Hypothesis about the nature of time and rate of clocks

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ABSTRACT. This paper is built on two, deeply analyzed, fundamental ideas: the mathematical nature of Newtonian and relativistic time and the consequent need to build physical theories of time from the measurements obtained by real clocks. We remark that relativistic theories are founded on axiomatic assumptions about clocks, probably not verified by experiments, if we use clocks of different construction. We introduce the concept of evolutionary internal time and we conclude that a new interpretation of the nature of physical time should rise from a deep and accurate reflection about the rate of clocks. We believe that this approach to the question could open new theoretical perspectives about the evolution of physical systems.

1 Introduction

This paper aims to provide a critical contribution about the operational definition of time in physics, with particular regard to the measurement of durations. It means to investigate the possible link between the change of position and the internal evolution of bodies, starting from the analysis of the behavior of clocks having different internal structure. The explicit references are on the one hand the Einstein theory of relativity and, on the other, the alternative theory proposed by Franco Selleri, who attributes a different cause to the not equivalent durations measured by two clocks in different states of motion. We chose to analyze this alternative relativistic theory because it is the most recent attempt of a new elaboration of the ideas of Poincaré, Lorentz, Builder, Dingle, Reichenbach and other physicists and epistemologists who proposed critical observations (or autonomous theories, as in the case of Mansouri-Sexl) of some interest to Einsteinian relativity. This work however does not propose a comparison between antagonistic theories, but it highlights the absence or lack of adequate theoretical justifications about the different measurements provided by clocks in different gravitational or pseudo-gravitational potentials. From these criticism we argue new remarks about the problem of time measurement in physics. The fundamental idea developed in this critical analysis is the operational nature of physical time, to which an instrument of measure must be associated. Only from clocks measurements we may obtain consisting theories about the existence or the nature of time. Although it appears obvious that a physical quantity, to be such, must be measurable, it is remarkable that in recent theories some speculative aspects, often unclear, coexist with operational considerations, making the synthesis rather uncertain. The implicit dialectic between the concepts of time, (external) movement and (internal) change of bodies, makes difficult the operational foundation of the one from the others. The here proposed analysis is therefore intended to give substance and explicit argumentation to the basic idea that animates these reflections, so that only time linked to the internal evolution of a system has a true physical reality, while Newtonian or relativistic time, as it will be clear from the development of the argumentation, is a quantity whose operational reality is different from that of internal evolutionary time, whose theoretical and experimental meaning the last paragraphs intend to explore.

2 Time and becoming

This work investigates the possible link between the concept of time introduced in mechanics, rooted in the Mach's idea of time as an abstraction that we extract from motion, at which we arrive through the changes of things [1], and the internal evolution of bodies, then the internal change of things. Although we do not intend to enter the details of the recent theories about the illusory reality of physical time, proposed in particular by Julian Barbour and Carlo Rovelli [1], it is interesting to point out that these theories in some ways refer to the last Einstein [2],

[1] "Time is ignorance: a reflex of our incomplete knowledge of the state of the world" [2].

[2] In a letter to the family of his lifelong friend Michele Besso, after learning of his death (March 1955), Einstein wrote: "People like us, who believe in physics, know that the distinction between past, present, and future is only a stubbornly persistent illusion" [3].

who admits his impossibility to understand the physical meaning of the present and the psychological consciousness we have of it, feeling the elusive physical reality of becoming [3]. As observed by Karl Popper [4], general relativity in fact implies the idea of the illusory nature of time, of the Universe as a four-dimensional Parmenidean Sphere containing the whole physical reality. A similar judgment about the Einsteinian theory was expressed also by Kurt Gödel [6]. In a larger perspective, we may think that the twentieth century physics (with the exception for some border theories, such as Prigogine's) deliberately removed or ignored the idea of becoming, to marry an idealistic theory in which the temporal evolution of material bodies is neglected. In more recent speculative forms, this theory was developed in particular by Henry Bergson, in parallel with the radical revolutions of physical thinking. Sometimes overflowing in literary and psychological suggestions, the time-becoming theory embodies all aspects of change, internal and external. The intention of this work is not to recall the criticism, probably obsolete, the French philosopher has developed around Einstein's theory (with particular reference to the concepts of time and simultaneity), but rather to clarify the possible gap between the conceptual frameworks that, in physics, are related to the problem of time intervals measurement. This paper aims to develop the central question of the measure of durations, highlighting the presence, in relativistic theories, of axiomatic assumptions about clocks, that further justify the need of a general critical review of the concept of physical time starting from the internal structure of clocks.

3 Time and motion in Newton and Einstein

In Newton's and Einstein's theories (in Selleri's too, as paradigmatic of the alternative theories to Einstein's relativity: see the following section) the operational definition of time implies the mathematical nature of this quantity. In fact, Newton does not propose any operational definition

[3] Rudolf Carnap [4] writes: "Once Einstein said that the problem of the Now worried him seriously. He explained that the experience of the Now means something special for man, something essentially different from the past and the future, but that this important difference does not and cannot occur within physics".

[4] In a late interview with Einstein, alluding to the block-universe theory, Popper writes: "I tried to persuade him to give up his determinism, which amounted to the view that the world was a four-dimensional Parmenidean block universe in which change was a human illusion, or very nearly so: he agreed that this had been his view and while discussing I called him Parmenides" [5].

of time, since duration is a conceptual abstraction derived from motion. According to Newton, absolute, true and mathematical time, of itself, and from its own nature flows equably without regard to anything external, and by another name is called duration: relative, apparent and common time is some sensible and external (whether accurate or not equable) measure of duration by the means of motion, which is commonly used instead of true time. We argue that Newtonian clocks, as real devices that provide a sensible and external measure of duration by the means of motion, make Newtonian time a simple abstraction of movement, since the measurement of true time is impossible. The variable t is real as movement is real: time-movement is a single concept that for convenience we split in two, calling clock a device in which a periodic motion allows to measure, in appropriate units, the duration of a phenomenon, counting oscillations or fractions of them. Einstein's theory, born from the need to build, in special relativity, a rigorous conceptual framework for mechanics and electromagnetism, does not differ from Newton's theory as for the implicit identity between time and motion. Starting from the assumption of the invariance of the speed of light, it simply deduces the need to anchor the measurements of durations to the observers. It is not possible, in special relativity, to highlight the different average lifetimes of a sample of muons if, at least for an observer, that sample is not in movement: time dilation is a consequence of the relative motion of observers. Newton's mechanics and Einstein's relativity are indifferent to the possible quantification of the internal change of bodies: the existence of this change is a phenomenon without importance in their conceptual framework. Einstein's progress consists in overcoming the Newtonian concept of space and time as absolute separate entities and in acquiring the exciting idea of not invariant duration, ignoring that the point-events of the four-dimensional variety, conceived as mathematical abstractions necessary to explain physical phenomena, may have, in the real world, an internal structure in evolution, probably independent from the worldlines they describe in spacetime between two fixed points. This aspect, implicitly believed trivial (physical theories work on an abstracted image of the world, forgetting that this image is subjected to an internal becoming), is central in this critical analysis, where a new area of theoretical investigations is proposed, in which it will be possible to debate, in a renewed form, the question of dualism between mathematical and evolutionary time. This idea can help to settle an issue having its roots in a speculative region made of epistemological as well as physical thought. A detailed analysis of relativistic theories will allow us to understand that the different quantification of durations, measured by clocks in dependence on their state of motion, is based on axiomatic, then arbitrary assumptions without adequate experimental justifications, since in these theories is implicitly postulated that all clocks, regardless of their internal structure, should provide equivalent measurements. Particularly we will see that in Einstein the problem of the quantification of different durations, in dependence on the worldline, requires the conceptual apparatus of general relativity, since only in the framework of this theory it is possible to analyze the behavior of real clocks.

4 Clock-twin effect. Selleri's theory

The empirical-theoretical reference of the critical analysis proposed in this paragraph, from which the whole argumentation of the paper is derived, is the well known clock-twin effect, around which in 20th century a great variety of interpretations of different nature has flourished. We simply consider that twin B, initially in the same state of uniform rectilinear motion of A, accelerates, then maintains the reached speed, and finally decelerates up to rejoin A. Franco Selleri [7], taking important critical remarks of Geoffrey Builder [5] [9], observes that if the traveler changes the path length of his uniform rectilinear motion, leaving unchanged the speed and without modify accelerations and decelerations, he correspondingly changes his age difference from the one that did not alter his state of motion. It follows that speed, not acceleration, must be the cause of aging asymmetric. Selleri also endorses the objections of Herbert Dingle [10], according to which, being experimentally incontestable the quantification of different durations, it must be acknowledged that if an absolute effect is a function of velocity, then velocity itself is absolute: no manipulation of formulas or devising of ingenious experiments can alter this simple fact. According to Selleri, a continuous increasing of the path length traveled by B at a constant speed causes a rate delay and a progressive reduction of the duration measured by his clock with respect to A (which therefore gets much older), where, in order to have the asymmetry, the presence of accelerations and decelerations of B with

[5]While in the conceptual framework of special relativity (Einstein 1905) the aging asymmetric is due to the different speeds of twins, the interpretation proposed by Paul Langevin [8] implies that the difference of the measures is due to the phases of acceleration and deceleration. This interpretation in contrasted by Builder, to which Selleri refers in his critical analysis of clock effect.

respect to A is needed, whose intensity and duration appear however to be irrelevant. Selleri's relativistic theory deeply differs from Einstein's, since it postulates the existence of an absolute reference, it believes anisotropic the speed of light relative to a reference frame different from absolute, it admits superluminal signals, it considers conventional (in agreement with Poincaré) the relativistic synchronization of clocks and the notion of relativistic simultaneity of distant events, it believes to be absolute the phenomena of length contraction and time dilation. Given two inertial systems S and S_0, whose origins at $t = t_0 = 0$ are coincident, S being in motion at speed v with respect to S_0 so that the origin of S, observed from S_0, moves parallel to the x-axis, according to Selleri: a) space is homogeneous and isotropic and time is homogeneous, at least if judged by observers at rest in S_0: b) in S_0 the speed of light is c in all directions, so clocks in S_0 can be synchronized and every speed relative to S_0 is measurable; c) the round trip speed of light is the same in all directions and in all inertial systems; d) a clock in motion at speed v delays by the factor $R = \sqrt{1 - v^2/c^2}$. Selleri introduces the inertial transformations between the S and S_0 coordinate systems. They are equivalent to Lorentz transformations regarding the spatial coordinates:

$$x = \frac{x_0 - vt_0}{\sqrt{1 - \frac{v^2}{c^2}}}, \quad y = y_0, \quad z = z_0 \tag{1}$$

while the transformation law of the time coordinate (founded, according to Selleri, on solid empirical basis) is given by:

$$t = t_0 \sqrt{1 - \frac{v^2}{c^2}} \tag{2}$$

We believe that the weak point of Selleri's model (in which time and space do not form a continuum, since the invariance of c is not postulated) is the need to axiomatically admit that each clock must register a variation of its proper frequency in dependence on its velocity relative to absolute space, leaving in vague both the concept of clock and the theoretical analysis of the link between the proper period of instruments with different internal structure and the speed.

5 Clock effect: Einstein's interpretation

In Einstein's theoretical framework (whose explanation here we believe unnecessary, as surely well known to the reader), clock effect, in general, can be interpreted as a speed or a potential effect. If clock B is observed in A's frame, from which clock B moves away, special relativity interprets the different time interval measured from B as due to its velocity with respect to A. If clock B is observed at rest, in a reference frame in its same state of motion, general relativity interprets the different measure provided by this clock as a consequence of the different gravitational or pseudo gravitational potential, due to frame acceleration. The experimental proofs of time dilation law, performed from the forties, have shown that the non proper duration, elapsed with respect to an observer between two events (e.g. emission and decay of a particle) that occur in two distinct points of space, is dilated by the factor $\gamma = 1/\sqrt{1-\beta^2}$ with respect to the proper duration, measured by an observer who sees the two events occur at the same point. Experiences of this kind, in agreement with the foundational postulates of relativistic kinematics (homogeneity and isotropy of space, homogeneity of time, invariance of the speed of light in vacuum and principle of relativity), lead to infer a precise relationship between the durations, but this does not allow to conclude anything about the possible different measurements taken from real clocks. A careful analysis of the experiments [11], performed between forties and sixties, shows that the dilation law was indirectly verified from measurements of distances, velocities, electric fields, radius of circular orbits described by charged particles in magnetic fields, wavelengths, obtained by the observer A, even by using laws alien to the theory (particularly, in the case of unstable particles, for measuring the proper average lifetime, the radioactive decay law). In experiments whose purpose is to test the clock effect one needs to compare the measurements of real durations obtained by initially synchronized clocks, then separated along not equipollent world lines and finally gathered and compared in the same reference frame. In the Einsteinian theoretical framework, if clock B, before it rejoins A, travels at a constant speed along a more or less long worldline, assuming accelerations and decelerations to be negligible, it measures a shorter duration without any variation of its proper period: the shorter time interval is a consequence of the shorter length of the worldline described by the traveling clock in spacetime.

6 The problem of real clocks

This preliminary analysis of Einstein's and Selleri's theories clearly shows the need to assume that there must be clocks that provide measures in agreement with the postulates or the laws that from these postulates can be obtained. Accepting as an explanation of clock effect the variation of the path length in spacetime may sound like tautological, as it (consistently) solves the problem within the theory, while Dingle's claims, revised by Selleri, are implicitly linked to the possible experimental verification of the effect with real clocks: the asymmetrical aging of the twins simulates the different measure of clocks describing two not equipollent worldlines. Compared to Einstein's, Selleri's theory in addition does not offer a convincing operational solution, being closed in the statement linked to equation (2), without the possibility to extend the analysis to the influence of gravitational and pseudo gravitational potential on clocks rate. In the following of the work, except for the final synthesis, we will then refer only to Einstein's theory. It is however inevitable to remark that in relativistic theories clocks do not have a structural identity: they have to measure durations in a consistent way, unless the contrary is proved in real experiments. This proof is to date limited to atomic clocks, as the following theoretical analysis of the Hafele and Keating experiment clearly shows.

7 Hafele-Keating experiment. Hafele's theoretical analysis

In Hafele-Keating's experiment [12] the different measurements of durations can be interpreted as a consequence of the rate variation of clock in flight [6] that is due, for a co-rotating observer, to the variation of gravitational and pseudo gravitational potential. It is shown that: a) the greater altitude of (traveling) clock B with respect to A (on Earth) implies an increasing of gravitational potential, then a decreasing of its proper period; b) the centripetal acceleration of the co-rotating frame implies also the presence of a pseudo-gravitational potential that justifies, added to gravitational, the different measurements of B relative to A (B delays or anticipates with respect to A depending on whether the motion is towards the east or the west). Starting from the law [7]:

$$\Delta E = \Delta E_0 \sqrt{1 + 2\frac{\chi}{c^2}} \tag{3}$$

[6] In the following we neglect the acceleration (during take-off and approach to the circular path) and deceleration (under ground return) of the plane.

[7] The experiments carried out since the early sixties have verified, thanks to the discovery of the Mössbauer effect in 1957, that the energy E of the photons absorbed or emitted by nuclei or atoms depends on the gravitational potential according to the relation $E(R + h) \approx E(R)(1 + gh/c^2)$. Similar effects have also been verified with nuclei or atoms on a rotating disc, then in the presence of a pseudo-gravitational potential.

which expresses the energy difference between two fixed levels in an atom, observed at rest, as a function of gravitational or pseudo gravitational potential χ, we obtain [11] that the proper period of an atomic clock on the plane is given by

$$T(R+h) = T_0 \left\{ 1 + \frac{1}{c^2} \left[\frac{GM}{(R+h)} + \frac{1}{2} [v + (R+h)\Omega]^2 \right] \right\} \tag{4}$$

where $T_0 = h/\Delta E_0$ is the period and ΔE_0 is the energy difference between two fixed energy levels in an atom in a null potential. Comparing (4) with (5), which expresses the period of the clock on the ground:

$$T(R) = T_0 \left[1 + \frac{1}{c^2} \left(\frac{GM}{R} + \frac{1}{2} \Omega^2 R^2 \right) \right] \tag{5}$$

we observe that the velocity v (positive for the flight to the east, negative for that to the west), together with the different altitude at which the motion takes place, involves the quantification of a different gravitational and pseudo-gravitational potential, responsible for the variation of the natural period of B with respect to that of A. Comparing (4) and (5) to the law that quantifies the period of a clock at a distance $r \geq R$ from the center of the Earth:

$$T(r) = T_0 \left[1 - \frac{1}{c^2} [\varphi_G(r) + \varphi_A(r)] \right] \tag{6}$$

where $\varphi_G(r)$ is the gravitational potential of the Earth at a distance r from the center, and $\varphi_A(r)$ is the pseudo gravitational potential at the same distance due to the centripetal acceleration of the reference, we deduce that equation (4) contains both the effect of gravitational and pseudo-gravitational potential. Hafele's theoretical treatment [13] makes use of the metric of a non-rotating system centered in an homogeneous gravitational sphere (the Earth). Hafele (through successive integrations) gets the relationship between the time intervals measured by a clock on a plane and a clock on the ground:

$$\frac{\Delta\tau(R+h)}{\Delta\tau(R)} = \frac{1 - \frac{GM}{c^2(R+h)} - \frac{[\Omega(R+h)+v]^2}{2c^2}}{1 - \frac{GM}{c^2 R} - \frac{R^2\Omega^2}{2c^2}} \tag{7}$$

This formula, as the author shows, can be greatly simplified if $h << R$:

$$\frac{\Delta\tau(R+h)}{\Delta\tau(R)} = 1 + \frac{gh}{c^2} - \frac{2R\Omega v + v^2}{2c^2} \tag{8}$$

where $g = GM/R^2 - R\Omega^2$ is the gravity acceleration measured on Earth surface at the equator. Since the time interval measured by a clock is inversely proportional to its proper period, the above formulas can be obtained as the ratio between the proper period of an atomic clock on Earth surface and at the height h, respectively given by (5) and (4). It is remarkable that Hafele develops its calculations without paying attention to the real clocks used in the experiment, while equation (3) shows that only the particular structure of atomic clocks (whose proper period varies as a function of potential, according to equation (4)) allows to obtain measurements in agreement with his theoretical analysis. We can conclude that, if B describes an orbit of greater radius, at different heights from the ground, his atomic clock must measure, according to relativistic predictions, a different duration, since its proper period must change in agreement with equation (4), due to a variation of both the gravitational and pseudo-gravitational potential. These considerations are decisive in the development of the present critical analysis, as they help to conceive experimental tests that allow to shed light on a clear operational definition of time in physics.

8 Atomic clocks in a Dingle-Selleri experiment

In Dingle-Selleri's thought experiment, where clocks are separated after a phase of negligible acceleration of B, they remain in uniform rectilinear motion at different speeds and finally they rejoin after a negligible phase of deceleration, according to Einstein's theory clock B must have measured a shorter duration since it has described a shorter worldline. The problem of the different measures, without any variation of the potential, is therefore resolved through a theoretical idealization, irrespective of the experimental answer of real clocks: it is assumed that the time interval is contained in the worldline, regardless to the structure of the clock that describes it. Since, according to (4), the proper period of atomic clocks does not vary in a constant potential, we propose to submit two atomic clocks to a Dingle-Selleri experimental test to observe their behavior under such conditions. The result of the measures would be a necessary completion of the Hafele and Keating experiment, with the aim to verify whether these clocks are in agreement with relativistic predictions even in situations in which the contraction of the duration, measured from the traveler twin, is due to a velocity change without any potential variation.

9 Radioactive particles in linear beams

In 1940 Bruno Rossi and David Hall [14] measured the average lifetime of muons in flight in the atmosphere, by calculating the ratio $\tau = l/v$, after having quantified the average distance l, traveled by the particles before their disintegration, and their velocity v. Despite the atmosphere has influenced the measures, especially for the particles of higher energy, the experiment has confirmed the Einstein law:

$$\tau = \frac{\tau_0}{\sqrt{1-\beta^2}} \tag{9}$$

in agreement, in the opinion of the authors, with the hypothesis about the relativistic change of the rate of clocks in flight [8]. From the fifties, through linear accelerators, the inertial motion, at relativistic speeds, of radioactive particles in vacuum was studied. In absence of perturbation factors due to impacts of muons with air molecules in Rossi and Hall's experiment, in David Ayres experiment (1971) [15], with positive and negative pions in flight, it was achieved (proceeding in a similar manner) a most accurate confirmation of law (9). It is noteworthy that motion, in atmosphere as in vacuum, was rectilinear and uniform, so an observer in the same state of motion of particles (particularly in the linear accelerator experiment), must obtain a measurement of the lifetime identical to that quantified on a sample at rest in the laboratory, as a simple consequence of the principle of relativity. It can be deduced that the average lifetime is not altered by the different state of motion with respect to the terrestrial laboratory, in blatant contradiction with the Rossi and Hall hypothesis about the rate change of clocks-particles in flight. Let us consider, in this regard, a Dingle-Selleri experiment, in which the observer in the same state of motion of pions, initially in the laboratory, after the voyage rejoins the observer in the laboratory and compare the amount of decayed particles in flight with those decayed, given the same initial parent substance, in a sample remained at rest. The theory states that the flying observer had quantified a minor amount of daughter substance as a consequence of the minor length of the worldline described in spacetime. In absence of variation of the average proper lifetime of pions in flight, it may be admitted that the amount

[8]"The softer group of mesotrons was found to disintegrate at a rate about three time faster than the more penetrating group, in agreement with the theoretical predictions based on the relativity change in rate of a moving clock". (p. 223)

of daughter substance is the same in both cases: this possibility, if experimentally confirmed, implies the falsification of Einstein's theory of durations, that real clocks should quantify to be different between two extreme points in spacetime along different paths.

10 Muons in a storage ring. Radioactive clocks

In the CERN experiment with muons in a storage ring (1977) [16], a dilation of the average lifetime of radioactive particles, in uniform circular motion with respect to the laboratory, was measured, obtaining the same result as in the case of muons in flight in linear beams. The average lifetime of particles in flight was measured also in this case as the ratio between the average distance l, traveled before the disintegration, and the velocity v. It is noteworthy that the enormous centripetal acceleration of 10^{18} g (the authors of the experiment remarked with great interest the fact that such acceleration had not affected the internal structure and the average lifetime of particles [9]) had no effect on the muons with respect to the observers in the laboratory, who have interpreted the experiment as a simple speed effect, so that the average lifetime was dilated by the factor γ compared to that (τ_0) measured from the laboratory reference on a sample of muons at rest, in agreement with law (9). According to general relativity, a co-rotating observer at the center of the ring, for which the particles are at rest, explains the lifetime dilation, with respect to the measure made by an observer on a sample at rest in the laboratory, as an effect of pseudo gravitational potential due to the reference centripetal acceleration. The theoretical analysis developed within the conceptual framework of special relativity implies therefore a speed effect, while a co-rotating observer, within the framework of general relativity, notices a pseudo gravitational potential effect. The results are identical, as it is expected, and bring to the relationship (9) between proper and in flight average lifetime. The problem is relative to the different physical meaning of the alternative theoretical processing. In the case of muons observed in flight, it was not measured their average lifetime, since the operational definition of this quantity implies that the radioactive sample must be at rest with respect to the observer. The only operationally correct measure of the average lifetime

[9] "The possibility also exists that very large accelerations may modify in some way the internal constitution of particles. No such effects, in so far as they affect the particle lifetime, are seen in this experiment where the transverse acceleration is 10^{18} g." (p. 304)

is given by the co-rotating observer: the laboratory observer, although consistent, measures a quantity of different nature (called average lifetime in flight), that does not express a characteristic property of a radioactive sample. As above remarked, general relativity provides that the co-rotating observer should measure a quantity of decayed substance, related to the pseudo gravitational potential, less than the measured quantity in an identical sample at rest in the laboratory. If we introduce the concept of radioactive clock [17], a device consisting of a radioactive sample that allows to obtain measures of durations by quantifying the mass of decayed substance in relation to a certain phenomenon (e.g. the travel of a plane), we can control its behavior comparing it to a similar clock remained in the laboratory, in an Hafele-Keating's experiment, where on the plane we bring also radioactive aside from atomic clocks. Such a test would be an interesting alternative experiment that allows to check whether weak interactions, responsible for the decay of unstable particles, are sensitive to the variation of gravitational or pseudo gravitational potential to the extent predicted by Einstein's theory.

11 Mathematical and operational reality of relativistic time

Special relativity (in Minkowski's four-dimensional formulation) implies the reality of spacetime, deduced from the c invariance postulate. It is possible either to postulate the reality of spacetime and deduce the c invariance or vice versa: the theoretical content of the two statements is the same. Spacetime substance is made of universe points moving along worldlines. In this mathematical entity the concept of internal evolution is inessential: evolution is simply related to variations in the position of point-bodies caused by motions. A different length of the worldline implies a different proper time, so that a traveling clock (provided that it is in accordance with the definition of relativistic clock, as we will see in the next paragraph), moving along a given worldline, must measure a duration dependent on line length: clocks are deduced from time, in relativity. The cathedral of theory was built on mathematical-operational foundations: special relativity, based on the group of Lorentz transformations of the coordinates, was founded on the principles of c invariance and relativity; general relativity, based on the principle of equivalence and the geometrization of spacetime, was founded on the group of continuous, Riemannian, transformations of coordinates. Space and time are coordinates of a four-dimensional variety, while our senses and our instruments probe and measure properties of matter-energy as constituent attributes of a three-dimensional space. Time rises in this context as an operational concept transformed, in fact, in a useful mathematical variable, of which clocks should provide quantifications in agreement with theoretical predictions. Special and general relativity are philosophies of space and time that work, in matter of measurement of time intervals, only using particular clocks, then if it is axiomatically accepted the concept of time that those clocks (or equivalent others, of identical construction) imply. If we try to design not equivalent clocks and we use them in the same operating environment in which atomic work well, we almost certainly will not obtain measures in accordance with expectations. Clock of different internal structure could give incommensurable measures of durations. This means that every theory of relativity (Einstein's as Selleri's), in matter of measurements of durations, gives incorrect predictions? To a so delicate question we must provide a prudent and cautious answer. If it extends to all clocks the properties that apply only to clocks of particular construction, it will probably provide incorrect predictions, since it overlaps potentially incommensurable concepts of time. If we accept the perspective according to which a physical theory, consistently founded and logically developed, should be tested with measuring instruments that work according to the rules of the game, by definition ignoring all the others, relativistic theories are correct if an experimental verification is done with instruments consistent with the theoretical hypotheses. A careful analysis shows, however, as we will see in the next paragraph, that relativistic clocks, to be such, must operate in freely falling reference frames and must provide measures in agreement with theoretical predictions, i.e. they must correctly quantify durations varying the world line.

12 Definition of relativistic clock. Freely falling reference frames

Ludwik Kostro [18] proposes some interesting considerations about what, according to Einstein, the characteristics of an instrument for measuring durations should be. Starting from a review of the definitions of clock proposed by Einstein from 1905 to 1938 (the presence in the instrument of identical phases, then of a periodic phenomenon is necessary), Kostro argues that a relativistic clock, to provide reliable measurements, should be ideally point-like. The need (according to Max von Laue's [19] criterion) that the instrument presents, in addition to a vibrating system, an intrinsic device to supply energy and a feedback mechanism that allows to recharge it, does not exclude from the set of clocks hourglasses and pendulums, whose operational mechanism, however, according to Einstein's strong equivalence principle, ceases to act in a freely falling reference frame. A relativistic clock requires an internal process that does not cease to occur in free fall: this necessary condition includes both atomic and radioactive clocks, since in free fall atoms still emit photons and muons decay. Pendulums and hourglasses are not (relativistic) clocks because, in a similar reference frame, they cease to operate: this does not preclude, however, that at a given location they can keep time together with atomic or radioactive clocks. In presence of a gravitational field, or more generally in not freely falling references, such gravitational clocks reduce their proper frequency away from the source of the field, while atomic clocks increase it: the fact that they cannot be considered relativistic clocks, for the above mentioned reasons, does not prevent us to observe with some interest, without reducing it to a mere curiosity, this abnormal behavior. About freely falling references, another interesting observation arises, related to the following thought experiment. Let us consider a traveling clock that, after a phase of negligible acceleration, describes a free fall motion (e.g. inside an orbiting spacecraft), then, after a phase of negligible deceleration, it rejoins its twin. This issue is similar to that previously proposed about the physical cause of the rate variation of a clock in an experiment identified by the name of Dingle-Selleri. In the situations analyzed by these thought experiences, Einstein's theory explains the different quantification of durations as a recording of the different lengths of worldlines described by the instruments. In the event that a (radioactive or atomic) clock, in a Dingle-Selleri experiment, quantifies the same time interval of its twin, it is to be argued, as above observed, a falsification of the Einsteinian theory of durations as measurements, obtained by clocks, of the lengths of worldlines and a speculative and operational activity could open, starting from the analysis of the behavior, in different experimental situations, of real clocks, also depending on their internal structure.

13 Evolutionary internal time. Reversible and irreversible evolutions

Though relativistic theories present a rigorous and coherent conceptual framework as regards the logical-mathematical structure, the epistemological error highlighted from the above analysis is related to the possible overlap between two concepts of time of different nature: time-movement and time-evolution. Relativistic clocks measure durations depending on their state of motion or their position into a field: these measures, without any physical justification other than the matching between durations and lengths of worldlines, are also related to the internal evolution of bodies in the same state of motion of clocks, regardless of their structure. This axiomatic jump, whereby time must flow in itself, then in the same way for everything and everybody being in the same state of motion (or position into a field), is undoubtedly the most critical conceptual-operational aspect of these theories. If we observe the movement of a body and we find a way to measure its proper duration through a clock in the same state of motion, we can only conclude that this duration is related to motion, not to the internal evolution of body. Relativistic theories are founded on an operational-dynamic concept of time that is postulated also to be evolutionary. The fundamental thesis of this work is the need to distinguish between the internal evolution and the change in movement or position inside a field, and to redefine the scope, in matter of measurement of time intervals, of relativistic theories. General relativity is a theory of gravitation in which a conventional definition of time-motion and time-position is introduced, that applies only in its particular framework. The currently performed experiments prove that atomic clocks behave as relativistic clocks in situations in which the instrument is in a changeable gravitational or pseudo gravitational potential, since their proper period is linked to the potential according to (4). These experimental tests do not allow to extend such behavior to cases in which the potential is constant or zero, then in situations similar to the Dingle-Selleri thought experiment, i.e. the experiment with radioactive particles in uniform rectilinear motion in linear beams, or the experiment with clocks in freely falling reference frames. According to the fundamental idea that inspires it, this work believes necessary to study, inside every clock, the evolutionary processes in relation to the variation of potential, assuming that this variation in some cases could not influence the internal evolution. In the case of radioactive particles, since the CERN experiment has unequivocally proved that centripetal acceleration (with respect to the laboratory) has no effect (for values of 10^{18} g) on muons, is to be considered probable that a variation of the pseudo gravitational potential (with respect to a co-rotating observer) may not influence the rate of a radioactive clock. In the linear beams experiment two radioactive clocks should measure, when rejoined, the same duration, as the daughter substance produced at rest and in flight is with good probability the same, since the potential is not changed. Currently we do not know, for lack of experimental data, if the behavior of radioactive clocks (in the same experimental situations) is similar to that of atomic clocks: not being well known if the processes that cause the decay are influenced by the potential at the same manner as the energy variation between two levels in an atom, we do not know whether they behave as the atomic clocks in an Hafele-Keating's experimental test. In relation to the operation of the different clocks, reversible from irreversible processes have to be distinguished. The variation of the period of an atomic clock is due to the variation of gravitational and pseudo gravitational potential: the rate changes without the occurrence of irreversible processes inside the clock, i.e. without a permanent alteration of its internal structure once it returns, after a motion along a given path, to the starting point. Radioactive clocks operate through evolutionary processes of clearly irreversible nature, since the amount of mother substance available to the internal change progressively reduces: decay implies a transformation of the substance that cannot spontaneously return to its initial state, once the instrument comes back, after having described a given path, to the departure point. Since we do not believe to be able of adequately investigate it, here we only suggest that the cause of the possible discrepancy between the measures of evolutionary and relativistic durations is to be found in the thermodynamic nature, as well as quantum, of the evolutionary processes, whereby the increase in entropy within a system, with good approximation isolated, can lead to a total independence of a clock, e.g. radioactive, from external factors (or, at the limit, to their negligibility) that, in the case of relativistic (atomic) clocks, are instead dominant. This idea can certainly be explored in the future also in its quantum aspects.

14 An alternative road toward time

In his scientific autobiography [20], Albert Einstein observes that special relativity introduces two kinds of physical objects: 1) measuring rods and clocks, and 2) all other things, so the electromagnetic field, the material point, etc. This dualism (extendable to general relativity, if we include in all other things also the gravitational field, interpreted as a curvature of spacetime), is rather problematic, as Einstein himself recognizes, since measuring rods and clocks (objects consisting of atomic configurations in movement) should be deduced as solutions of the fundamental equations on which theory has been built, and not be designed as theoretically self-consistent entities[10]. However, as Einstein remarks, it was clear from the beginning that the axiomatic foundations of relativity were not strong enough to enable sufficiently complete equations to deduce a theory of measuring instruments. The conscious sin referenced by Einstein involves the explicit declaration of a potential incompatibility, particularly between real clocks and durations that, in accordance with equations that are deduced from the foundations on which theory was built, the measuring instruments should quantify. Einstein chose to proceed, inspired by a necessary empirical faith, from spacetime to measuring instruments, particularly from time intervals to real clocks. The fact that on that methodological sin also general relativity was founded is proven by the experimental situations analyzed in this work, summarized in the previous paragraph, so every clock should correctly quantify the duration predicted by the theory as if it was able to measure the length of the worldline along which it moves. The alternative road involves the approach to the problem of measuring durations starting from real clocks. According to this setting, a variation of the measurement must be linked to a change in the proper period of the instrument. Since the rate of a clock can change only in consequence of a variation of the gravitational or pseudo gravitational potential, it is deduced that a simple variation of speed, between two extreme points, of a clock relative to another, cannot cause a variation of the measurement of the duration, whatever the internal structure of the clock. In the case of radioactive clocks, the possibility remains open that they are not affected even from a potential variation, so they could quantify, regardless of the path followed between two extreme points, even in presence of different potentials, the same decay product, so they should measure the same duration. Consistently with the need to measure evolutionary times, we must submit different clocks to experimental tests designed to check if and how their rate changes varying the path between two extreme point-events. Starting from an accurate analysis of the behavior of clocks having different internal structure, the problem of the nature of time can be operatively refounded, as it is apparent from the following conclusive arguments.

[10] "Strictly speaking, measuring rods and clocks would have to be represented as solutions of the basic equations (objects consisting of moving atomic configurations), not, as it were, as theoretically self-sufficient entities [...] But one must not legalize the mentioned sin so far as to imagine that intervals are physical entities of a special type, intrinsically different from other variables." (pp. 59, 61)

15 Conclusions. From clocks to time

The conclusion of this work is a series of hypotheses related to the nature of time, whose value corresponds to new operational strategies or open questions. The analysis about relativistic theories has highlighted the conflictual reality of time, in both the theories of Einstein and Selleri, because the measure of durations is linked to axiomatic preliminary assumptions, without being able to consistently justify, in the different experimental situations, the answer of real clocks. To the implicit question about the nature of time every physical theory gives answers linked to conjectures, developed according to logical chains that ultimately boil down to tautologies. Only Newton's theory explicitly lays its foundation on a tautology, since it recognizes the metaphysical nature of time, believing mathematical durations to be inaccessible to measuring instruments. Relativistic theories, that seem having rooted the concept in a rigorous and apparently irrefutable operational foundation, reduce to mathematical conjectures, since durations are implicitly contained in the worldlines (Einstein) or have to depend on the speed with respect to the absolute reference frame (Selleri), so only instruments that obtain measures in agreement with theoretical predictions are clocks. The irreversible nature of phenomena that determine the operation of clocks, that very probably do not provide measures in accordance with relativity, implies that some of them could measure evolutionary durations independent from the state of rest or motion of the instrument. If this hypothesis is supported by appropriate experimental tests (the most notable case here we suggest to investigate is that of radioactive clocks), of time reality it would be impossible to give a unitary definition. Particularly the measure of cosmic time could assume a purely conventional meaning, as derived from a synthesis of measurements of the cosmic microwave background radiation, giving thermodynamic indications about the cooling time, and measures relative to the expansion, giving information of geometric and dynamic nature. If these implicit clocks had to provide incommensurable measures [11], Universe could be interpreted as a container of different evolutions not traceable to a unitary temporal flow. The foundational ideas that animate the speculative heart of scientific theories should therefore be called into question, starting from a clear analysis of the concept of clock in the different theoretical and

[11] The known issue about the greater age of some stars with respect to the age of the Universe could be a consequence of the overlap between incommensurable time scales.

operational areas where it is used to obtain measures of durations. The primary objective is to establish whether clocks giving physically different measures exist, impossible to refer to a unified theoretical framework, as claimed by Einstein's theory of relativity that, in matter of measurement of durations, aims to provide mathematical laws that predict the evolution of all clocks-bodies in relation to the world lines, then to the state of motion or the position within fields. In the light of the above analysis the impossibility of a unified theoretical vision, that strongly inspired Einstein's reflection, founded on the ideal, mathematical root of physical phenomena, is to be argued. It could be necessary to establish a new basis for the mathematical framework on which the physical idealization of experimental facts is founded: if, as Rovelli states, time is ignorance, a reflex of our incomplete knowledge of the state of the world, an appropriate critical revision is needed, founded on the here proposed observations. An accurate investigation about the different behaviors and the internal structure of clocks, to find new answers about the evolution rate of bodies and phenomena, may be the only way to bring theories to renew the operational concept of time, on which implicitly we can build, with no claim to universality, new explanatory hypotheses about the complexity of reality.

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