The evolution of the concept of time in modern physics

A evolução do conceito de tempo na física moderna

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ABSTRACT
The main object of this article is to contribute to a synthesis study of the notion of time through the physical theories. In detail, we focus on the evolution of the concept of time from Newton's classical theory to various modern theories such as relativity and quantum mechanics and more modern ones such as string theory and quantum computing. We are also interested in the notion of the arrow of time, which according to thermodynamic principles cannot be reversed. However, in the context of quantum computing, we show an interesting work in which it has been demonstrated that one can reverse the arrow of time.

Keywords: time, relativity, time arrow, string theory, quantum theory, quantum computer.

RESUMO
O objetivo principal deste artigo é contribuir para um estudo síntese da noção de tempo através das teorias físicas. Em detalhes, nos concentramos na evolução do conceito de tempo desde a teoria clássica de Newton até várias teorias modernas, como a relatividade e a mecânica quântica, e outras mais modernas,
como a teoria das cordas e a computação quântica. Também estamos interessados na noção da seta do tempo, que, de acordo com os princípios termodinâmicos, não pode ser revertida. Porém, no contexto da computação quântica, mostramos um trabalho interessante no qual foi demonstrado que é possível reverter a flecha do tempo.

**Palavras-chave:** tempo, relatividade, seta do tempo, teoria das cordas, teoria quântica, computador quântico.

1 INTRODUCTION

Time is complex and can be defined in various ways depending on the context. It has evolved in physics over the centuries and is still evolving today, guided by important scientific discoveries. The fundamental element of theoretical physics is time, which allows us to describe changes in the universe [1,15,16]. It is related to the notion of duration, which is used to measure events that occur in space and time. In everyday life, time is a concept that permits us to measure the duration of activities and events. It is related to concepts such as clocks, calendars and dates.

Initially, the concept of time was simple and intuitive. Time was considered as an absolute and eternal entity that flows uniformly and independently of any other phenomenon [2].

Classical physics began to formalize the notion of time in the seventeenth century. Galileo was the first who introduce time as a fundamental physical quantity, a quantifiable quantity that can order experiments and relate them mathematically. Newton was the first to define time in mechanics in his Principia: time flows uniformly; it is universal, and absolute; it flows from the past to the future, according to an invariable course.

However, a complete revolution was announced in 1905 by Albert Einstein's special theory of relativity, which showed that time was not an absolute and eternal entity but rather depended on the observer. Different observers relative motion can influence the flow of time. It can therefore stretch or contract depending on its speed and gravity.

Einstein's general theory of relativity, which was announced in 1915, describes that gravity is the curvature of space-time that results from the presence
of masses and energies. It is demonstrated that time flows more slowly in regions of strong gravity than in regions of weak gravity.

During the 20th century, the concept of time in physics continued to evolve thanks to new theories, such as the quantum theory of time, string theory, etc [1,3].

Here are two different answers given by two contemporary scholars in response to the question about the reality of time [24]:

Table 1 – Comparison between different answers given by two famous contemporary researchers on the reality of time

<table>
<thead>
<tr>
<th>Pr Barbour J.</th>
<th>Pr Smolin L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time is when things change.</td>
<td>Time is the most real aspect of our perception of the world.</td>
</tr>
<tr>
<td>Time is simply a complex set of rules that control our perception and change.</td>
<td>Non-causal children time is the most real of the world.</td>
</tr>
<tr>
<td>Time is can be inferred from things.</td>
<td>Space is emergent and approximate concept.</td>
</tr>
<tr>
<td>Time is in the instant.</td>
<td>Laws and nature evolve in time</td>
</tr>
</tbody>
</table>

Source: Sinchi, 2022.

In this paper, we will explore the different stages of this evolution by referring to the work of some of the greatest physicists in history and by discussing the following aspects:

- Objectivity/subjectivity of time: Is time an objective reality, independent of the observer, or is it simply a subjective construction of our mind?
- Flow of time: The time seems to be uniform and inevitable, but why does this happen?
- Relativity of time: Einstein’s theory of relativity showed that time depends on the observer’s speed and gravity, which has challenged the traditional notion of absolute and universal time.
- Quantum time: In quantum physics, time is considered as quantum operator, which suggests a radical new conception.
- Direction of time: Why does time always seem to move in one direction, from past to future, without ever moving in the other direction?

These issues show that the concept of time is still largely misunderstood and is being researched and debated in various fields.
2 FROM CLASSICAL TO MODERN THEORIES

Multitude of definitions, considerations, and attempts to understand the "reality" of time has prompted us to shed light on the evolution of the notion of time during different periods of modern physics development [18].

To address this thorny subject of time, we will review the three major stages of the evolution of the notion of time in physics, namely:

2.1 ANTIQUITY

Saint Augustine said about time: If one does not ask me what it is, I know clearly, but if one questions me, I no longer know! [23].

A.H. Zewail (Nobel Prize winner in Chemistry in 1999) said: "Probably the three questions that have occupied humanity for thousands of years regarding time are: What is time? What is the reason for its flow in a certain direction and not in others, and how can we comprehend and explain it? And it is the first question that is the most complicated." [25].

Initially, the principle of continuity was dominant throughout the history of physics until the 19th century. This continuity appeared in all the laws of physics, with the concepts of continuous space, which is considered to be composed of an infinity of homogeneous points, and continuous time, also composed of an infinite number of homogeneous instants that flow at a constant speed, uniformly in all directions of the universe, alludes to this continuity in all physics.

2.2 CLASSICAL PHYSICS

In Newtonian theory, time is considered absolute and uniform, regardless of what is happening in the universe. This concept of time is based on Newton's law of gravity, which describes the behavior of objects in space in terms of their position, speed, and acceleration. Celestial mechanics is a field of physics that studies the movements of objects in space, such as planets, stars, and comets. It is based on Newtonian laws of mechanics, which describe the gravitational interactions between celestial objects. Methods of determining time include observing astronomical phenomena such as eclipses and transits, as well as using ultra-precise atomic clocks and satellite navigation (GPS) [19,20,24].
2.3 MODERN PHYSICS

The theory of relativity, developed by Einstein at the beginning of the 20th century, is one of the most famous theories of modern physics. There are two theories of relativity, special and general, both based on the principle of relativity announced by Galileo in 1636. The theory of relativity changed many notions related to basic physics terminology, such as space, time, mass and energy. It created a qualitative leap in theoretical physics and astronomy with its launch in the early 20th century. It revised the theoretical foundations of Newtonian mechanics dating back to 200 years.

Let's turn to quantum mechanics, which was developed in the first decades of this century. Classical physics could not properly account for the behavior of atoms, and in particular the interactions between matter and light, so it was replaced by a revolutionary formalism, the quantum formalism, whose fecundity now concerns all branches of physics.

The theory of relativity has modified:

✓ The Newton’s notion of movement states that all movement is relative.
✓ The notion of time has changed from absolute to relative, becoming a fourth dimension integrated into the three dimensions of space.
✓ Time and space have become one thing, called space-time, after they were treated as two different things.
✓ Time depends on the speed of the object and the gravity of the medium in which the object movements.
✓ Time expansion and contraction have become new concepts for understanding the universe.

The special theory of relativity provided an explanation for the difficulties encountered in interpreting the results of the Michelson & Morley experiment (1887) [22], on the speed of light. This experiment, based on the diffraction of light in different directions, contradicted the relative speed law, which assumes that if a car is traveling at a speed very close to that of light, at about 99%, the light from the car’s headlights should have a speed close to twice the speed of light. However, the theory of relativity postulates that the speed of light is constant and does not depend on relative speed.
As for the general theory of relativity, developed by Einstein between 1907 and 1915 and published in 1916 with assistance from other scientists after 1915, it gives the current conception of gravity in modern physics.

Newtonian mechanics is a model based on classical mechanics principles that has been very useful to explain and predict the movements of objects on a macroscopic scale. However, for research on the concept of time, Newtonian mechanics has several limitations.

Newtonian mechanics cannot explain phenomena related to Einstein’s theory of relativity, which shows that time and space are interconnected and depend on the observer’s reference frame. It considers time as an absolute and uniform parameter, while general relativity shows that time is relative and depends on gravity [5].

Also, it cannot explain quantum phenomena such as superposition and interference, which suggest that time is not a uniform and absolute parameter.

In summary, Newtonian mechanics has limitations for research on the concept of time, as it cannot explain phenomena related to general relativity and quantum mechanics.

In 1905, Albert Einstein published his groundbreaking article on special relativity, which radically changed our understanding of time. It becomes relative and depends on the observer’s speed.

Equation of special relativity [7]:

\[ E^2 = (mc^2)^2 + (pc)^2 \]  

(1)

This equation, derived by Einstein in 1905 [6], relates a particle’s energy (E) to its mass (m) and momentum (p). It shows how energy and mass are linked and depend on the object’s speed. This fundamental equation of physics led to the notion of time dilation and the relativity of time as a function of speed. For example, two synchronized clocks will no longer be synchronized if one of them is set in movement. This theory has been confirmed by experiments such as the Langevin twin paradox and the Hafele-Keating experiment [11].

The twin paradox is a thought scenario that shows how special relativity can lead to different aging effects for twins who separate and reunite at different
speeds. According to special relativity, time passes more slowly for a moving observer in compared to an observer at rest. Thus, a twin who travels at high speed in space will age more slowly than a twin who stays on Earth. This scenario was popularized by the movie "Interstellar" [21].

Formula of time dilation [7]:

\[ \Delta \tau = \frac{\Delta t}{\sqrt{1 - \frac{v^2}{c^2}}} \]  

Here, \( \Delta t \) represents the time interval between two events for an observer in some inertial frame, known as the proper time, \( \Delta \tau \) is the time interval between those same events, as measured by another observer, initially moving with speed \( v \) with respect to the former observer and \( c \) is the speed of light.

The theory of gravitation relies on the theory of relativity is called the theory of general relativity. It describes how gravity affects time and space, such as the presence of mass and energy curving space-time, which affects the way time passes. For example, time flows more slowly near a massive object like a star or a planet. This theory has been confirmed by experiments such as the observation of the Shapiro effect [7].

“It is surely the most beautiful of physical theories”, said Lev Davidovich Landau in the second volume of his monumental Course of Theoretical Physics in ten volumes. “The most beautiful of theories” is also the title of the first of seven brief lessons in physics that Carlo Rovelli proposes.

Proper time equation in general relativity [7]:

\[ d\tau^2 = g_{\mu\nu}dx^\mu dx^\nu \]  

This equation represents the spatio-temporal interval \( d\tau \) of an object moving in a gravitational field. It is based on the space-time metric \( g_{\mu\nu} \), which describes the curvature of space-time in the presence of mass. It shows how time is affected by gravity and how it varies depending on the observer's position and speed. This is a fundamental equation that allows for the description of time measurements in a space-time curved by the presence of mass or energy. It plays an essential role
in understanding the nature of time in the context of general relativity. When moving in a gravitational field, the proper time measured by a clock moving along a specific trajectory may vary compared to the time measured by another clock moving differently in space-time."

Thus, by solving Einstein's equations for a particular physical system, one can obtain the corresponding metrics and, consequently, determine how proper time evolves along trajectories in this curved space-time.

Furthermore, Geraint F. L. et al have confirmed that just 1.5 billion years after the Big Bang, time ran five times slower than it does today. The Scientists have used quasars as ticking cosmic clocks [9]. For this aim, searched through data collected over two decades, which allowed them to study almost 200 quasars in detail. The discovery shows that time is relative in regards to the age of the Universe, too, just like Einstein predicted.

The arrow of time refers to one-way time flows, from the past to the future. In physics, the arrow of time is associated with the increase of the entropy in an isolated system with time, this is provided by the second law of thermodynamics. This temporal asymmetry between the past and future is an active research topic in physics [12].

Figure 1 - Arrow of time

**Psychological arrow**
- Past events
- Memories of the past, not the future
- Possible events

**Cosmological arrow**
- Small, dense and hot universe
- Expansion of the Universe
- Large, expanded and cold universe

**Thermodynamic arrow**
- Ice cube (crystal structure)
- Increase in entropy
- Puddle (no structure)

The flow of time, especially so-called arrow of time, that is, the existence of a physical criterion to distinguish between the past and the future, continues to pose significant problems of interpretation for physicists and philosophers. In fact, fundamental, classical, and modern physics are based on reversible dynamical descriptions, thus unable to separate the past from the future, which is in flagrant contradiction with the phenomenological perception of irreversibility that characterizes our everyday lives. To find a solution to this problem, toward the end of the 1860, Ludwig Boltzmann developed what is now called "statistical physics."

The idea is to describe the behavior of macroscopic systems. That is to say, the reality that we observe on a human scale, as arising from a multitude of microscopic variables (therefore on a molecular, or even atomic, scale) whose number is higher that we suppose; we can never know them all. We must therefore settle for a statistical approach, with chance and probability becoming key elements of our representation of the world. The flow of time in this view represents only the evolution of a system from a less probable state to its most probable state.

The 20th century saw the birth of the two most beautiful physical theories ever invented. The first, general relativity, is the work of Albert Einstein alone. Its field of application is infinitely large. The second, quantum mechanics, is the collective work of some of the greatest minds of the 20th century. Its field of application is the infinitely small. These two theories make physics the "queen of sciences".

But they are incompatible with each other. If one seeks to unite them in what is called "the theory of everything", one encounters insurmountable difficulties.

Quantum physics is a physical theory that describes the behavior of subatomic particles. According to this theory, time is a continuous and smooth variable, but there are quantum phenomena that defy the usual understanding of time.

For example, in the quantum tunneling effect, an object such as an electron or atom passes through a potential energy barrier that, according to classical mechanics, the object does not have sufficient energy to enter or surmount. This phenomenon has been experimentally confirmed and challenges our common understanding of time and causality.

Schrödinger's Equation [8]:

\[
i\hbar \frac{\partial \Psi}{\partial t} = \mathcal{H}\Psi
\]

(4)
This equation was formulated by Austrian physicist Erwin Schrödinger in 1925, and it is the fundamental equation in quantum mechanics. It describes the time evolution of a wave function $\Psi$ of a quantum system. It shows how quantum states evolve over time, particularly during measurements and observations.

It governs the behavior of subatomic particles such as electrons, protons, or neutrons. It can calculate the probability of finding a particle in a certain quantum state at a given time.

As it is a partial differential equation, it relates the spatial and temporal variation of the wave function $\Psi$. It describes how the wave function evolves over time, depending on the Hamiltonian operator $\mathcal{H}$.

Solving Schrödinger's equation gives the wave function $\Psi$ that completely describes the quantum state of a given system at a given time. This wave function can be used to calculate physical properties of the system, such as the expected values of observables (position, momentum, energy, etc.) and the probabilities of measuring certain quantities during an experiment.

This equation has revolutionized our understanding of the microscopic world and has paved the way for many advances in quantum physics [8].

3 RECENT IMPORTANT THEORIES

In the book "The Universe in Nutshell" Stephen Hawking [14,15] popularized the notion of imaginary time. Mathematically, imaginary time is the Wick rotation of real time, it means that the coordinates are multiplied by the imaginary unit $i$. In this context the real time can be represented as a horizontal line and the imaginary time in the vertical direction. This concept has been introduced in order to solve some physical problem in Quantum Mechanics and Cosmology [9]. For example, if we use imaginary space-time, the Big Bang singularity will be removed and the Big Bang becomes a smooth four-dimensional space-time.

The string theory is a physical theory that postulates that elementary particles are not point-like objects but rather vibrating strings of infinitely small dimensions. According to this theory, time is not a fundamental quantity but rather an emergent phenomenon of the geometry of space-time as the action surface of the strings. This perspective has opened up new avenues of research in theoretical physics to understand the nature of time.
Today, the “string theory” seems to be succeeding where all previous theories have failed. So, it upends our conception of matter, space, and time. It is the full story of this revolution in progress—where elementary particles turn out to be like endless pieces of string, where space-time tears, repairs, and folds into ten invisible dimensions, and the Big Bang and black holes take unexpected forms—that one of its eminent actors tells us here.

In a review article, Rovelli (2011; see also: 2010) examines the main areas of fundamental physics and indicates why, in his opinion, progress advances (particularly in the path of unifying general relativity and quantum mechanics) will be opened by accepting the non-existence of time. This is understood in the sense of abandoning the time variable, i.e. the mathematical parameter $t$, in the physical equations written at the most fundamental level. The author shows that this option can also be followed in general relativity, quantum mechanics (Rovelli, 1990), and also in loop quantum gravity (Rovelli, 1991), where the aim is to unify these last two theories. Julian Barbour (1999) speaks of the non-existence of time in similar terms (see also, among others, DaCosta and Sant’Anna, 2001) [10].

Recently, with the creation of quantum computers, several strange phenomena involving the notion of time were observed. Let us first cite the work carried out by Lesovik G. B et al [19]; in which it was shown that the arrow of time can be reversed. Indeed, it has been shown that it is possible to design a quantum algorithm that is capable of reversing a given quantum state. Using this algorithm on an IBM quantum computer allows scientists to experimentally demonstrate inverse temporal dynamics for an electron scattered across a two-level impurity. Another phenomenon was the subject of the paper of Dumitrescu, P.T.et al [4]. In this work the physicists have created a remarkable, never-before-seen phase of matter by shining a laser pulse sequence inspired by the Fibonacci numbers at atoms inside a quantum computer. The phase has the benefits of two time dimensions despite there still being only one singular flow of time.

4 CONCLUSION

In conclusion, the notion of time in physics has undergone considerable evolution over the centuries as the understanding of physics has developed,
moving from an absolute and universal conception to a relativistic and quantum conception. However, fundamental questions about the nature of time remain open and continue to be explored by physicists around the world. The concept of time, whether in its familiar sense or as found in physics, notably involves the notions of change and evolution, memory, flow and movement, present, past, future, instant(s), irreversibility and direction, duration, simultaneity, chronology, causality, continuity, dimension, and finally, parameterization and periodicity.

The subject of time has always been one of the most important topics discussed by humans. For some, time is limitless on both sides; "time has no beginning or end." (Secular-eternal); for others, it is only an illusion or does not even exist! Some believe that time is infinitely divisible; for others, its divisibility is limited by an indivisible "entity." From other perspectives, time is absolute for some (Newton); or relative, depending on the observer's motion (Einstein); linear and irreversible flow, in one direction, towards the future; or circular, where the beginning and end meet...

Finally, the nature of time is a fascinating and constantly evolving research topic. Its concept has always been difficult to grasp, despite the abundance of studies and debates on this subject. Physicists have succeeded in making time an operational concept without being able to precisely define it.

We are still searching for the answer to this eternal question: What do clocks really indicate when we say they give the time?
REFERENCES


