Review Article

Philosophical Aspects of Time in Modern Physics

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In classical physics, the concept of time appeared to be well-understood. With space, it provided a kind of stage where the events followed each other in an orderly way. The introduction of relativity and quantum mechanics profoundly changed this intuitive view. To address these challenges, the Aristotelian vision of time and the now is a promising starting point. His approach is compatible with the absence of absolute time and time′s granularity, required by relativity and quantum mechanics, respectively. Several issues, like Einstein's point coincidence argument and Wheeler′s delayed choice experiment, enter the discussion. The Aristotelian approach appears to lead to a novel understanding of time in modern physics.

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1. Introduction

In classical mechanics, time is treated as an absolute and independent parameter that flows uniformly and independently of other physical processes. Its meaning agrees largely with common sense intuition. In his widely used textbook on classical mechanics, Herbert Goldstein writes about space and time: these concepts *will not be analyzed critically here; rather. they will be assumed as undefined terms whose meanings are familiar to the reader*[1].

However, with the advent of modern physics, particularly Einstein′s theory of relativity, our understanding of time underwent a profound change. Time is no longer absolute, and simultaneity becomes an issue. Thomas Kuhn encounters a paradigm shift from Newton to Einstein:

> What had previously been meant by space was necessarily flat, homogeneous, isotropic, and unaffected by the presence of matter. If it had not been, Newtonian physics would not

> have worked. To make the transition to Einstein’s universe, the whole conceptual web whose strands are space, time, matter, force, and so on, had to be shifted and laid down again on nature whole[2].

The work on the conceptual web regarding relativity is still in progress. For example, it was only recently that the full impact of Einstein's point (spacetime) coincidence argument became evident[3]. It relates to the problem of observables in general relativity[4]. The review of Giovanelli[5] provides a detailed account of Einstein’s struggle with the meaning of coordinates in his theory.

The other new theory, Quantum Mechanics (QM), poses an additional challenge by considering fundamental uncertainties in time and position, e.g.[6]. The Heisenberg relation not only addresses the fundamental limits of the observer but also reflects a fundamental limit on the precision of complementary pairs of properties, see e.g.[7]. QM also postulates discrete steps in the movement or change of particles and radiation., the so-called quantum jumps. These lead eventually to the granularity of time and space. In addition, QM introduces final states that influence the outcome of an event in a way that is closely analogous to the initial state. An event here and in the following is considered as something with a certain extension in space that changes in time, not just a point in four-dimensional spacetime as defined, e.g., in[1].

Kuhn is addressing the challenges in the transition to Einstein’s universe. The proverbial weirdness of QM[8] also emphasizes the need for a paradigm shift. The author intends to provide a tentative version of the new conceptual web in the present study. Like in the work of Hoenen[9], the objective is to discover intelligibility instead of weirdness or counterintuition. It is like solving a puzzle. It is not possible to prove the correctness of each piece. Instead, the coherence of the complete picture will justify the choices made. The pieces of the puzzle lose value in the moment they are falsified. However, alternatives alone do not exclude them as pieces of the puzzle.

A good starting point for the puzzle's solution lies in Aristotle's concepts and methods. For him, the empirical evidence gathered through observation forms the most important source for establishing facts[10]. There is a significant difference with him, however. In contrast to the times of Aristotle, today, the observational evidence of modern science is only accessible to specialists. In contrast, scientists are often unaware of the philosophical discussions about the foundations of their science. In the present study, the Aristotelian approach is followed even if certain parts may be a problem for the scientist, whereas others may be challenging for the philosopher.

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Many publications intended for the general reader deal with time in modern physics. In some cases, these writings have reached millions of readers, demonstrating the desire of many to know more. One may mention Stephen Hawking: *A Brief History of Time*[11], Robert Penrose: *Cycles of Time*[12], Sean Carroll: *From Eternity to Here: The Quest for the Ultimate Theory of Time*[13]; see also[14], Richard Muller: *Now: The Physics of Time*[15], and Carlo Rovelli: *The Order of Time*[16].

In the following, the author intends to focus on the philosophical aspects of time in modern physics. In literature, there are many approaches to tackle the issue of time in philosophy; see, e.g.,[17][18][19][20][21][22][23][24][25][26][27], and[28]. In the present study, a classical line of thought is followed, initiated by Aristotle and taken up by Aquinas, and more recently, by Hoenen[9] and Elders[29].

When dealing with a wide arch of arguments, focusing on the main line of reasoning is necessary. The challenges already start when summarizing the results of modern physics: there is no general agreement on the foundations. Necessarily, the author has to make choices. Regarding physics, he intends to accept the mainstream results. In philosophy, the situation is different, as he would like to demonstrate that a classical approach established by Aristotle is promising for creating the conceptual web mentioned in Kuhn's quotation above. In a previous study[30], the author showed the convenience of the Aristotelian analysis for a philosophical understanding of movement and change. In particular, he examined whether this line of argumentation could provide a basis for a better insight into the philosophical aspects of QM. The main argument depended critically on a correct understanding of the nature of the continuum. This concept will also be fundamental in our understanding of the characteristics of time.

After these introductory remarks, the article's main body will consider time in classical philosophy. It starts with Aristotle's definition and then concentrates on time as a continuum. The present now and its relation to time will receive special attention. The typical Aristotelian notion of potentiality will be paramount in discussing the relation between the continuum and its parts.

After that, a section summarizes the two modern theories, relativity and QM. It is written to provide the background in physics for the philosophical analysis. It starts with time and relativity and concentrates on the *now*. Next, the focus is on time and QM. The granularity of time is an important issue related to the occurrence of natural minima in the parts of any continuum, including time. Another aspect of QM, the influence of the final state, asks for an additional discussion.

The last section presents a summary of the argumentation and a brief discussion.

2. Time in classical philosophy

2.a. The definition of time by Aristotle

Classical, premodern physics considers the universe a vast stage where things and events evolve according to a continuously ticking, absolute clock[31],[32]. The stage itself is an Euclidean space[1]. Our everyday life experiences seem to confirm this stage view. With Einstein's theory of relativity, see the next section, this Newtonian view had to be given up. In relativity, the Euclidean is interchanged by the Minkowski space, and universal time appears as an illusion.

Remarkably, Aristotle starts with a different line of reasoning. In his philosophy, not space but an object's place belongs to reality. (Physica IV 4, 212a20-21). *Hence, the place of a thing is the innermost motionless boundary of what contains it.*[33]. That means there is no entity outside the place of the objects that would constitute the universe. Aquinas, quoted in[29] and[34]) expresses this in the following words: *From the preceding, it is manifest that outside the universe, there is neither place, vacuum, nor time.*

As we focus on time, we do not enter the discussion of the Aristotelian place and refer to textbooks like[9] and[29] or[35] and[36]. In this vision, objects are locally related not by reference to the stage, as mentioned above, but by immediate contact with a neighboring object. A chain of objects linked by direct contact constitutes a reference for objects further away.

In a previous study, the author discussed the Aristotelian approach to change or movement and the foundation of QM[30]. Central in this approach is the notion of the continuum. It is an unbroken, connected whole. Aristotle argued that a continuum cannot be composed of indivisible points. It is, however, infinitely divisible into reduced parts with the same characteristics as the whole. One should distinguish the fluent continuum (*continuum fluens*) from the static continuum (*continuum permanens*). The latter is any static material reality endowed with unity. On the other hand, the fluent continuum involves time. In the case of movement or change, one deals with a continuum extending in space and time. Quitting the space dimensions altogether, one ends with a specific fluent continuum: time.

Roeper[37] analyzes the Aristotelian continuum and compares it to the contemporary approach, which takes it as a totality of points, the ultimate parts. He questions himself:

> Aristotle's view has considerable intuitive plausibility. So why did the point conception win out over the Aristotelian conception and form the basis of classical geometry?

> One reason is metaphysical in character: the view that the parts of a whole are ontologically prior to the whole. (...) Another reason is that the logic invoked to describe structure is a logic based on (domains of) individuals.

The general properties of an Aristotelian continuum can be summarized as follows: it is an object of reality, and it is a whole. It is potentially divisible into parts with a similar nature as the whole. The parts of a line are small lines, the parts of a change or movement are small changes or movements, and the parts of time are brief time intervals. A typical Aristotelian subtlety enters the characteristics of the parts of a continuum. Besides being actually (*in actu*) and its denial, being not at all, there is a third intermediate position: being potentially (*in potentia*). In this way, a continuum has no parts; otherwise, it would be an aggregate. Nevertheless, *in potentia*, it can be divided into parts. As long as the division has not occurred, these parts are not an object of reality.

Another issue regards the divisibility of a concrete physical continuum, e.g., a copper wire. Representing the wire by a line, one abstracts from all physical properties and eventually ends up in geometry and mathematics. In this level of abstraction, the continuum is infinitely divisible. However, the situation will change if one considers the nature of this specific continuum, i.e., the physical properties. The wire's nature (in Greek physis) determines an ultimate limit for the division: the *minima naturalia*. These are the copper atoms; further division would result in parts with different natures: protons, neutrons, and electrons.

The general properties of the continuum apply also to the *continuum fluens*. The change or movement is an object of reality, and its duration is a whole. Mathematically, the division into smaller movements or small durations may be possible. However, the physics of the concrete situation would set the ultimate limits to the possibility of division. In QM, in many cases, no division at all is allowed. An example is the fixed spin ½ of the electron. For more details, see[30] and the section below on QM.

Both time and movement are fluid continua, but they are not identical. In our imagination, time without change appears to be weird. Aristotle states (Physica IV, 219a2-219-a3):

> It is evident, then, that time is neither movement nor independent of movement. We must take this as our starting-point and try to discover—since we wish to know what time is—what exactly it has to do with movement.[33]

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Other visions are possible in philosophy. Shoemaker[38] argues that time without change or movement is conceivable. The literature still discusses his position; see[26].

To prepare the definition of Aristotle of time, Hoenen[9] distinguishes, in analogy with space, two possible structures of time: the topological and the metric structure. Consider, for example, local movement from position A to B. One could say that the position of an in-between point C is obtained after A and before B. Regarding a fourth point, D, between A and C, one could state that D is before C and after A. This topological structure of 'before' and 'after' does not include statements about the extent of time passing in the local movement. In the metric structure of time, this information is provided, e.g., by counting the occurrence of periodic events.

There is a direction in the flow of time in the movement, often called the arrow of time. It appears that an Aristotelian approach could clarify this issue. Starting with reality, with a concrete movement, there is no doubt about the topological structure before and after. If, however, priority is given to the mathematical description of the movement, then the arrow of time remains an issue.

Now, we may introduce Aristotle's definition (Physics 219, b1), which relates to time's topological structure. *For time is just this—number of motion in respect of 'before' and 'after'.* The original Greek text employs *arithmos* and is translated here as *number*. Hoenen[9] emphasizes that a better translation should be *numbering*.

The reason for this becomes apparent if one reads the following sentence in the above-given quotation (Physics 219, b2): *Hence time is not movement, but only movement in so far as it admits of enumeration.* In this quotation from the Greek original, the same word, *arithmos*, is used and now translated by *enumeration*. The meaning is obvious: in a movement, one arrives in the beginning at a first moment or phase, then a second, a third, and eventually at a moment of the movement already near the end. The appropriate translation of the Greek *arithmos* remains a point of discussion. Several authors translate it as measurement, see[18].

It is difficult to grasp the depth of the above definition of time. Time is related to a moving thing, an event extending in space and time. If another event is in direct contact with the first, one could extend time and space to include both events. Including more and more events, one could define the metric structure of time and establish a local universal time. In analogy, one could determine the metric structure of space from the contact relation between objects. In this way, Newton's classical view of a stage and a universal time becomes locally feasible.

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Common sense always relates time to the numbering of periodic movements. For slow processes, the regular rhythm of the year cycle is appropriate. The earth's rotation with the day and night changes is more convenient for shorter times. Later in history, the pendulum, the quarts- or the atomic clock counts stable periodic processes. In this way, the metric structure of time becomes more and more accurate. With our familiarity with time's metric structure, we often do not realize that Aristotle focuses mainly on the topological structure.

2.b. The Now and Time as a Continuum

Our special attention focuses on the now in the following. A few quotations may illustrate the central role of the now in the philosophical analysis of time. Aquinas comments: *But nothing exists of time except now (S.Th. I. q. 46, a. 3, ad 3).*

[Dunshirn 2006][20] observes: *The now has always been considered the center of Aristotle's theory of time.* He continues with a quote from Heidegger:

> Aristotle sees the essence of time in the νυν (now), Hegel in the now. Aristotle grasps the νυν (now) as ορος (limit), Hegel takes the now as "limit". Aristotle understands the νυν (now) as στιγμη (point). Hegel interprets the now as a point. Aristotle labels the νυν (now) as τοδε τι (a this). Hegel calls the now the "absolute this".

With the theory of relativity, the now and simultaneity are becoming a discussion point, e.g.,[39]. Einstein even denies the adequacy of the now for physics. In a letter from 1952, he states that *Physics has no possibility of expression for the Now* (quoted in[25]).

In our analysis, we start with the observation that, according to Aristotle, time is a continuum. Above, we mentioned that the parts of a continuum are on their turn continua. These have, of course, diminished extension. What can we say about the now? Is it part of the time? Probably not, as the now is like a point and surely not a continuum. Aristotle employs several analogies for a more in-depth understanding; see part IV of[18] and[20]. Coope explains that the now is not the past nor the future; it is *a link of time, for it binds together the past and the future* (222 a 10–11). Besides binding, the now also has the function of separation. It is the closing limit of the past and the future's starting point. Moreover, with the flow of time, *the now is in a way the same always and in a way not the same* (219 b 12-13). It is a point in time; without extension, it is not a part of the time. It is like a point moving on a line. Here, one must remember that the point may be on a line but is not part of a line. Aristotle considers an analogy that involves the point on a line and the thing-in-motion and comments. *The now and time are together, as are the thing-in-motion and its movement* (220 a 1–3). This comparison emphasizes the importance of the now because if something moves, the most important is that something and not the motion.

One could now ask what happens if something has no before and after, in other words, if something does not change as it is principally unmoved. Aristotle explicitly discusses this in Physics, VIII, 6 (259 a 12-15) when he speaks about the unmoved mover (the first mover):

> Here it is sufficient to assume only one mover, the first of unmoved things, which being eternal will be the principle of motion to everything else. The following argument also makes it evident that the first mover must be something that is one and eternal.

In the view of Aristotle, it would be possible to say that the now remains the crucial relationship with time in the unmoved mover, and there is only a single now. The unmoved mover is always remaining the same; its now is the *nunc semper stans* in contrast to the *nunc fluens* of all other realities[29],[40]. Aquinas comments (In IV Phys., lect 18, n. 586),

> For the "now," insofar as it corresponds to a mobile that is continually other and other, distinguishes the "before" and "after" in time and by its flow makes time, just as a point makes a line. But if that varying status of the mobile be removed, the substance remains always in the same state; whence the "now" is then understood as always standing still and not as flowing nor as having a "before" and "after."

Taking the Aristotelian vision of the now, one envisages a question. Will the now be universal? In other words, is there a global or cosmic now? Reading the extended comments of part IV of[18] *The Sameness and Difference of Times and Nows,* one understands that Aristotle did not restrict himself to local simultaneity. In relativity, however, that question plays a fundamental role; see[41],[23],[42].

Assuming that the now is only locally well-defined, one still can accept the Aristotelian vision of the now. Two events interact when there is contact in a shared now and when they share the same place. In that case, the observation of Coope seems the correct interpretation of Aristotle *to gar nun to auto pot' ēn* (219b 10-11). *The now (whichever now it is) is the same*. Coope comments: *His (that of Aristotle) point is that the times of simultaneous changes are all bounded by one and the same now*[18].

In this way, one may arrive at a statement about the interaction between events and causal chains originating from agents: An event can undergo immediate causal influences from other events or agents

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only if they are simultaneous, i.e., if they share the same now. Besides, they should stay in local contact at this moment. The latter condition excludes action at a distance.

In section 3.a, we will consider time in relativity. Here, it is sufficient to mention that Einstein, in the derivation of general relativity, introduces the point-coincidence argument[43],[5] that expresses the same idea: *Nature's laws are merely statements about temporal-spatial coincidences* [44]. Dieks[23] explains that a*ccording to relativity, material bodies and fields can only feel and influence each other directly per space-time point at which they are co-present.*

This statement for interacting events or chain of causes does not need any reference to space or time coordinates. Einstein claims that *the last remnant of physical materiality of the coordinate system has been dissolved.*[3].

The full meaning of the point coincidence argument becomes manifest when it includes the unmoved mover with the *nunc semper stans.* The claim is that the now of the unmoved mover coincides with the now of any event. Here, one should respect the asymmetry in this relation of coincidence. An arbitrary event's now is not the same as the *nunc semper stans* of the unmoved mover. For the unmoved mover, the condition of coinciding with any change is always guaranteed. Here, we do not discuss the local aspects further but state that the unmoved mover is not localized but rather ubiquitous.

These considerations about the now and the unmoved mover may appear entirely speculative and irrelevant to modern physics. Nevertheless, QM's weirdness severely challenges our imagination, especially when discussing in section 3.c. the role of the final state and delayed choice experiments[45].

A question remains about the different types of continua we encountered above: the static one, i.e., the spatial extensions of a thing, and the fluent one, like time and movement. The continuum is a whole, which could potentially be divided into parts. The question now arises about the fundamental lower limits for these parts, the *minima naturalia*. Aristotle discussed the infinite divisibility of the whole (Physics 1.4 187b14-21). Medieval Arabic and Latin commentators further developed the minima doctrine[46]. It proves that for Aristotle, the occurrence of minima in the case of the continuum was not a point of discussion. Aquinas explained more precisely why minima are present in the physical world. Like a line, mathematical continua are divisible to infinity, but physical continua have specific properties. The division may be possible, but only down to specific minima. Extending the analogy to the fluent continuum, the movement and time, one should expect that the nature of the particular movement inhibits division to infinity. This point of granularity of time will be discussed in the QM section.

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3. Time in Modern Physics

3.a. Time and Relativity

It is challenging to summarize the basics of the theory of relativity and introduce the philosophically relevant concepts. Even now, more than a century after the introduction of general relativity[3], new aspects like a complete understanding of the point coincidence argument ask for more profound work of the specialist. Considered in the first instance as a triviality[47], it soon appeared to be related to the coordinates of space and time. Giovanlli[5] explains the history of this argument and contributes with a detailed analysis of the private communications between Einstein and the Leiden group. In these communications, the full potential of the argument is unfolded. Giovanni mentions the members of this group, such as Lorentz, Ehrenfest, de Sitter, Droste, Nordström, and the young physicist Fokker. At the death of Einstein, Fokker published a personal memory about the work of Einstein[48] and his periodic stay in Leiden as a visiting professor. Fokker spent the winter semester of 1913-14 in Zurich, working under Einstein's guidance on general relativity. In 1960, he published a Dutch textbook on relativity, which was later translated into English[49]. The quotations from this textbook illustrate our line of reasoning, which is also in accordance with Giovanelli's view.

Above, we spoke about events that extend in space and time. A three-dimensional sketch works well for our imagination. Therefore, literature often encounters a pseudo-three-dimensional picture of the light cones, see Fig. 1 taken from[50]. It contains the hypersurface of the present and shows past and future light cones. One recognizes two of the three spatial coordinates and, vertically to it, the time coordinate. The point at the origin between the two light cones on the hypersurface of the present is the present now. If nothing happens, the hypersurface of the present moves up in time. Accordingly, the now is moving upwards on the time axis. If an object moves from the origin to the right, its location changes with time. The new hypersurface of the present would move upwards in time and to the right in the local position. In classical physics and also in special relativity, the two hypersurfaces would remain parallel. The connection of all origins of a moving object would define its world line. If one increases the object's speed, more and more space changes in time. Eventually, the object reaches a maximum speed, the speed of light. Why is there a maximum? In Newtonian mechanics, this limit does not exist; Einstein made this postulate. Modern physics confirms this postulate in experiments and theory. We would obtain the so-

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called light cone if we drew the worldline of light spreading in all directions. All moving objects starting from the origin would have worldlines inside the future light cone.

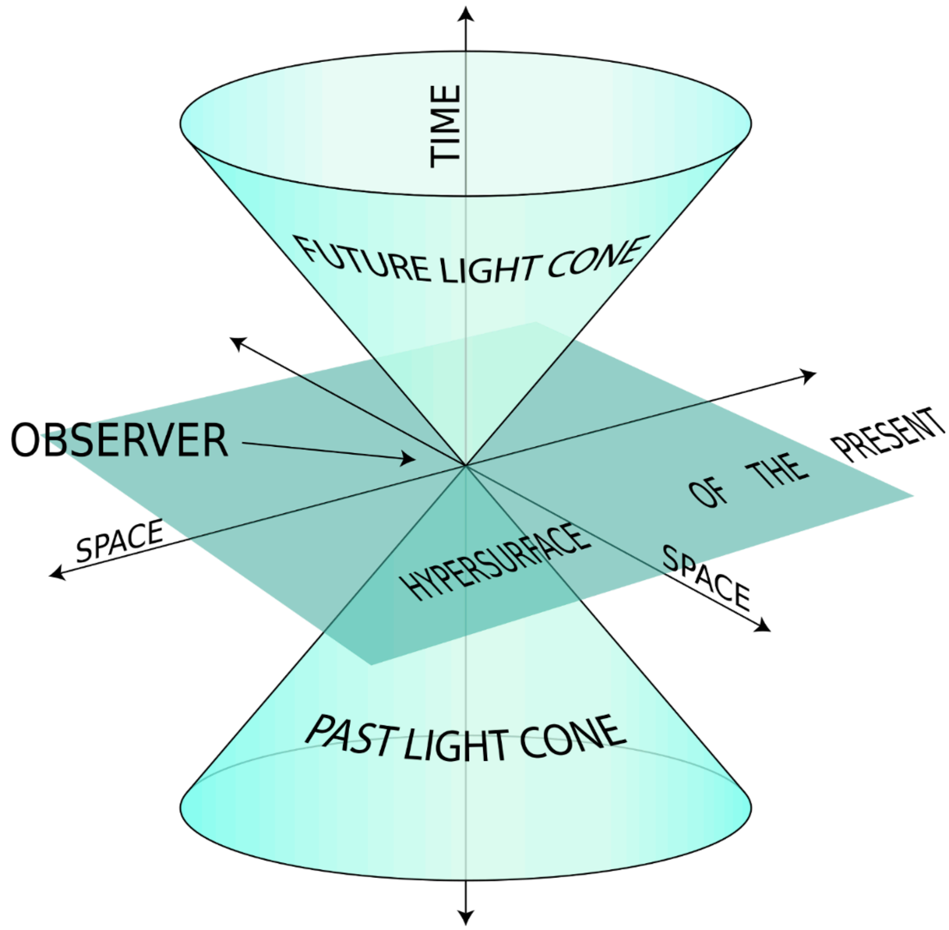

Fig. 1. Diagram of a light cone. A light cone (or "null cone") is the path that a flash of light, emanating from a single event (localized to a single point in space and a single moment in time) and traveling in all directions, would take through spacetime.

The origin, the now of the observer, separates the past from the future. What can one say about the material influences the observer may undergo in the present? Common to all influences is that they should arise from within the past light cone. Similarly, all effects and movements starting at the origin will only reach objects inside the future light cone. What about the large volume outside the two light cones? They are the locus of all events that do not influence the observer's now nor will undergo changes originating from events starting at the origin.

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Above, we have worked with parallel hypersurfaces, which is correct in special relativity. In general relativity, these surfaces may turn over for two reasons. The first is the effect of speed, and the other is the effect of gravity. The most remarkable effect of relativity is time dilatation. As a philosopher, one must separate physics from physical facts' philosophical interpretation. Newton's idea of a universal time does not appear in the Aristotelian analysis. Time is the numbering of a movement regarding before and after. Primarily, time addresses the topological structure of the event. The crucial point now is that the topological structure of time does not change in time dilatation with relativity. However, the metric structure of time may depend on location and speed. Going back to the light cone picture, one can state that events within the past light cone are always before the now of the origin. Furthermore, events in the future light cone will occur after the now of the origin. The topological structure of time is not affected.

What can one say about the events between the future- and past light cones? They are events neither-before-nor-after. Two quotations may clarify the challenging ideas expressed in the light cone picture. The first text is from the textbook of Adriaan Fokker[49]:

> It is often believed that space and time have a meaning independent of events, in the sense that space and time as such are recognizable entities. Space then is comparable with an empty stage, which can be occupied by the actors, and time is something like an empty pause, waiting for the beginning of the play.
>
> This view however is not correct. Events do not take place in a pre-arranged space and time, but rather we find space and time within events. Time and space are names for the possibilities of certain relationships between occurring events, that is relationships of the kind ***before-and-after***, and of the kind ***neither-before-nor-after***.

Fokker characterized the events situated outside the light cones of the past and the future *neither-before-nor-after.* A contemporary physicist, Carlo Rovelli, extends this view and explicitly connects these events with the present, the now of the origin. The events outside the volumes of future and past light cones occur in the expanded present[16]:

> There is our past: all the events that happened before what we can witness now. There is our future: the events that will happen after the moment from which we can see the here and now. Between this past and this future there is an interval that is neither past nor future and still has a duration: fifteen minutes on Mars; eight years on Proxima b; millions of years in the Andromeda galaxy. It is the expanded present. It is perhaps the greatest and

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strangest of Einstein's discoveries. The idea that a well-defined ***now*** exists throughout the universe is an illusion, an illegitimate extrapolation of our own experience.

The light cones are fundamental for understanding relativity. Photons (the light particles) propagate along the light cone surface. What can one say about events originating on the past light cone and terminating at the origin? Consider, e.g., the emission of a photon from a galaxy millions of lightyears apart and detected now in a telescope. What is the relation of this event with time? Does it belong to the expanded present or the past? The mathematical formalism of relativity results in a very peculiar conclusion: a photon belongs to the expanded present and simultaneously to the past.

This point is conveniently illustrated by the equation for spacetime intervals Δs in the light cone picture:

$$\Delta s^2 = c^2 \Delta t^2 - (\Delta x^2 + \Delta y^2 + \Delta z^2) \qquad \text{(Eq. 1)}$$

Where c is the speed of light, Δt is the time interval between the events, and Δx, Δy, Δz are the differences in the spatial coordinates. On the light cone, the contribution of the time interval equals the contribution of the spatial coordinates. As a result, the spacetime interval Δs becomes zero. Fokker explains[49]:

> Perhaps the deepest enigma brought to light by chronogeometry is the occurrence of zero intervals, connecting events which are located by observers with spatial distance and temporal duration between them. Zero interval means no separation at all, an immediate transmission of momentum and energy, as if there were contiguity. Not only action at a distance, but action across a gap in duration as well.

Several studies address the peculiar properties of photons and other massless particles like gravitons. Roger Penrose confirms this conclusion[12]

> The point is that, according to a massless particle, the passage of time is as nothing. (...) One might well say that 'eternity is no big deal' for a massless particle such as a photon or a graviton. (...) Indeed, massless particles do not appear to be particularly concerned with the ***metric*** nature of space-time.

In a lecture at the University of Leiden Penrose confirms[51]: *Eternity is no time at all for a photon.*

Relativity theory opens a stunning view of reality. There is no space and time outside the objects and events; the stage view has to be given up. Several authors[4] and[5] describe Einstein's struggle to abolish the notion of a preferred coordinate system. Giovanelli writes while quoting Einstein:

> In this sense, the point-coincidence argument, far from being a mere trick to escape from the hole argument, can be considered as Einstein's mature stance toward what is actually observable in physics. "Physical experiences [are] always assessments of point-coincidences (spacetime coincidences)" [52] [p.3]

The unexpected characteristics of relativity become increasingly recognizable if the speed of objects approaches the speed of light. It is evident that photons, propagating with the speed of light, are the most relativistic particles. Section 3.c. section will demonstrate that they also possess remarkable quantum properties.

3.b. Time and Quantum Mechanics: granularity of time

In the preceding section about relativity, the Aristotelian view of time was confirmed in the sense that there is no universal time. Instead, time is the numbering of movements or changes according to before and after. For quantum mechanics, another property of time is relevant: time, like motion, is a continuum, a whole. The whole may be potentially reducible to several parts. Mathematically, a continuum is divisible infinitely. However, looking at the physics, i.e., the nature of the specific continuum, the situation is entirely different: there are minima.

In a study on physics and reality, Albert Einstein addresses the molecular structure of all that happens in the section about quantum theory and the fundament of physics. Here, we should clarify the use of the word continuum. Einstein distinguishes the old concept of a continuous space-time system from the molecular structure of all that happens. He foresees already a molecular or granular structure of the physical continua[53]:

> However, it has been pointed out that even the introduction of a spatiotemporal continuum could possibly be regarded as contrary to nature in view of the molecular structure of all that happens on a small scale. Perhaps Heisenberg's method's success points to a purely algebraic method of describing nature, to the elimination of continuous functions from physics. But then, the use of the space-time continuum must also be abandoned in principle. (Translation by the author).

Returning to the Aristotelian view on time, one remains with a not-so-easy task, separating the two types of fluent continua: movement (change) and time. Aristotle stresses that time is not an object of reality on its own. Time does not exist independently of any movement. What is real is the movement

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itself with a given time extension or, otherwise said, with a specific duration. Therefore, studying minima of time means looking for minima of movement. The main point of our previous study[30] was to demonstrate that the minima in the movement are related to the so-called Quantensprünge, quantum jumps in QM. The introduction of QM confirms theoretically and experimentally that movement is quantized. In this way, QM abolishes the view of Leibniz: *Natura non facit saltus* (nature does not make jumps)[54].

One could now ask whether there are minima for time, or better said, for the duration of movements. Several arguments confirm the existence of such minima, however small they may be. First, there is the Heisenberg uncertainty principle (HUP). This principle relates time with energy. It states that the product of the uncertainty in time or duration and the uncertainty in an event's energy has a minimum value. This value is extremely small for most practical situations: the Planck constant h.

The HUP is often presented as a fundamental limit for observing tiny objects in popular literature. It seems to be related to the limitation of the observer, who cannot extract the correct magnitudes from his experiment. For example,[55] explains that *the uncertainty principle states that we cannot know both the position and speed of a particle, such as a photon or electron, with perfect accuracy*. The uncertainty, however, is intrinsic to the physical system under consideration, independent of what any observer may know. In[7], the author has studied the characteristics of a wavelength measurement apparatus, a macroscopic table-top instrument. Its wavelength resolution can be derived directly from the HUP. In other words, the HUP determines the technical performance of a macroscopic apparatus independent of any observer.

If one goes to increasingly small durations of a movement, the uncertainty in time becomes smaller and smaller. Accordingly, with the HUP, the uncertainty in energy will rise. There is only finite energy available in a finite universe like ours. If the uncertainty in energy exceeds the universe's total energy, then the minimum uncertainty in time is reached.

In the extreme case of quantum gravity, the Planck scale is reached. Rovelli comments[16]:

> The time measured by a clock is "quantified," that is to say, it acquires only certain values and not others. It is as if time were granular rather than continuous. ***Granularity*** is the most characteristic feature of quantum mechanics, which takes its name from this: "quanta" are elementary grains. A minimum scale exists for all phenomena. For the gravitational field, this is called the "Planck scale." Minimum time is called "Planck time."

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Another argument about granularity in time involves information. Consider a common problem in classical mechanics: calculating the planets' movement in our solar system. It appears that Newton already knew the relevant equations. However, there is no analytical solution, even simplifying planets and the sun as dimensionless mass points and restricting oneself to two planets. Only numerical methods would provide an approximative solution.

Full precision in classical physics would require infinite information. Nicolas Gisin comments on a peculiar relation between information and volume. He writes[56], see also[57]:

> This argument is based on the assumption that no finite volume of space can contain an infinite amount of information. This is a well accepted result that follows from the holographic principle, known as the Bekenstein bound.

Finite information in the universe means that movement and time cannot be reduced infinitely. There is a minimum step in time, and again, one encounters granularity in time.

One of the fundamental relations of QM, the Schrödinger equation, is continuous in time. But it deals with wavefunctions, whose squares give only values for specific probabilities. The step from probability to the actual event, the collapse of the wavefunction, is definitively not continuous in time.

The arguments based on the Planck scale and the information limit above are taken from still-developing fields of physics. Nevertheless, they indicate that granularity or minima in time are reasonable options.

3.c. Time and Quantum Mechanics: causality and the influence of the final state

For a correct understanding of QM, one should focus on causality. Aristotle distinguished four aspects: the material and formal cause, the efficient cause, and the final cause[58]. The latter is of particular interest when dealing with time. The reason is that the final cause is, in two ways, related to time. It is the first aspect of causality, explaining why the efficient cause is acting. Speaking with an anthropomorphic notation, one could say that the final cause motivates the efficient cause to initiate the causation process. Simultaneously, the final cause is related to the change's aim, objective, or end. The final point is realized only in the future at the final point of the change or movement. In a certain way, the future is present initially and contributes to the movement's characteristics.

We have already spoken about the HUP above. It is responsible for the granularity of time and granularity in position. It also changes the view on causality of people working in science. Classical physics favored the deterministic concept of causality. Heisenberg felt urged to abandon it with his famous statement:

quantum mechanics has definitively confirmed the invalidity of the principle of causality[59]. Philosophically more correct, one could state that physics abandons determinism but not the rich concept of causality encountered in classical philosophy. There is a discussion on Aristotle's support of strict deterministic causality. Lee concludes in his Ph.D. thesis[60]: *I believe that Aristotle is an outright indeterminist.*

Dealing with the continuum, we already encountered the Aristotelian distinction of being potential besides being actually and not being at all. This third alternative allows for a relevant subtlety to understand causality better. Cause and effect are not necessarily rigidly connected because condition A should always result in event B. In a mechanistic system, this is always true, but not in quantum mechanics. There, the mathematical formulas express as usually the laws of nature. These formulas, however, do not determine the effect rigidly but only state what potentially may happen. The relevant equations make even quantitative predictions with high precision. In that case, the degree of potentiality is called probability. For the single event, this appears to be weak causation. However, if the same experiment is often repeated, the theoretically determined probability agrees very well with the experimental results.

In QM, theory can determine the probability that a particular effect occurs. In many cases, the laws of science do not further define this. Nevertheless, the events happen in a specific way. In that sense, one may state that physics is not complete. Einstein summarizes his findings about QM as follows[53]:

> I also try to explain why, in my opinion, quantum theory does not seem suitable for providing a valuable foundation for physics: One runs into contradictions if one tries to regard the quantum-theoretical description as a complete description of the individual physical system or process. (Translation by the author)

A well-known equation in QM is called Fermi's Golden Rule. It relates the transition rate of a quantum system with the initial and final state; see[6] and[61]. The final state influences the probability of an event similar to the initial state. And the final state may be in the future. How is it possible that a future constellation determines the outcome in the same way as the initial state? A comparison with everyday life may clarify the unexpected character of QM. If the taxi driver starts his journey with his client to his hotel, the exact route and travel time are only approximately determined by the starting point and the destination. Imagine the client receiving a phone call to pass urgently to another site during the journey. The taxi driver will change direction but cannot undo the first part of the trajectory.

In QM, the situation is different when performing experiments with photons. The light path between light emission and absorption is a whole that only potentially, but not actually, consists of parts. The final point, where absorption of the photon occurs, depends on the final state. The remarkable fact here is that the final constellation influences the complete trajectory. Furthermore, this happens even if the decision about the final point is made well after the photon's emission. This peculiar situation leads to Wheeler's delayed-choice Gedanken experiments[45],[62]. Meanwhile, these are experimentally confirmed[63] and[64].

4. Discussion and conclusions

In the present study, we did not repeat the details of our previous work on Aristotle and the foundation of QM[30]. Instead, we focussed on the Aristotelian concept of time. His definition, *for time is just this—number of motion in respect of 'before' and 'after'* demonstrates the close link to motion or change. To understand time, one has to understand motion. In an Aristotelian view, both are considered as a continuum. Here, one encounters the typical Aristotelian peculiarity regarding the whole, the continuum, and its parts. As long as no division is made, the whole is real, and the parts -if any- are only *in potentia* available. Division of a continuum results in parts of identical nature. Division of time or duration results in smaller pieces of time or shorter durations. Perhaps unexpectedly, the center of the theory of time, the *now*, is no part of the time. It is like a point on a line.

Focusing on relativity, an Aristotelian view has the great advantage that not space but a thing's place is real. A coordinate system for space or time could be helpful for a specific restricted range, but it remains an arbitrary human construct. Time is the numbering of concrete changes; there is no universal time.

In section 2.b. we stated that interaction between two events is only possible when they share at a given moment the same now and are located in the same place. This is closely related to Einstein's point coincidence argument. There is criticism of Einstein's point coincidence argument. Weinert[65] comments:

> Finally, the philosophical notion of physical reality must be in harmony with the scientific findings. The 'point-coincidence argument' therefore led physicists to the invariance criterion of physical reality but Einstein's notion of 'local action' (no-action-at-a-distance) has not found the approval of quantum physicists.

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If one includes the Aristotelian unmoved mover, with his persisting now (*nunc semper stans*) a solution appears that[49] considers explicitly:

> We all know the experience of remembrance, as the presence here and now (in our mind we are inclined to say, in the events constituting our mind) of an event, past and distant. That comes very close to zero intervals. The mathematical formula is quite simple and plain, nevertheless it relates to one of God's secrets and implies His sempiternal ubiquitous presence.

Fokker mentions a mathematical formula, the above given Eq. 1. In this quotation, Fokker speaks about God. Perhaps it is more convenient to refer to the unmoved mover, who, according to Aristotle, is the principle of motion to everything else wherever it may be. The point coincidence argument would acquire a new dimension if one allowed for the causal influence of the unmoved mover sharing the now and here of any event.

Considering QM, we find in the Aristotelian view the possibility of probabilistic laws of nature and a tentative understanding of the role of the final state. Another aspect is the granularity of movement and time, expressed in the popular concept of quantum jumps (Quantenspünge).

Characteristics of time	motivated by relativity	motivated by QM
preference of topological above metric structure of time	x	
no absolute time	x	
no universal now	x	
point coincidence argument for the interactions of two events	x	
granularity of time		x
initial and final state involved in the causality of the event		x
possibility of delayed choice		x

Table I. characteristics of time motivated by modern physics

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Table I summarizes the characteristics of time motivated by modern physics. Our Aristotelian approach is a good candidate for fulfilling these severe demands.

In the introduction, we discussed the paradigm shift Thomas Kuhn expected with the transition to Einstein's universe. Our updated Aristotelian approach could be a good Ansatz for a paradigm shift. It is new, addresses the challenges of the theories of relativity and QM, and follows a well-defined route from old Greek philosophy and medieval Thomism to present-day studies. However, considering Aristotle a founding father of the theories of modern physics would be an anachronism.

Our approach builds upon previous work by[9][29][49][26] and intends to provide a new insight and new understanding of the philosophical aspects relevant to modern physics. There are interesting studies about modern science and philosophy relating them to Kant[66][65], and[67] or to mechanicism[68]. We found an adequate description of our endeavor in[65]:

> According to Max Born the revision of old concepts has to happen under the constraints of new experience.[69] We can consider them as physico-philosophical notions because they are not tied to any particular physical theory and have often been the subject of philosophical reflection from the Greeks to the present day.

In conclusion, we have presented an effort to bridge classical philosophy with modern physics. Reality confronts us with situations that severely challenge our imagination and capacity for understanding. The author hopes that the above study demonstrates that classical Aristotelian philosophy provides valuable concepts and tools for a deeper understanding of modern physics.

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