derived time dilations and lengths contraction, the equivalence of all inertial reference frames, and the agreement on the 2-way speed of light between inertial observers (D. 17, D. 18, and SR1, SR2).

Postulate P. 3 also connects the holographic nature of the information sampling in the Present with the unitarity of evolution in spacetime. In a framework defined through the differences from the previous instant, it assures that everything changes either in the in the causal time or in the imaginary time of motion (D. 19). Moreover, through Eq. (8), P. 3 sets the basis for a quantum description of the time in the Present.

From a unitary probability of evolution, we have elaborated on an alternative description of the same phenomenology, through the concept of spacetime momenta, defined in Eq. (9) and (10). We have connected the probability of evolution in the causal time (counting proper ticks) or in the space lattice (as steps in imaginary paths, as growing tunnels to potential locations) with a momentum in time and in space (D. 20), and mathematically expressed their relation with Eq. (11) and (12).

With Eq. (13) and (14), we have proposed a definition of rest mass in respect to the surrounding causal information and connected it with the momentum in time and in space. Moreover, we have verified a null rest mass and a null experience of causal evolution for any elementary observer always moving in every instant (D. 21).

Finally, in Equation (15) and (16), we have proposed a description of the probability of evolution in spacetime, of postulate P. 3 and Equation (8), as a quantum *state of evolution*, and defined a *causal window amplitude* and an *imaginary paths amplitude*. We have concluded suggesting a holographic interpretation of the Born rule (D. 22).

On Possible Next Steps

In the last part of our contribution, we have elaborated on some possible additional next steps, to be developed in future works.

First, with Eq. (17), we have speculated on a possible gravitational state for each atom of space and connected curvature to non-hermicity. From an imaginary vector opposite to the escape velocity, this gravitational state encodes the potential at an atom of space as related to an asymmetric tunneling amplitude towards the source of attraction. In this formalism, we have suggested a connection between the increased probability of sampling information in the imaginary space with the reduction of the "available memory" in the Present (causal window amplitude) at the same location.

Finally, as a last proposed next step to be better elaborated in coming contributions, we have suggested an argument towards a derivation of P. 1 (*only the Present exists*) from a lighter version (P. 1′), that simply postulates a local atomic evolution in time. First, we have considered the need for a global synchronicity (D. 0). Then, following a "parsimony of information", we have concluded that, if an instant of time is enough to derive the emergence of a relativistic spacetime (with no information about irreversible events beyond their causal consequences at the past boundary of the Present), then we should consider that only the Present exists. Why would Nature need to invest more energy in the encoding of "more time" than just the Present? (D. 0′).

Conclusion

We have proposed a model of spacetime inspired by Presentism and based on a space lattice evolving in atomic instants. We have shown how this framework, naturally related with discrete information, is compatible with SR and gives a coherent interpretation of the same phenomenology.

The discrete evolution in time and space, the emergence of a continuous spacetime from the sampling of causal or imaginary information, and the probabilistic and holographic nature of spacetime, experienced through amplitudes of causal windows and imaginary tunnels, seem to us powerful conceptual tools to describe our universe.

Information Theory has proven once more its relevance in the description of Nature. It has allowed the coexistence between the seemingly opposite perspectives, claiming that "*only the Present exists*" and that "*the experience of the passage of a causal time is relativistic*", leading, Heraclit of Efes, Plato, and Einstein, eventually, on the same page. Moreover, with a universe tick (even if inaccessible as an absolute clock) and a relational description of space, both Newton and Leibniz could, at least somehow, be satisfied.

Concluding, we believe that the concept of a thick Present, intended as both a maximum rate of change in the causal evolution and an ontological memory encoding the information potential of an imaginary space of non-local possibilities, could be on the right path towards a deeper understanding of the quantum foundations of our universe.

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References

[1] L. Smolin, Time Reborn: From the Crisis in Physics to the Future of the Universe, 2013.

[2] L. Smolin, "The dynamics of difference," *Found Phys,* vol. 48, 2018.

[3] L. Smolin and C. Verde, "The quantum mechanics of the present," *arXiv:2104.09945v1,* 2021.

[4] N. Gisin, "Indeterminism in Physics, Classical Chaos and Bohmian Mechanics. Are Real Numbers Really Real?," *Erkenn,* 2019.

[5] N. Gisin, "Classical and intuitionistic mathematical languages shape our understanding of time in physics," *Nature Physics,* vol. 16, pp. 114-116, 2020.

[6] A. Schlatter, "On the Principle of Synchronization," *Entropy,* vol. 20, pp. 741 - doi:10.3390/e20100741, 2018.

[7] A. Schlatter, "On the Reality of Quantum Collapse and the Emergence of Space-Time," *Entropy,* no. 21, pp. 323 - doi:10.3390/e21030323, 2019.

[8] A. Schlatter, "On the Foundation of Space and Time by Quantum-Events," *Found Phys,* vol. 52, pp. 7 - doi.org/10.1007/s10701-021-00526-w, 2022.

[9] L. Hardy, "Foliable Operational Structures for General Probabilistic Theories," *arXiv:0912.4740,* 2009.

[10] G. Chiribella, G. M. D'Ariano and P. Perinotti, "Informational derivation of quantum theory," *PHYSICAL REVIEW A,* vol. 84, no. 012311, 2011.

[11] I. Lubashevsky, "Thick Presentism and Newtonian Mechanics," *arXiv:1603.01806v1,* 2018.

[12] R. Riek, "On the time continuous evolution of the universe if time is discrete and irreversible in nature," *Journal of Physics: Conf. Series,* vol. 1275, pp. 12064 - doi:10.1088/1742-6596/1275/1/012064, 2019.

[13] R. Riek, "Entropy Derived from Causality," *Entropy,* vol. 22, no. 6, pp. 647 - doi.org/10.3390/e22060647, 2020.

[14] A. Elitzur and S. Dolev, "Becoming as a Bridge between Quantum Mechanics and Relativity," in *R. Buccheri et al. (eds.); Endophysics, Time, Quantum and the Subjective*, World Scientific Publishing Co., 2005, pp. 197-201.

[15] R. E. Kastner, S. Kauffman and M. Epperson, "Taking Heisenberg's Potentia Seriously," *International Journal of Quantum Foundations,* vol. 4, no. 2, pp. 158-172, 2018.

[16] Y. Aharonov, S. Popescu and J. Tollaksen, "Each Instant of Time a New Universe," in *Struppa, D., Tollaksen, J. (eds) Quantum Theory: A Two-Time Success Story*, Milano, Springer , 2014, pp. doi.org/10.1007/978-88-470-5217-8_3.

[17] E. Cohen, M. Cortes, A. C. Elitzur and L. Smolin, "Realism and causality I: Pilot wave and retrocausal models as possible facilitators," *Phys. Rev. D,* vol. 102, no. 12, 2020.

[18] E. Cohen, M. Cortes, A. C. Elitzur and L. Smolin, "Realism and causality II: Retrocausality in energetic causal sets," *Phys. Rev. D,* vol. 102, no. 12, 2020.

[19] S. A. Kauffman, "Quantum Gravity If Non-Locality Is Fundamental," *Entropy,* vol. 24, no. 4, pp. 554 - doi.org/10.3390/e24040554, 2022.

[20] A. Capurso, "The Potential of a Thick Present through Undefined Causality and Non-Locality," *Entropy,* vol. 24, no. 3, pp. 410 - doi.org/10.3390/e24030410, 2022.

[21] A. Capurso, "The Universe as a Telecommunication Network," *presented at the Tenth International Workshop DICE2022, Castiglioncello, Italy - doi.org/10.31219/osf.io/c7bg4,* 2022.

[22] J. D. Bekenstein, "Universal upper bound on the entropy-to-energy ratio for bounded systems," *Phys. Rev. D* , vol. 23, pp. 287 - dx.doi.org/10.1103/PhysRevD.23.287, 1981.

[23] F. Del Santo and N. Gisin, "The Relativity of Indeterminacy," *Entropy,* vol. 23, no. 10, pp. 1326 - doi.org/10.3390/e23101326, 2021.

[24] T. C. N. Boekholt, S. F. Portegies Zwart and M. Valtonen, “Gargantuan chaotic gravitational three-body systems and their irreversibility to the Planck length,” *Monthly Notices of the Royal Astronomical Society,* vol. 493, no. 3, 2020.

[25] F. Del Santo and N. Gisin, "The Open Past in an Indeterministic Physics," *Found Phys,* vol. 53, no. 4, 2022.

[26] S. W. Hawking, "Quantum gravity and path integrals," *Phys. Rev. D,* vol. 18, no. 6, pp. 1747-1753 - DOI:10.1103/PhysRevD.18.1747, 1978.

[27] S. W. Hawking, The Universe in a Nutshell, Bantam Spectra, 2001.

[28] S. De Bianchi, “Eternity, Instantaneity, and Temporality: Tackling the Problem of Time in Plato’s Cosmology,” in *Time and Cosmology in Plato and the Platonic Tradition*, Brill, 2022, p. 156–178; doi.org/10.1163/9789004504691_008.

[29] C. Mariani and G. Torrengo, "The Indeterminate Present and the Open Future," *Synthese,* vol. 199, pp. 3923–3944 - doi.org/10.1007/s11229-020-02963-y, 2021.

[30] J. Tallant and D. Ingram, “The rotten core of presentism,” *Synthese,* vol. 199, pp. 3969–3991 - doi.org/10.1007/s11229-020-02965-w, 2021.

[31] A. Capurso, "Notes on a Common Beat," *OSF Preprints - doi.org/10.31219/osf.io/6agcz,* 2021.

[32] F. Giacomini, "Spacetime Quantum Reference Frames and superpositions of proper times," *Quantum 5, 508 (2021),* vol. 5, pp. 508 - doi.org/10.22331/q-2021-07-22-508, 2021.

[33] R. Landauer, "The physical nature of information," *Phys. Lett. A,* vol. 217, no. 4-5, p. 188–193, 1996.

[34] G. Jaroszkiewicz, "Particle Decays," in *Quantized Detector Networks: The Theory of Observation*, Cambridge, Cambridge University Press, 2017, p. 198–216.

[35] L. Susskind, "The World as a Hologram," *J. Math. Phys,* vol. 36, no. 11, pp. 6377–6396 - doi:10.1063/1.531249, 1995.

[36] J. Maldacena and L. Susskind, “Cool horizons for entangled black holes,” *Progress in Physics,* 2013.

[37] C. Lv, R. Zhang, Z. Zhai and Q. Zhou, "Curving the space by non-Hermiticity," *Nat Commun,* vol. 13, pp. 2184 - doi.org/10.1038/s41467-022-29774-8, 2022.

[38] I. L. Paiva, A. Te'eni, B. Peled, E. Cohen and Y. Aharonov, "Non-inertial quantum clock frames lead to non-Hermitian dynamics," *arXiv:2204.04177v1,* 2022.