Time and Causation

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In this review paper, we consider the fundamental nature of time and causality, most particularly, in the context of the theories of special and general relativity. We also discuss the issue of closed timelike curves in the context of general relativity, and the associated paradoxes, the question of directionality of the time flow and, rather briefly, the problem of time in quantum gravity.

Time present and time past
Are both perhaps present in time future
And time future contained in time past.
If all time is eternally present
All time is unredeemable.
What might have been is an abstraction
Remaining perpetual possibility
Only in a world of speculation.
What might have been and what has been
Point to one end, which is always present.

Burt Norton
T.S. Eliot

I. INTRODUCTION

Time is a most mysterious ingredient of the Universe and does stubbornly resist any simple definition. Intuitively, the notion of time seems to be intimately related to change, and subjectively it is clearly perceived as something that flows. This view can be traced back as far as Aristotle (384 BC - 322 BC), a keen natural philosopher, who categorically stated that time is the measure of change. Throughout history, one may find a wide variety of reflections and considerations on time, dating back to ancient religions. For many civilizations, cycles in nature were an evidence of the circular nature of time. Indeed, it was only in the 17th century that the philosopher Francis Bacon (1561 - 1626) clearly formulated the concept of linear time, and through the influence of Newton (1643 - 1727), Barrow (1630 - 1677), Leibniz (1646 - 1716), Locke (1632 - 1704) and Kant (1724 - 1804) amongst others, by the 19th century the idea of a linear time evolution was a dominant one both in science and philosophy (a very partial list of references include 1 2 3 4 5 6 7 8 9).

In a scientific context, it is perhaps fair to state that reflections on time culminated with Newton’s concept of absolute time, which assumed that time flowed at the same rate for all observers in the Universe 10. Newton compared time and space with an infinitely large vessel, containing events, and existing independently of the latter. However, in 1905, Albert Einstein (1879 - 1955) changed altogether our notion of time, through the formulation of the special theory of relativity and stating, in particular, that time flowed at different rates for different observers. Three years later, Hermann Minkowski (1879 - 1909) 11 suggested the unification of the time and space parameters, giving rise to the notion of a fundamental four-dimensional entity, spacetime (see e.g. 12 for an extensive discussion). Furthermore, in 1915, Einstein put forward the general theory of relativity where it was shown that the flat or uncurved spacetime of special relativity is curved by energy/matter. Since then the discovery of new forms of energy/matter in physics has often given rise to new spacetime geometries. Physics and geometry are once again intertwined (see for instance 13).

In this context, an interesting description of spacetime is the so-called Block Universe which represents spacetime as an unchanging four-dimensional block, where time is considered a dimension. In this representation, a preferred present is non-existent and past and future times are equally present. All points in time are equally valid frames of reference, and whether a specific instant is in the future or past is frame dependent. However, despite the fact that each observer does indeed experience a subjective flow of time, special relativity denies the possibility of universal simultaneity, and therefore the possibility of an universal present. We refer the reader to Ref. 14 for details on the objections to the Block Universe viewpoint.

An important aspect of the nature of time concerns its flow. The modern physical perspective regards the Universe as described by dynamical laws, from which, after specifying a suitable set of initial conditions for a physical state, the time evolution of the system is determined. The fundamental dynamical equations of classical...
and quantum physics are symmetrical under a time reversal, i.e., mathematically, one might as well specify the final conditions and evolve the physical system back in time. However, in macroscopic phenomena, which are accurately described by thermodynamics, as well as some instances in general relativity and quantum mechanics, the evolution of the systems seems to be essentially time asymmetric. This enables observers to empirically distinguish past from future. Indeed, the Second Law of Thermodynamics, which states that in an isolated system the entropy (which is a measure of disorder) increases provides a direction for the flow of time. It is an interesting possibility that the Second Law of Thermodynamics and the thermodynamic arrow of time are a consequence of the initial conditions of the Universe, which sets a cosmological direction for the flow of time, that inexorably points in the evolution flow of the Universe’s expansion.

One should notice that as time is incorporated into the very fabric of spacetime, concern should arise from the fact that general relativity is contaminated with non-trivial geometries that generate closed timelike curves, and apparently violates causality. A closed timelike curve allows time travel, in the sense that an observer who travels in spacetime along this curve, returns to an event that coincides with the departure. This fact apparently violates causality and produces time travel paradoxes [13]. The notion of causality is fundamental in the construction of physical theories; therefore time travel and its associated paradoxes have to be treated with great caution [16].

This review paper is outlined in the following way: In Section II, we consider the fundamental nature of time in special and general relativity, paying close attention to the time dilation effects. In Section III, we address the issue of closed timelike curves and the violation of causality, and in Section IV we discuss the issue of directionality of the time flow. In Section V, we present some open issues, such as the correlation of the arrows of time, and the problem of time in quantum gravity. Finally in Section VI, we present our conclusions.

II. RELATIVISTIC TIME

The conceptual definition and understanding of time, both quantitatively and qualitatively is somewhat complex. Special relativity provides us the framework to quantitatively address the fundamental processes related to time dilation effects. The general theory of relativity, on its hand, accounts for the effects on the flow of time in the presence of gravitational fields. Both, special and general relativity are most successful theories from the experimental point of view. General relativity, for instance, is well established in the weak gravitational field limit [17], [18]. Its predictions range from the existence of black holes, gravitational radiation to the cosmological models predicting a primordial beginning, the Big-Bang [19], [20].

A. Time in special relativity

In 1905, Einstein abandoned the postulate of absolute time, and assumed instead the following two postulates: (i) the speed of light, c, is the same in all inertial frames; (ii) the principle of relativity, which states that the laws of physics take the same form in every inertial frame. Considering an inertial reference frame O, with coordinates (t, x, y, z), moving along the x direction with uniform velocity, v, relative to another inertial frame O, with coordinates (t, x, y, z), and taking into account the above two postulates, Einstein deduced the Lorentz transformation, the transformations relating the two coordinate systems, which are given by

\[
\begin{align*}
    t' &= \gamma (t - vx/c^2), \\
    x' &= \gamma (x - vt), \\
    y' &= y, \\
    z' &= z,
\end{align*}
\]

where \( \gamma = (1 - v^2/c^2)^{-1/2} \). One immediately verifies, from the first two equations, that the time and space coordinates are mixed by the Lorentz transformation, and hence, the viewpoint that the physical world is modelled by a four-dimensional spacetime continuum.

Considering now two events, A and B, respectively, with coordinates \((t_A, x_A, y_A, z_A)\) and \((t_B, x_B, y_B, z_B)\) in an inertial frame O, then the interval between the events is given by

\[
\Delta s^2 = -c^2 \Delta t^2 + \Delta x^2 + \Delta y^2 + \Delta z^2, \tag{2}
\]

where \( \Delta t \) is the time interval between the two events A and B [21]. One verifies that the expression (2) is invariant under Lorentz transformations, and as advocated by Minkowski, space and time are united in a four-dimensional entity, spacetime. Thus, the interval (2) may be considered as an underlying geometrical property of the spacetime itself, actually the distance between points (events) in spacetime.

The sign \( \Delta s^2 \) is also invariantly defined, so that \( \Delta s^2 < 0 \) is a timelike interval; \( \Delta s^2 = 0 \), a null interval; and \( \Delta s^2 > 0 \), a spacelike interval. Observers moving with a relative velocity \( v < c \) travel along timelike curves, which are referred to as the worldline of the observer. There is now a unique time measured along a worldline, the proper time. A photon travels along null curves.

The special theory of relativity challenges many of our intuitive beliefs about time. For instance, the theory is inconsistent with the common belief that the temporal order in which two events occur is independent of the observer’s reference frame. Thus, whether a specific instant is in the future or past is frame dependent. Special relativity rules out the possibility of universal simultaneity, and hence the possibility of a universal present.

Another of our intuitive beliefs challenged by the special theory of relativity is related with the time dilation effects. Let us exemplify this issue. Suppose that a clock sits at rest with respect to the inertial reference frame O',
in which two successive clicks, represented by two events $A$ and $B$ are separated by a time interval $\Delta t'$. To determine the time interval $\Delta t$ as measured by $\mathcal{O}$, it is useful to consider the inverse Lorentz transformation, given by

$$t = \gamma(t' + vx'/c^2),$$

which provides

$$t_B - t_A = \gamma \left[ t_B' - t_A' + v (x_B' - x_A')/c^2 \right],$$

where $t_A$ and $t_B$ are the two clicks measured in $\mathcal{O}$. As the events are stationary relative to $\mathcal{O}'$, we have $x_B' = x_A'$, so that one finally ends up with

$$\Delta t = \gamma \Delta t',$$  \hspace{1cm} (5)

where $\Delta t = t_B - t_A$ and $\Delta t' = t_B' - t_A'$. As $\gamma > 1$, then $\Delta t > \Delta t'$, so that time as measured by the moving reference frame $\mathcal{O}'$ slows down relatively to $\mathcal{O}$. This feature has been observed experimentally, in particular, in the Hafele-Keating experiment performed on October 1971 [22]. We note that the fact that a moving clock slows down is completely reciprocal for any pair of inertial observers, and this is essentially explained as both disagree about simultaneity.

### B. Time in general relativity

The analysis outlined above has only accounted for flat spacetimes, contrary to Einstein’s general theory of relativity, in which gravitational fields are accounted through the curvature of spacetime. In the discussion of special relativity, the analysis was restricted to inertial motion, but in general relativity the principle of relativity is extended to all observers, inertial or non-inertial. In general relativity it is assumed that the laws of physics are the same for all observers, irrespective of their state of motion. However, given that a gravitational force measured by an observer depends on his state of acceleration, one is led to the principle of equivalence, which states that there is no way of distinguishing the effects on an observer of a uniform gravitational field from the ones of a constant acceleration.

As already mentioned, general relativity is a quite well established theory from the experimental view point. For instance, the global positioning system (GPS) would not work at all without the general relativistic corrections to Newtonian mechanics and gravity (see for instance, [23] and references therein). Actually, likewise in special relativity, one expects time dilation effects now due to gravitational fields. In order to exemplify this imagine the following idealized thought experiment, actually suggested by Einstein himself [24]. Consider a tower of height $h$ hovering on the Earth’s surface, with a particle of rest mass $m$ lying on top. The particle is then dropped from rest, falling freely with acceleration $g$ and reaches the ground with a non-relativistic velocity $v = (2gh)^{1/2}$. Thus, an observer on the ground measures its energy as

$$E = mc^2 + \frac{1}{2}mv^2 = mc^2 + mgh.$$  \hspace{1cm} (6)

The idealized particle is then converted into a single photon $\gamma_1$ with identical energy $E$, which returns to the top of the tower. Upon arrival it converts into a particle with energy $E' = m't'^2$. Notice that in order to avoid perpetual motion, $m' > m$ is forbidden, hence, we consider $m = m'$, and the following relationship is obtained

$$\frac{E'}{E} = \frac{mc^2}{mc^2 + mgh} \approx 1 - \frac{gh}{c^2},$$

as $gh/c^2 \ll 1$. From the definitions $E = h\nu$ and $E' = h\nu'$, where $\nu$ and $\nu'$ are the frequencies of the photon at the bottom and top of the tower, then from Eq. 7, one obtains

$$\nu' = \nu \left( 1 - \frac{gh}{c^2} \right).$$

Now, in order to get the result that clocks run at different rates in a gravitational field, consider the following gedanken or thought experiment. The observer at the bottom of the tower emits a light wave, directed to the top. The relationship of time between two crests is simply the inverse of the frequency, i.e., $\Delta t = 1/\nu$, so that from Eq. 8, one obtains in the approximation $gh/c^2 \ll 1$:

$$\Delta t' = \Delta t \left( 1 + \frac{gh}{c^2} \right).$$

This clearly shows that time flows at a faster rate on top of the tower than at the bottom. Note that this result has been obtained independently of the gravitational theory.

Actually, this experiment is a well-known test of the time dilation effects in general relativity, first preformed by Pound and Rebka [25], which confirmed the predictions of general relativity to a 10% precision level [26]. These results were subsequently improved to a 1% precision level by Pound and Snider [22]. To within experimental errors, all experimental results are consistent with the special and general relativistic predictions.

It is remarkable that any particle, however elementary, is subjected to gravity as described above even at quantum level, as recently proved experimentally for ultracold neutrons [28]. This experiment is also consistent with the equivalence principle [24].

### III. CLOSED TIMELIKE CURVES AND CAUSALITY VIOLATION

As time is incorporated into the very structural fabric of spacetime, it is interesting to note that general relativity is contaminated with non-trivial geometries which generate closed timelike curves [10]. A closed timelike...
curve (CTC) allows time travel, in the sense that an observer which travels on a trajectory in spacetime along this curve, returns to an event which coincides with the departure. The arrow of time leads forward, as measured locally by the observer, but globally he/she may return to an event in the past. This fact apparently violates causality and produces time travel paradoxes [12]. The notion of causality is fundamental in the construction of physical theories, therefore time travel and its associated paradoxes have to be treated with great care. These paradoxes fall into two broad groups, namely the consistency paradoxes and the causal loops.

The consistency paradoxes include the classical grandfather paradox. Imagine traveling into the past and meeting one’s grandfather. Nurturing homicidal tendencies, the time traveler murders his/her grandfather, impeding the birth of his/her father, therefore making his/her own birth impossible. The consistency paradoxes occur whenever possibilities of changing events in the past arise.

The paradoxes associated with causal loops are related to self-existing information or objects, trapped in spacetime. Imagine a researcher getting the full formulation of a consistent theory of quantum gravity from a time traveler from the future. He/she eventually publishes the article in a high-impact journal and as the years advance, he/she eventually travels to the past providing the details of the consistent quantum gravity theory to a younger version of himself/herself. The article on the theory of quantum gravity exists in the future because it was written in the past by the young researcher. The latter wrote it up, after receiving the details from his older version. Both parts considered by themselves are consistent, and the paradox appears when its elements are considered together. One is liable to ask, what is the origin of the information, as it seems to arise out of nowhere. The details for a complete and consistent theory of quantum gravity, which paradoxically were never created, nevertheless exist in spacetime. Note the absence of causality violations in these paradoxes.

A great variety of solutions to the Einstein field equations containing CTCs exist, but two particularly notorious features seem to stand out [20]. Solutions with a tipping over of the light cones due to a rotation about a cylindrically symmetric axis [31], and solutions that violate the energy conditions of general relativity, which are fundamental in the singularity theorems and theorems of classical black hole thermodynamics [16, 19].

A. Solutions violating the energy conditions

In this fashion, solutions violating the energy conditions have been obtained. One of the simplest energy conditions is the weak energy condition, which is essentially equivalent to the assumption that any timelike observer measures a positive local energy density. Although classical forms of matter obey these energy conditions, violations have been encountered in quantum field theory, the Casimir effect being a well-known example. By adopting the reverse procedure, solutions such as traversable wormholes [16, 32, 33], the warp drive [34, 35, 36], and the Krasnikov tube [37] have been obtained. These solutions violate the energy conditions and through rather simple manipulations generate CTCs [38, 39, 40, 41].

We briefly consider here the specific case of traversable wormholes [32]. A wormhole is essentially constituted by two mouths, $A$ and $B$, residing in different regions of spacetime [32], which in turn are connected by a tunnel or handle. One of the most fascinating aspects of wormholes is actually how easy they allow for generating CTCs [38]. There are several ways to generate a time machine using multiple wormholes [16], but the manipulation of a single wormhole is the simplest way [38]. The basic idea is to create a time shift between both mouths. This is done invoking the time dilation effects of special or general relativity, i.e., one may consider the analogue of the twin paradox, in which the mouths are moving one with respect to the other, or instead, the case in which one of the mouths is placed in a strong gravitational field.

To create a time shift using the twin paradox analogue, consider that the mouths of the wormhole may be moving one with respect to the other in external space, without significant changes of the internal geometry of the handle. For simplicity, consider that one of the mouths $A$ is at rest in an inertial frame, whilst the other mouth $B$, initially at rest when close by to $A$, starts moving out with a high velocity and then returns to its starting point. Due to the Lorentz time contraction, the time interval between these two events, $\Delta T_B$, measured by a clock comoving with $B$ can be made to be significantly shorter than the time interval between the same two events, $\Delta T_A$, as measured by a clock resting at $A$. Thus, the clock that has moved has been slowed by $\Delta T_A - \Delta T_B$ relative to the standard inertial clock. Note that the tunnel, between $A$ and $B$ remains practically unchanged, so that an observer comparing the time of the clocks through the handle will measure an identical time, as the mouths are at rest with respect to one another. However, by comparing the time of the clocks in external space, he/she will verify that the time shift is precisely $\Delta T_A - \Delta T_B$, as both mouths are in different reference frames. Now, consider an observer starting off from $A$ at an instant $T_0$, measured by the clock at rest in $A$. He/she makes his/her way to $B$ in external space and enters the tunnel from $B$. Consider, for simplicity, that the trip through the wormhole tunnel is instantaneous. He/she then exits from the wormhole mouth $A$ into external space at the instant $T_0 - (\Delta T_A - \Delta T_B)$ as measured by a clock positioned at $A$. His/her arrival at $A$ precedes
his/her departure, and the wormhole has been converted into a time machine.

For concreteness, following the analysis of Morris et al.\cite{38}, we consider the metric of the accelerating wormhole given by

$$ds^2 = -(1 + g l F(l) \cos \theta)^2 e^{2k(l)} \ dt^2 + dl^2 + r^2(l) (d\theta^2 + \sin^2 \theta \ d\phi^2),$$

(10)

where the proper radial distance, $dl = (1 - b/r)^{-1/2} \ dr$, is used. $F(l)$ is a form function that vanishes at the wormhole mouth $A$, at $l \leq 0$, rising smoothly from 0 to 1, as one moves to mouth $B$: $g = g(l)$ is the acceleration of mouth $B$ as measured in its own asymptotic rest frame. Consider that the external metric to the respective wormhole mouths is $ds^2 \cong -dT^2 + dX^2 + dY^2 + dZ^2$. Thus, the transformation from the wormhole mouth coordinates to the external Lorentz coordinates is given by

$$T = t, \quad Z = Z_A + l \cos \theta, \quad X = l \sin \theta \cos \phi, \quad Y = l \sin \theta \sin \phi,$$

(11)

for mouth $A$, where $Z_A$ is the time-independent $Z$ location of the wormhole mouth $A$, and

$$T = T_B + v \gamma l \cos \theta, \quad Z = Z_B + \gamma l \cos \theta, \quad X = l \sin \theta \cos \phi, \quad Y = l \sin \theta \sin \phi,$$

(12)

for the accelerating wormhole mouth $B$. The world line of the center of mouth $B$ is given by $Z_B(l)$ and $T = T_B(l)$ with $ds^2 = dT_B^2 - dZ_B^2$; $v(t) = dZ_B/dT_B$ is the velocity of mouth $B$ and $\gamma = (1 - v^2)^{-1/2}$ the respective Lorentz factor; the acceleration appearing in the wormhole metric is given $g(t) = \gamma^2 \ dv/dl$\cite{38}.

Novikov considered other variants of inducing a time shift through the time dilation effects in special relativity, by using a modified form of the metric\cite{10}, and by considering a circular motion of one of the mouths with respect to the other\cite{42}. Another interesting way to induce a time shift between both mouths is simply to place one of the mouths in a strong external gravitational field, so that times slows down in the respective mouth. The time shift will be given by $T = \int_f^i (\sqrt{g_{tt}(x_A)} - \sqrt{g_{tt}(x_A)}) \ dt$\cite{10, 41}.

### B. Possible solutions of the time travel paradoxes?

In what concerns the solution of the violation of causality, if one regards that general relativity is a valid theory, then it is plausible to at least include the possibility of time travel in the form of CTCs. However, a caution reaction is to exclude time travel due to the associated paradoxes, although the latter do not prove that time travel is mathematically or physically impossible. The paradoxes do indeed indicate that local information in a spacetime containing CTCs is restricted to rather unfamiliar situations. In what regards to the grandfather paradox, it is logically inconsistent that the time traveler murders his/her grandfather. But, one can ask, what exactly prevents him/her from accomplishing the murderous act given the opportunities and the free-will to do so. It seems that certain conditions in local events have to be fulfilled, for the solution to be globally self-consistent. These conditions are referred to as consistency constraints\cite{43}. Much has been written on two possible remedies to the CTC paradoxes, namely the Principle of Self-Consistency and the Chronology Protection Conjecture.

Novikov’s Principle of Self-Consistency stipulates that events on a CTC are self-consistent, i.e., events influence one another along the curve in a cyclic and self-consistent way. In the presence of CTCs the distinction between past and future events are ambiguous, and the definitions considered in the causal structure of well-behaved space-times break down. What is important to note is that events in the future can influence, but cannot change, events in the past. According to this principle, the only solutions of the laws of physics that are locally allowed, and reinforced by the consistency constraints, are those which are globally self-consistent.

Hawking’s Chronology Protection Conjecture is a more conservative way of dealing with the causality paradoxes. Hawking puts forward his conjecture based on the strong experimental evidence that “we have not been invaded by hordes of tourists from the future”\cite{44}. An analysis reveals that the value of the renormalized expectation quantum stress-energy tensor diverges close to the formation of CTCs, which destroys the wormhole’s internal structure before attaining the Planck scale. There is no convincing demonstration of the Chronology Protection Conjecture, but perhaps the expected answers will arise from the quantum gravity theory.

### IV. Arrows of Time

By the second half of the XIX century, the development of the kinetic theory of matter by Maxwell (1831 - 1879), Clausius (1822 - 1888) and Boltzmann (1844 - 1906) did revive the discussion on the problem of linear time evolution and of the eternal recurrence of motion. The idea of a cyclic time and of an eternal return was discussed by the philosophers Herbert Spencer (1820 - 1903) and Friedrich Nietzsche (1844 - 1900) about the same time that Poincaré (1854 - 1912) showed his fundamental theorem. Of course, their arguments are not at the level of rigour as in physics and mathematics, but, interestingly, the “proof” of Nietzsche contains elements which are relevant for any discussion of the subject, such as a finite number of states, finite energy, no creation of the universe and chance-like evolution.

The starting point of physical discussion is the fact that Newton’s equations have no intrinsic time direction, being invariant under time reversal. Nevertheless, Poincaré showed in 1890, in the context of classical mechanics, a
general recurrence theorem, according to which any isolated system, which includes the universe itself, would return to its initial state given a sufficiently long time interval.

Poincaré’s theorem is valid in any space \( X \) where there exists a one parameter map \( T_t \) from sets \([U]\) and a measure \( \mu \) on \( X \) such that: i) \( \mu(X) = 1 \) and ii) \( \mu(T_{t_0}(U)) = \mu(T_{t_0+t}(U)) \) for any subset of \( X \) and any \( t_0 \) and \( t \). In classical mechanics, condition i) is ensured by demanding that space \( X \) is the phase space of a finite energy system in a finite box. If \( \mu \) is the distribution or density function, \( \rho \), in phase space and \( T_t \) is the evolution operator of the mechanical system (the Hamiltonian or the Liouville operator), then condition ii) follows from Liouville’s theorem: \( d\rho/dt = 0 \). Hence, it implies that classical mechanics is inconsistent with the Second Principle of Thermodynamics.

Naturally, the recurrence theorem was a major issue in Boltzmann’s approach to the problem of irreversibility. Indeed, in the 1870s, he realized that deducing an arrow of time from the mechanics of atoms was impossible without using averaging arguments. The developed formalism allowed him to understand statistical equilibrium with the Liouville equation and in 1872 he obtained a time-asymmetric evolution equation, now referred to as the Boltzmann equation, whose solution was a single-particle distribution function of a molecule in a diluted gas. From this distribution function he could construct a strictly decreasing function of time, the so-called \( H \)-function. The identification of the \( H \)-function with minus the entropy, allowed him to claim to have solved the irreversibility problem at molecular level.

A crucial point however, was that in order to arrive at his result Boltzmann had to rely on the assumption that molecules about to collide are uncorrelated, but that after the collision they are correlated as their trajectories are altered by the collision, the molecular chaos hypothesis or Stosszahlansatz. However, in 1876, Johann Josef Loschmidt (1821 - 1895), a friend of Boltzmann, argued that the time-asymmetry obtained by Boltzmann was entirely due to the time-asymmetry of the molecular chaos assumption. Twenty years later, Ernest Zermelo (1871 - 1953), a young assistant of Planck (1858 - 1947) in Berlin, attacked Boltzmann again, now armed with Poincaré’s recurrence theorem. Boltzmann tried to save his case via a cosmological model. He proposed that as a whole the universe had no time direction, but that time-asymmetry could arise in some regions when through a large fluctuation from equilibrium it would yield states of reduced entropy. These regions of low entropy would evolve back to the most likely state of maximum entropy, and the process would then follow Poincaré’s theorem. We know today that Poincaré’s theorem cannot be applied to the whole Universe given the existence of spacetime singularities in general relativity.

By 1897, Planck started tackling the irreversibility problem in a series of papers which actually culminated with his discovery of the quantum theory of radiation in 1900. It was clear that a finite system of particles would be recurrent and not irreversible in the long run, and for this reason he considered instead a field theory, electrodynamics. The hope was to derive irreversibility from the interaction of a continuous field with a set of particles. Planck’s arguments led Boltzmann to remark that as a field could be seen as a mechanical system with an infinite number of molecules, an infinite Poincaré recurrence period should then be expected, and thus a long term agreement with the observed irreversibility from which the Second Principle would follow.

Despite of that the persistent objections of influential opponents such as Ernst Mach (1838 - 1916) and Friedrich Ostwald (1853 - 1932), led Boltzmann into depression and into a first suicide attempt in Leipzig, before assuming Mach’s chair in Vienna in 1902. The intellectual isolation and the continuous deterioration of his health led him eventually to suicide at the age of 62, at Duino, a seaside holiday resort on the Adriatico coast near Trieste, on the 5th September 1906.

Even after Boltzmann, the irreversibility problem has resisted any simple explanation. In 1907, the couple Ehrenfest, Paul Ehrenfest (1880 - 1933) and Tatjana Afanasyeva (1876 - 1964) further developed Boltzmann’s idea of averaging over a certain region, \( \Delta \), of the phase space and showed that the averaged \( H \)-function would remain strictly decreasing in the thermodynamical limit, after which \( \Delta \) could be taken as small as compatible with the uncertainty principle (see e.g. Ref. [45]).

In 1928, Pauli (1869 - 1958) when considering the problem of transitions in the context of quantum mechanical perturbation theory showed that satisfying the Second Principle of Thermodynamics would require a master equation:

\[
\frac{dp_i}{dt} = \sum_j (\omega_{ij}p_j - \omega_{ji}p_i),
\]

where \( \omega_{ij} \) is the conditional probability per unit time of the transition \( j \rightarrow i \) and \( p_i \) is the probability of state \( i \). Assuming the \( H \)-function to be given by

\[
\mathcal{H} = \sum_i p_i \ln p_i,
\]

it follows that \( \frac{d\mathcal{H}}{dt} \leq 0 \). This approach is fairly suggestive as it makes clear that that irreversible phenomena should be understood in the context of microscopic physics, the very essence of Boltzmann’s work.

More recently, Prigogine (1917 - 2003) and collaborators put forward a quite radical idea, according to which the irreversible behaviour should be already incorporated at the microscopic level (see e.g. Ref. [46] for a general discussion). Mathematically, the problem consists in turning time into an operator which does not commute with the Liouville operator, itself the commutator of the Hamiltonian with the density matrix. Physically,
this proposal implies that reversible trajectories cannot be considered, leading to an entropy-like quantity which is a strictly increasing function of time.

One should realize that besides the difficulty in explaining from microphysics the irreversible behaviour of macroscopic systems, there exists in nature a variety of phenomena whose behaviour exhibit an immutable flow from past to present, from present to future. The term “arrow of time”, coined by the British physicist and cosmologist Arthur Eddington (1882 - 1944) [17], is often used to refer to this evolutionary behaviour. Let us briefly describe these phenomena and their main features:

1) The time asymmetry inferred from the growth of entropy in irreversible and dissipative macroscopic phenomena as discussed above.

2) The nonexistence of advanced electromagnetic radiation, coming from the infinite and converging to a source, even though this a possible solution of the Maxwell’s equations.

3) The measurement process and the ensued collapse of the wave function of a quantum system and the irreversible emergence of the classical behaviour, despite the fact that the fundamental equations of quantum mechanics and statistical quantum mechanics, Schrödinger’s and Von Neumann’s equations, respectively, are - likewise Newton’s equation of motion - invariant under time inversions for systems described by a time-independent Hamiltonian (see e.g. Ref. [48, 49] for a thorough discussion).

4) The exponential degradation in time of systems and the exponential growth of self-organized systems (for a sufficiently abundant supply of resources). In the development of self-organized systems, an important role is played by complexity. The fascinating aspects of complex phenomena has led some authors to refer to their rather unique evolution behaviour as “creative evolution”, “arrow of life” or “physics of becoming” [2, 6, 46]. In the context of complex systems, the chaotic behaviour plays an important role given that these systems are described by non-linear differential equations. This chaotic behaviour gives rise to a rich spectrum of possible evolutions and the surprising feature of predictable randomness given that chaotic branches are deterministic (see for instance, Refs. [6, 50]).

5) From the discovery of the CP-symmetry violation in the $K^0 - \bar{K}^0$ system, one infers from the CPT-theorem, a fundamental cornerstone of quantum field theory, that the T-symmetry is also violated. This means that on a quite elementary level there exists an intrinsic irreversibility. The violation of the CP-symmetry and also of baryon number in an expanding universe are conditions from which the observed baryon asymmetry of the universe (BAU) can be set (see for instance [51] and references therein). An alternative route to explain the BAU is through the violation of the CPT-symmetry itself [52]. This is possible, for instance, in the context of string theory [53].

6) The psychological perception of time is obviously irreversible and historical. The past is recognizable and can be scrutinised, while the future is open and unknown. This perception is presumably intimately related with the issue of causation and the branching of possible outcomes towards the future. A fascinating related question is whether this irreversible psychological perception of time is the only one compatible with the laws of thermodynamics or whether it is the result of an advantageous evolutionary adaptation of our brain. The recent observation of a common cortical metrics of time, space and quantity [54] might lead one to conjecture that the anatomical structure of our brain makes the associations of time with change and space with time rather natural.

7) Systems bound gravitationally exhibit the so-called gravito-thermal catastrophic behaviour [55], meaning that their entropy grows as they contract, which in turn implies that their specific heat is negative. On the largest known scales, the expansion of the Universe, which is itself adiabatic, is a unique phenomenon, and as such, is conjectured to be the arrow of time to which all others might be subordinated.

V. OPEN ISSUES

Let us briefly discuss here some problems related to the nature of spacetime that remain essentially unsolved. These include a putative correlation between the above discussed arrows of time and the question of nonexistence of an explicit time variable in the canonical Hamiltonian formulation of quantum gravity.

A. Are the arrows of time correlated?

One could argue that the existence of systems, from which a time direction can be inferred, is not at all so surprising, as this feature is the essence of all dissipative phenomena. It is possible that this directional flow reflects, for instance, a particular choice of boundary conditions which constrain the state of the universe, rather than any restriction on its dynamics and evolution. However, this point of view cannot account for the remarkable fact that all known arrows of time do point from past to present, to present to future. In what follows, we briefly discuss some of the views put forward to relate the arrows of time among themselves. Thorough discussions can be found in Refs. [56, 57, 58].

For instance, the philosopher Hans Reichenbach (1891 - 1953) [52] argued in his book *The Direction of Time*, that the arrow of time in all macroscopic phenomena has its origin in causality, which in turn should be the ori-
gin of the growth of entropy. The argument is somewhat circular, but the suggested connection is the most important point of the discussion. Possibly, one the most original ideas about a putative correlation of time arrows is due to the cosmologist Thomas Gold (1920 - 2004), who in 1958, suggested that all arrows of time should be subordinated to the expansion of the Universe [60].

This speculation gave origin to some attempts, not quite successful, to correlate the propagation of electromagnetic radiation to the expansion of the Universe [61] [62]. Indeed, it is somewhat puzzling that the found solutions indicate that retarded radiation is compatible only with a steady-state universe, while advanced radiation is found to be compatible only with evolutionary universes (expanding or contracting ones). Clearly, these solutions show evidence that the problem requires more complex and realistic modelling.

A different starting point is considered by Roger Penrose, based on the Thermodynamics of Black Holes. It is suggested that the gravitational field must have an associated entropy which should be measured by an invariant combination involving the Weyl tensor [63]. This idea allows for a consistent set up for cosmology of the Generalized Second Principle of Thermodynamics, as it arises in physics of black holes. This formulation states that the Second Principle should apply to the sum of the entropy of matter with the one of the black hole [64] [65]. The main point of Penrose’s proposal is that it resolves the paradox of an universe whose initial state is a singularity or a black hole protected by a horizon, and hence with an initial entropy that exceeds by many decades of magnitude the entropy of the observed universe. Indeed, Penrose’s suggestion explains the low entropy of the initial state from its isotropy and homogeneity as in this situation the Weyl tensor vanishes [66]. The gravitational entropy will then increase as the Weyl tensor grows as the universe becomes lumpier.

The growth of the total entropy can, in principle, account for the asymmetry of psychological time as in this way the branching of states and outcomes will occur towards the future.

Let us conclude this discussion with some comments on some recent developments in the context of superstring/M-theory. These suggest a multiverse approach of the landscape of vacua of the theory. This corresponds to a googleplexus of $10^{500}$ vacua [67], which should be regarded as distinct universes. Naturally, a suitable selection criteria for the vacuum that corresponds to our universe should be found. If not, how then our universe has been chosen and emerged from the multitude of vacua of the theory? Anthropic arguments [68] and quantum cosmological considerations [69] have been proposed for this purpose. For sure, these meta-theories of initial conditions are not consensual, but they contribute to a better understanding of the problem. Naturally, one should keep in mind that non-perturbative aspects of string theory are poorly known [70]. The multiverse approach opens the possibility of interaction among different universes [71]. This interaction is suggested to be controlled by a Curvature Principle and it is shown, in the context of a simple model of two interacting universes, that the cosmological constant of one of the universes can be driven to a vanishingly small value. The main point of the argument is an action principle for the interaction of universes using the curvature invariant $I_i = R_{\mu \nu \lambda \sigma} R^i_{\mu \nu \lambda \sigma}$, where $R_{\mu \nu \lambda \sigma}$ is the Riemann tensor of each universe. The proposed Curvature Principle also allows for a possible solution for the entropy paradox of the initial state of the universe [71]. From the point of view of another universe, from which our universe can be perceived as if all its mass were concentrated in some point and therefore, $I = 48 M^2 r^{-6}$, where $r$ is the universe horizon’s radius and $M$ its mass - using units where $G = \hbar = c = 1$. Thus, if the entropy scales with the volume, then $S \sim r^3 \sim I^{-1/2}$; for the case that the entropy scales according to the holographic principle, suitable for AdS spaces [72] [73], then $S \sim r^2 \sim I^{-1/3}$. For both cases, given that $I \sim \Lambda^2$ for the ground state, one obtains that $S \rightarrow 0$ in the early universe and, $S \rightarrow \infty$ when $\Lambda \rightarrow 0$. The latter corresponds to the universe at late time, which is consistent with the Generalized Second Principle of Thermodynamics.

B. Time in quantum gravity

Quantum gravity is the theory that is expected to describe the behaviour of space-time at distances of the order of the Planck length, $L_P \simeq 10^{-35}$ m. It is still largely unknown, even though important developments have been made in the context of the superstring/M-theory, the most studied quantum gravity approach. This approach leads to a quite rich set of ideas and concepts, but has not provided satisfactory answers to some fundamental problems such as for instance to account for the smallness of the cosmological constant [74]. Furthermore, it exhibits the vacuum selection problem discussed above, which seriously compromise the predictability power of the whole programme.

In order to understand the conceptual difficulties that afflict quantum gravity, let us discuss how the procedure of quantization of gravity seriously challenge the well tested methods of quantum field theory. Indeed, even though the metric, $g_{\mu \nu}(\vec{r}, t)$, can be seen as a bosonic spin-two field, when attempting to consider its quantization through an equal-time commutation relation for the corresponding operator:

$$[\hat{g}_{\mu \nu}(\vec{r}, t), \hat{g}_{\mu \nu}(\vec{r}', t)] = 0 ,$$  \hspace{1cm} (15)$$

for $\vec{r} - \vec{r}'$ space-like, one faces a problem of definition: i) To start with, in order to establish that $\vec{r} - \vec{r}'$ is space-like, one must specify the metric; ii) Being an operator relationship, it must hold for any state of the metric; iii) Without a proper specification of the metric, causality is ill-defined.
These obstacles suggest that one should consider instead the canonical quantization procedure based on the Hamiltonian formalism. In this framework, one splits spacetime and selects foliations where the physical degrees of freedom of the metric are the space-like ones, $h_{ab} = _{(3)}g_{ab}$. The resulting Hamiltonian is a sum of constraints, one associated with invariance under time reparametrization, the others related with invariance under 3-dimensional diffeomorphisms. If one considers only Lorentzian geometries (a quite restrictive condition!), then only the first constraint is relevant. The solution of the classical constraint is given by: \[ H_0 = 0 \] where
\[ H_0 = \sqrt{h} \left[ h^{-1} \Pi_{ab} \Pi^{ab} - \frac{1}{2} h^{-1} \Pi_{a} \Pi^{a} - (^{(3)}R) \right] , \] \[ (17) \]
h being the determinant of the 3-metric $h_{ab}$, $\Pi_{ab} = \delta L / \delta h_{ab}$, the respective canonical conjugate momentum, obtained from the Lagrangian of the problem and $(^{(3)}R)$ the 3-curvature. The quantization consists in turning the momenta into operators for some operator ordering and applying the resulting Hamiltonian operator into a wave function, the wave function of the universe, $\Psi[h_{ab}]$:
\[ \hat{H}_0 \Psi[h_{ab}] = 0 \] \[ (18) \]
This is the well known Wheeler-DeWitt equation, the starting point of the so-called quantum cosmology (see e.g. \[76\] and references therein), where the canonical approach has been throughly used to study the initial conditions for the Universe.

In the context of the canonical formalism, the problem of time (see Ref. \[77\] for a thorough discussion) arises as one does not have a Schrödinger-type equation for the evolution of states, but rather, the constrained problem \[15\] where time is one of the variables within $H_0$. Of course, this does not mean that there is no evolution, but rather that there is no straightforward way to obtain from the formalism a variable that resembles the “cosmic time” that is employed in classical cosmology. Furthermore, it is somewhat hasty to conclude in this context that time is not a fundamental physical variable.

An attempt to solve this difficulty assumes a semi-classical approach \[78\], where time is identified with the scale factor or some function of it, once the behaviour of the metric is classical and the wave function of the universe admits a WKB approximation. In this context, the Wheeler-DeWitt equation can be written, at least in the minisuperspace approximation where one admits only a finite (or an infinite but numerable) set of degrees of freedom, as the Hamilton-Jacobi equation for the action in the WKB approximation. Physically it implies that time can be identified as such only after the metric starts behaving as a classical variable.

Another interesting proposal is the so-called Heraclitean time proposal \[79,80,81\]. This is based on a suggestion due to Einstein \[82\], according to which the determinant of the metric might not be a dynamical quantity. In this approach, usually referred to as unimodular gravity, the cosmological constant arises as an integration constant and an time variable can be introduced as the classical Hamiltonian constraint assumes the form \[74\]:
\[ H = \Lambda h^{1/2} , \] \[ (19) \]
and thus, for a given space-like hypersurface $\Sigma$, one can obtain a Schrödinger-like equation:
\[ i \frac{\partial \Psi}{\partial t} = \int \Sigma d^3x h^{-1/2} \hat{H}_0 \Psi = \hat{H} \Psi . \] \[ (20) \]
For sure, the problem of time in quantum gravity remains still an open problem and the presented proposals are examples of possible lines for future research.

**VI. CONCLUSIONS**

In this review paper we have examined the nature of time and its relationship with causation. Particular attention has been paid to the new feature of the special and the general theory of relativity according to which time flows at different rates for different observers. This is sharply contrasting with the situation in Newtonian physics where time flows at a constant rate for all observers, providing a notion of absolute time. It is shown, in the context of special relativity, how the concept of universal simultaneity is unattainable, and consequently, that the idea of an universal present is impossible.

In this context, the Block Universe description emerges, a formulation where all times, past and future are equally present, and the notion of the flow of time is a subjective illusion. This leads one to the possibility that time is indeed a dimension, and not a process. Despite of the popularity of the Block Universe representation in physics, most particularly in the relativistic community, this viewpoint is still met with some suspicion. Notice however, that for many scientists, Einstein included, irreversibility is essentially an illusion.

A related issue about the nature of time concerns its flow, from past to present, from present to future. The question here is the mismatch between macrophysics, described by the Second Law of Thermodynamics, and through which a distinct arrow of time arises from the growth of entropy in irreversible processes, and microphysics, whose fundamental evolution equations, classical and quantum, are symmetric under time reversal. In the context of statistical mechanics, it is assumed that the deterministic behaviour in the microphysics context is lost as the macroscopic description necessarily averages out the micro-properties of the systems. As discussed above, another possibility is to assume that the thermodynamic arrow of time is a consequence of the initial conditions of the Universe which is inexorably correlated to the direction of the Universe’s expansion.
Finally, in what concerns the fundamental ontological nature of time, we believe that it remains still an open question whether time is a real fundamental quantity or, instead, a composite or a convenient parameter to describe the physical laws and most particularly to pose, in unequivocal terms, causation. Causation that, as we have seen, is a most crucial feature not only in physics, but according to some philosophers, like David Hume (1711 - 1776), also for the very human understanding of reality.

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