DEFINING TIME AND DETERMINING THE FACTORS WHICH GOVERN TIME

F. Zahra, G. Abbas, M. Rasool, R. A. Qureshi

Sahiwal Medical College, Sahiwal
Riphah International University, Riphah College of Veterinary Sciences, Lahore, Pakistan
Government College University, Lahore
Department of Physics, University of Lahore, Pakistan
Corresponding Author's Email: Ghulamabbas_hashmi@yahoo.com

ABSTRACT: For centuries, the word 'time' has mystified almost every intellectual of every era. Man has always been in search of its proper definition but in vain. In this paper, we aim to give the best possible definition of time. Moreover, the former concept that time is a universally independent variable will also be rectified. Time depends on two basic factors, with a basic assumption that Einstein's proposal of the *space-time fabric* is correct. Pictorial representations will also be provided for a better understanding. The theoretical discussion will be further supported by mathematical proof.

Objectives: To give an appropriate definition of time. To prove that time depends on two quantities and is not an independent quantity in itself. To give mathematical derivations as a proof for the dependence of time on its various factors.

Keywords: Time; mass; velocity; curvature; bend; space-time fabric; speed; time dilation; relativity; gravity

INTRODUCTION

Time is a mysterious phenomenon associated to the transformation of the past and the present into the future. According to Einstein, time is an intrinsic property of the universe. In his papers, he discussed the presence of a space-time fabric throughout the universe (Einstein*: The Field Equations for Gravitation* 1916). According to him, the universe is made up of the fundamental fabric of space and time. Hence, time is present everywhere, even at places where there is nothing to observe its flow. According to Einstein, the fabric is flexible, such that when a mass is placed in it, it bends just like a rubber sheet (Padmanabhan: 2004). This bend in the space-time fabric results in gravity; the fundamental force of nature that is attractive in its nature and is responsible for the various planetary motions. The larger the mass, the greater is the bend in the omnipresent fabric of space and time. Hence, the smaller masses surrounding this greater mass start orbiting it. Thus, the force of gravity is explained on the basis of this same fabric (Einstein: 1916). Hence, we assume that the existence of this fabric is unquestionable.

In his famous published paper of 1905, namely 'On the Electrodynamics of Moving Bodies', Albert Einstein explains time as the simultaneity of two events. For example, if we say that a particular explosion took place at 3.30 pm, we actually mean that the explosion took place just when the hour hand of the clock reached 3 and the minute hand of the clock reached 30. Hence, the time that we measure is basically dependent on the fact that the two events under observation took place simultaneously. In the same paper, he discarded the commonly held notion of time by posing a simple question: will time not exist at a place where a watch or a clock is not present? The only logical answer to this question is that time does not depend on the existence of a clock or even an observer; it is present in the very fabric of the universe. Hence, time must exist at all places where the fabric is intact.

Another major contribution by Einstein to the concept of time is that he rejected *absolute time* put forth by Sir Isaac Newton. In Einstein's physics, absolute is nothing. Neither time nor mass and not even motion is absolute. Everything is relative with respect to other things, depending upon different frames of reference. In his special theory of relativity (1905), Einstein suggested that there is no such thing as absolute time by putting forward his equation for time dilation. Time dilation has now been proved at various levels in real life; it is no more a mere hypothetical phenomenon. The particle accelerators like LHC (Large Hadron Collider) have observed time dilation (Velkovska: 2014). Moreover, the GPS system takes time dilation into account for accurate measurements (Bahder: 2003).

MEASUREMENT OF TIME INTERVALS: The commonly held concept of time is associated with clocks and watches. However, the watches actually measure *time intervals*. The "time", that our watches measure, is a measurement of the time intervals in accordance to the motion of the Earth around the Sun. Hence, any such measurement cannot be regarded as real or actual time. In the ancient world, sundials, sand glass, water clocks, pendulum and obelisks were used to measure such time intervals. In the present era, atomic clocks (cesium clocks) are being used to measure time intervals to a greater level of accuracy (Audoin and Guinot: 2001).

DEFINITION OF TIME: The first ever definition of time came from the Greek philosopher Aristotle. According to him:
"(Time is) the calculable measure of motion with respect to before and afterness." (Source: Quanta Magazine)

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 unequable) measure of duration by the means of motion, which is commonly used instead of true time; such as an hour, a day, a month or a year." (Newton: *Philosophiae Naturalis Principia Mathematica*) 1678.

According to Einstein: "All our judgements in which time plays a part are always judgements of simultaneous events." (Einstein: 1905)

In another passage, he wrote: "It might appear possible to overcome all the difficulties attending the definition of 'time' by substituting 'the position of the small hand of my watch' for 'time'. And, in fact, such a definition is satisfactory when we are concerned with defining a time exclusively for the place where the watch is located." (Einstein: 1905)
However, another definition can be:
"Something that governs space without having any physical appearance."

In accordance with this paper, the definition of time is:

"The bend in the curvature of space due to masses is called time."

FACTORS ON WHICH TIME DEPENDS

Time depends on two major factors:

1. The mass that causes a bend in the fabric of space and time
2. The velocity by which this mass causes the space time fabric to bend

Time depends directly on the mass that causes a bend in the fabric of space time.

$$t \propto m$$

Moreover, time is directly proportional to the velocity by which the fabric of space is curved during an event.

$$t \propto v'$$

In our subsequent discussion, we shall focus on the proofs and mathematical derivations related to the above mentioned factors. Moreover, for simplicity, a 2 dimensional model of space and time will be discussed for the sake of simplicity and convenience.

METHOD

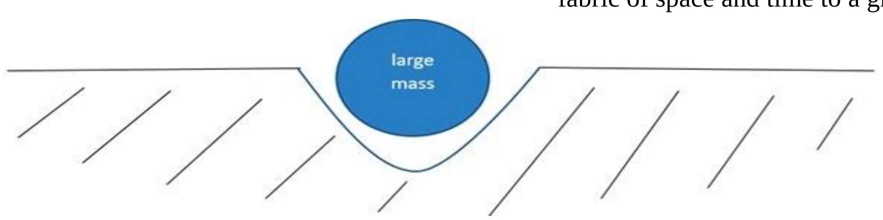
Newton was wrong when he wrote: time flows equably without regard to anything external.

1) MASS

To prove that the flow of time is directly proportional to the mass that causes a curvature in the space-time fabric, consider the discussion given below:

EXAMPLE 1

Depicted in this figure is a massive body that curves the fabric of space and time to a great extent.

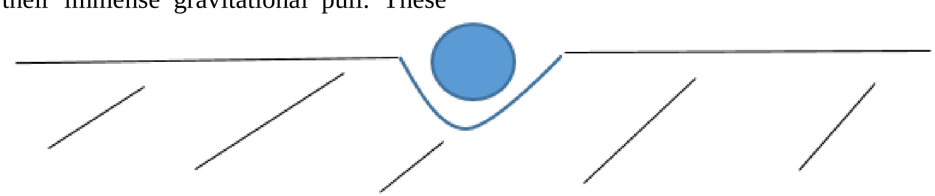


Since:

$$t \propto m$$

In the above example, the mass that causes a bend in the fabric of space and time is huge, hence there is great curvature in the fabric of space due to which actual time slows down i.e. the value of time increases (time intervals take more time to finish) near massive objects due to their immense gravitational pull. These phenomena are now commonly known to the physicists that near massive objects, time slows down.

EXAMPLE 2: Depicted in the figure below is a small mass that causes only a minor bend in the space-time fabric.



And since:

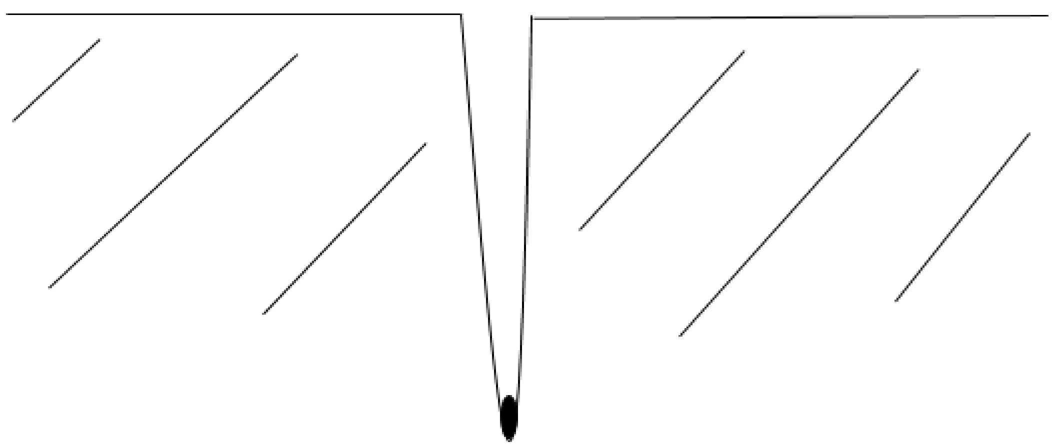
$$t \propto m$$

There is a minute bend in the fabric of space due to small mass; hence, actual time flows at a relatively fast speed in this case i.e. the value of time decreases (time intervals take less time to complete).

EXAMPLE 3: A black hole forms when a star has exhausted its supply of hydrogen and helium fuel. The star then grows bigger and hotter and eventually undergoes a supernova, which is a massive explosion during which a star collapses on itself. It results in the formation of the core of a black hole. These cores have extremely huge masses concentrated in extremely small regions of space. Black holes are said to have zero volume, hence their densities approach infinity. Because of this reason, black holes are said to contain singularities (infinite mass). Therefore, in a black hole, the mass that causes the curvature of space is massive, due to which the space time fabric bends to such an extent that it is just on the verge of ripping apart (or according to some, rips apart). Consequently, there is a huge time dilation, hence the value of time increases (intervals complete slowly) in accordance with the above mentioned relation:

$$t \propto m$$

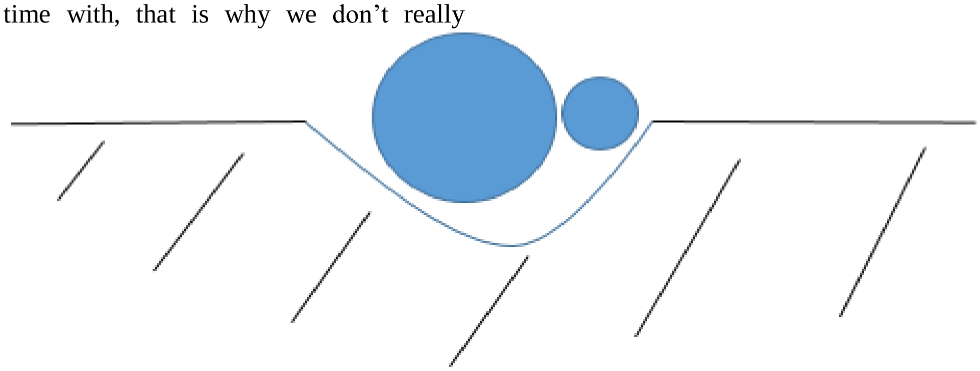
The figure below visually depicts the extreme curvature of the space time fabric, due to the presence of a singularity that constitutes the core of a black hole.



All the discussion that we have had is based on a 2D space time model. In a three dimensional model, the same results are again applicable. Even in a 3D model (which is more accurate), a black hole creates a singularity at which the deformation in the space time fabric becomes infinite.

EXAMPLE 4: At Earth, we don't have anything else to compare our time with, that is why we don't really comprehend if it is fast or not. Even at the sun, time flows at *almost* the same rate, because their masses on the huge cosmological scale differ only minorly.

Consider that two heavenly bodies come extremely close to each other such that the distance between the two is practically ignorable, as shown below:



For the sake of simplicity, let us consider these to be the sun and the Earth, then these two masses will undergo a huge time dilation because of a huge curvature in the fabric of space and time, since a massive amount of mass is concentrated in a small region of space, so much so that 1 Earth day will become equal to approximately 50,000 years. In such a case, time intervals take longer to complete; hence, time slows down tremendously.

PROOF: As we know from the special theory of relativity:

$$m = \frac{m_o}{\sqrt{1 - \frac{v^2}{C^2}}}$$

$$\sqrt{1 - \frac{v^2}{c^2}} = \frac{m_o}{m}$$

Which is equation (1).
Now:

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

Then, as mentioned in equation (1):

$$t = \frac{t_0}{m_0 / m}$$

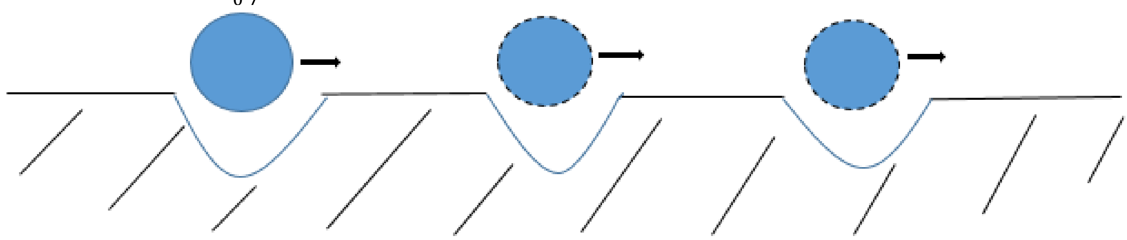
$$t = \frac{t_0 \times m}{m_0}$$

Since "t_o" and " m_o" are absolute quantities whose value remains constant:
Hence proved:

$$\boldsymbol{t \propto m}$$

2) **VELOCITY:** To prove that time is directly proportional to the velocity by which space is curved, consider the following discussion:

EXAMPLE 1: Consider an object moving at a speed which is very close to the speed of light, as shown in the figure below:



In the above figure, the object shown is travelling at a great pace, hence the speed by which space time fabric bends is great; therefore, according to the relation…

$$t \propto v'$$

actual time increases due to which the individual time intervals take longer to complete. The result is that time dilates at greater speeds.

EXAMPLE 2: In an analogous example, consider that the object in example 1 is now moving at a slow speed, supposedly 2 ms^{-1}**.** Then, the same object will curve space time at a lesser pace and hence, the value of time will decrease and the intervals will be over in a rather normal pace.

PROOF: According to Einstein, a body gains mass as its speed increases. To prove this, consider the inertial or relativistic momentum of a body that is written as:

$P' = ɣ\, m\, v$ (where 'ɣ' is a constant factor)

Now:

$$p' \propto v'$$

But:

$$p' \propto m$$

Therefore:

$$m \propto v'$$

Hence proved that the velocity by which space time fabric is curved depends directly on the mass that curves it.

$$\boldsymbol{v' \propto m}$$

Since we have proved in the previous section that:

$$\boldsymbol{t \propto m}$$

Then, it follows from the above two equations:

$$\boldsymbol{t \propto v'}$$

RESULT

The above mathematical relations prove that time, mass and velocity of the curvature of space are indeed correlated. Huge curvature in space always leads to huge time dilation. These concepts also give the *reason* of the slowing down of time when moving at fast speeds, a concept first given by Einstein (1905). All this discussion further emphasizes that nothing in our universe can be out of the influence of time, as the fabric of the universe has time in it. However, certain areas of the cosmos such as black holes (Hawking: 1988), where space-time fabric is highly compromised and either rips or is on the verge of ripping apart, the influence of time nullifies; hence, such regions are *timeless.*

DISCUSSION

Time is one of the seven base quantities (under the category of physical quantities: such quantities that are measurable). Base quantities are such quantities which form the basis for defining other physical quantities. Hence, time is one of the seven sovereign quantities that are used to express every other quantity in physics; as is evident from the definition of velocity: time taken to cover a particular distance (Emerson: 2014). However, it is to be noted that all the physical quantities which we deal with in physics are functions of time periods, not absolute time. All such quantities work on the same principle as described above by Einstein: the principle of simultaneity of two events. Hence, the time in velocity is actually the difference between the time at which the body was at a point A and the time at which the body was at a point B (time interval).

The beginning of time is essentially the beginning of the universe. As Stephen Hawking, the globally acknowledged theoretical physicist, explains in his publication *A Brief History of Time* (1988), time began as soon as the explosion of big bang took place about 13.8 billion years ago. Whatever happened before the big bang is out of the realm of time and reality, and hence is impossible to be explained by the laws of physics. We can only use physics as a tool to understand a universe which has time. Another conclusion can be drawn here: the laws of physics remain applicable, so long as time exists. Conversely, the rules of nature are only obeyed in the presence of time. Hence, time is essential to the very existence of not only life but also science.

In their well-known works on general cosmological questions, Einstein (Einstein: 1917) and de Sitter (de Sitter: 1917) arrive at two possible types of the universe; Einstein obtains the so-called cylindrical world, in which space has constant, time-independent curvature, where the curvature radius is connected to the total mass of matter present in space; de Sitter obtains a spherical world in which not only space, but in a certain sense also the world can be addressed as a world of constant curvature. (Klein, 1918) In doing so both Einstein and de Sitter make certain presuppositions about the matter tensor, which correspond to the incoherence of matter and its relative rest, i.e. the velocity of matter will be supposed to be sufficiently small in comparison to the fundamental velocity (Eddington: 1921) — the velocity of light.

The assumptions on which we base our considerations divide into two classes. To the first class belong assumptions which coincide with Einstein's and de Sitter's assumptions; they relate to the equations which the gravitational potentials obey, and to the state and the motion of matter. To the second class belong assumptions on the general, so to speak geometrical character of the world.

Time can be controlled, but only at great speeds. For a body travelling at the speed of light, time freezes (Einstein: 1905). The body then transcends the barrier of time, as the time dilation is so huge that even an infinitely small interval can become infinite. Such a body has both the past and the future, apart from the present, within its reach. It is also to be noted that the future already exists as does the past. We cannot observe these simultaneously with the present as the time we live in belongs to the present moment. To live in the past or future moment, a body will have to undergo time travel; a phenomenon only possible at (and beyond) the speed of light.

Space time fabric has a flexible nature. It is elastic, much like a rubber sheet, hence it has the ability to be bent. This hypothesis was also presented by Albert Einstein in his General Theory of Relativity (1916). In fact, it is this elasticity which gives rise to gravity. Thus, it must also obey the Hooke's Law to a certain extent. In other words, the space time fabric has its own limits. It tears apart when the load exceeds its elastic limit, as we can observe in the case of black holes.

Mass is essential for the flow (not existence) of time. Time cannot manifest itself without having a mass that induces it to do so. Moreover, the speed which causes disturbance in the fabric of the cosmos also governs the rate of flow of time.

Our space always has matter, either in the form of heavenly bodies or in the form of dust particles, particles from the atmosphere of planets, comets, asteroids, jets of matter ejected from stars, nebulas, or even just freely wandering atoms. Hence, everywhere in our observable universe, there is matter in one form or another. Hence, we conclude that absolutely everywhere in the observable universe, time not only exists but also flows. On the other hand, free space is completely devoid of all forms of matter. It is a hypothetical region of the universe where not even a single atom is present. Therefore, time does exist here but it cannot be observed or it simply does not flow noticeably because there is nothing to bend space time fabric in that particular region. In such regions, time is impossible to be detected because there is simply nothing to trigger it.

In the observable universe, we have not been able to find free space yet. However, if free space is discovered someday, it will actually be a discovery of such an area in which time cannot be calculated, because time simply will not flow in that region.

It is to be concluded that time needs mass to flow. Time is thus *not* a universally independent variable. It depends on mass.

In his *Principia*, Newton begins by defining absolute time: "Absolute time, without reference to anything external, flows uniformly". Since this is not a metaphysical claim, but a definition, it makes no sense to ask the question that is traditionally asked, that is, whether or not does Newton succeed in proving it. The appropriate question should instead be: is this a good definition? Does it actually define any physically meaningful quantity? In fact, two concepts are involved in Newton's definition: absolute equality of time intervals ("uniform flow"), and, less obviously but equally essentially, absolute simultaneity. Both are in fact necessary to the physics of the Principia - and, indeed, to all of seventeenth-century mechanics. Absolute simultaneity is the more pervasive concept, underlying as it does not only physics, but the notions of past, present, and future as understood at that time (and after, at least until special relativity). Even Leibniz, who claimed to reject absolute time, never doubted - on the contrary, central parts of his metaphysics required - the reality of the distinction between contemporaneous and successive events. In fact, this distinction is implicit in the idea of the spatial order of things at a given instant, and in the idea of relative motion as the change of spatial distances between bodies from moment to moment. Within Cartesian physics, absolute simultaneity was implicit in the theory that light is the effect of pressure that is instantaneously propagated through the celestial medium, which implied that distant events may be perceived simultaneously with their occurrence. Indeed, the pervasiveness of the concept can be judged from the revolutionary character of special relativity: centuries of polemics on the "relativity of time" scarcely prepared anyone for the relativity of simultaneity.

We are in the position to answer another question here. What happens when we (hypothetically) remove time from our universe? In other words, can a universe exist without time? The answer to this question is simply no. If Einstein’s notion of the space time fabric is correct, it then emphasizes that time is an intrinsic property of the observable universe. It is the very fabric from which our universe is built up of. Removing time from it would essentially mean the destruction of the building block of the cosmos, leading to an extent of chaos which we cannot yet comprehend. Moreover, everything in such a universe would be frozen and stuck; life would cease.

Another deduction from the above discussion can be that time is *not* an illusion. It is real and it has a specific direction. The arrow of time always moves from the past to the future. If it were reverse, then people would die before they were born!

Albert Einstein was the first person to argue that apart from the three dimensions of space: length, height and width, there is a fourth dimension, namely time. He considered time as a separate dimension as it has both positive and negative values. The axis of time has an origin (that describes the present), a positive axis (that describes the future) and a negative axis (that deals with the past). The fifth dimension has been found out to be gravity. However, the search for dimensions is far from being over, as the String Theory proposes over 26 dimensions. (Zwiebach: 2004)

Time needs motion to manifest itself. For bodies at absolute rest, time would cease to be noticeable, as the velocity by which space is curved would become zero. In our observable universe, absolute rest is not possible. Even if the body on the macro-scale appears to be at rest, its atoms still undergo vibrational, translatory or rotational motion and curve the space time fabric (however small the curvature may be). If a matter attains absolute zero someday (-273.15 K, as calculated from Charles’ Law), then the matter will not experience time at all, as there will be no mass to curve the space time fabric (due to zero volume, as predicted by the French scientist Jacques Charles) and also because of the absence of the speed of curvature of space and time. Thus, it is to be concluded that at absolute rest, the calculation and measurement of time becomes impossible.

Conclusion: We can deduct from the above discussion that:

- Time is not a universally independent variable.
- Time depends directly on the mass that causes a bend in the fabric of space.
- Time depends directly on the velocity by which space time fabric is bent due to a mass.
- Time is omnipresent: it exists everywhere, but flows only at places where matter is present.

REFERENCES

Agrawal, P. K. (2021). Structure of Space Fabric. *Natural Science*, *13*(12), 477-490.

Amelino-Camelia, G. (2011). Shedding light on the fabric of space-time. *Nature*, *478*(7370), 466-467.

Baeten, J. C. M., & Bergstra, J. A. (1997). Discrete time process algebra: Absolute time, relative time and parametric time. *Fundamenta Informaticae*, *29*(1-2), 51-76.

Barbour, J. (2001). *The end of time: The next revolution in physics*. Oxford university press.

Bardeen, J. M., Carter, B., & Hawking, S. W. (1973). The four laws of black hole mechanics. *Communications in mathematical physics*, *31*(2), 161-170.

Barnett, L., & Einstein, A. (2005). *The Universe and Dr. Einstein*. Courier Corporation.

Butterfield, J. (2013). On time in quantum physics. *A Companion to the Philosophy of Time*, 220-241.

Cartas, V. L. (2018, January). The Elasticity of Quantum Spacetime Fabric. In *Proceedings of the Nineteenth International Conference on Geometry, Integrability and Quantization* (Vol. 19, pp. 105-115). Institute of Biophysics and Biomedical Engineering, Bulgarian Academy of Sciences.

Chen, E. K. (2021). Quantum mechanics in a time-asymmetric universe: On the nature of the initial quantum state. *The British Journal for the Philosophy of Science*.

Chen, W. (2006). Time–space fabric underlying anomalous diffusion. *Chaos, Solitons & Fractals*, *28*(4), 923-929.

Currie, M. (2010). *About time*. Edinburgh University Press.

Dainton, B. (2016). *Time and space*. Routledge.

Davies, P. C. W. (1977). *The physics of time asymmetry*. Univ of California Press. de Sitter, On Einstein’s theory of gravitation and its astronomical consequences. Monthly Notices of the R. Astronom. Soc. 1916-1917.

Deutsch, D., & Lockwood, M. (2016). The quantum physics of time travel. *Science Fiction and Philosophy: From Time Travel to Superintelligence*, 370-383.

Dieks, D. (1988). Discussion: Special relativity and the flow of time. *Philosophy of Science*, *55*(3), 456-460.

Dieks, D. (2001). Space-time relationism in Newtonian and relativistic physics. *International Studies in the Philosophy of Science*, *15*(1), 5-17.

Dieks, D. (2014). Time in special relativity. In *Springer handbook of spacetime* (pp. 91-113). Springer, Berlin, Heidelberg.

DiSalle, R. (2006). *Understanding space-time: The philosophical development of physics from Newton to Einstein*. Cambridge University Press.

Eddington: Espace, Temps et Gravitation, 2 Partie, S. 10. Paris 1921

Einstein, A. (1905). On the electrodynamics of moving bodies. *Annalen der physik*, *17*(10), 891-921.

Einstein, A., & Davis, F. A. (2013). *The principle of relativity*. Courier Corporation.

Einstein, Cosmological considerations relating to the general theory of relativit y, Sitzungsberichte Berl. Akad. 1917.

Francis, C. (1999). The Fabric of Space-time. *arXiv preprint physics/9906042*.

George, A., & Zidick, C. (1991). Charles's law revisited. *Journal of chemical education*, *68*(12), 1042.

Giddings, S., Abbott, J., & Kuchař, K. (1984). Einstein's theory in a three-dimensional space-time. *General Relativity and Gravitation*, *16*(8), 751-775.

Gubser, S. S. (2010). Time warps. *Journal of High Energy Physics*, *2010*(1), 1-29.

Hawking, S. (2001). *The universe in a nutshell*. Bantam.

Hawking, S. (2002). *On the shoulders of giants: The great works of physics and astronomy*.

Hawking, S. (2012). The beginning of time. *Stephen Hawking*.

Hawking, S. W., & Ellis, G. F. R. (1973). *The large scale structure of space-time* (Vol. 1). Cambridge university press.

Hawking, S., & Hawking, S. W. (1994). *Black holes and baby universes and other essays*. Random House.

Hawking, S., & Penrose, R. (2010). *The nature of space and time* (Vol. 3). Princeton University Press.

Hawking, Stephen (1988). A Brief History of Time

Haworth, D. T. (1967). Charles' Law: A general chemistry experiment. *Journal of Chemical Education*, *44*(6), 353.

Hestenes, D. (2003). Spacetime physics with geometric algebra. *American Journal of Physics, 71*(7), 691-714.

Hilgevoord, J. (2005). Time in quantum mechanics: a story of confusion. *Studies in History and Philosophy of Science Part B: studies in history and philosophy of modern physics*, *36*(1), 29-60.

Horstemeyer, M. F. (2019, December). The Mechanics of the Space-Time Fabric of Space. In *2019-Sustainable Industrial Processing Summit* (Vol. 10, pp. 210-211). Flogen Star Outreach.

Jamali, A. (2021). On the Inherent Dynamics of the Fabric of Spacetime.

Joshi, P. S. (2007). *Gravitational collapse and spacetime singularities* (Vol. 2). Cambridge: Cambridge University Press.

Kennedy, J. B. (2014). *Space, time and Einstein: An introduction*. Routledge.

Kennedy, R. J., & Thorndike, E. M. (1932). Experimental establishment of the relativity of time. *Physical Review*, *42*(3), 400.

Kersting, M., & Steier, R. (2018). Understanding curved spacetime. *Science & Education*, *27*(7), 593-623.

Klein, On the integral form of the conservation theorems and the theory of the spatially closed world. GÈotting. Nachr. 1918.

Knox, E. (2014). Newtonian spacetime structure in light of the equivalence principle. *The British Journal for the Philosophy of Science*.

Ma, H. (2003). The nature of time and space. *Nature and science*, *1*(1), 1-11.

Marolf, D., & Maxfield, H. (2020). Transcending the ensemble: baby universes, spacetime wormholes, and the order and disorder of black hole information. *Journal of High Energy Physics*, *2020*(8), 1-72.

Matolcsi, T., & Ván, P. (2007). Absolute time derivatives. *Journal of Mathematical Physics*, *48*(5), 053507.

Mbagwu, J. P. C., Abubakar, Z. L., & Ozuomba, J. O. (2020). A Review Article on Einstein Special Theory of Relativity. *International Journal of Theoretical and Mathematical Physics, 10*(3), 65-71.

Mendelssohn, K. (1977). Quest for absolute zero: the meaning of low temperature physics.

Misner, C. W. (1969). Absolute zero of time. *Physical Review*, *186*(5), 1328.

Misner, C. W. (1969). Absolute zero of time. *Physical Review*, *186*(5), 1328.

Mladenov, I. M., & Yoshioka, A. THE ELASTICITY OF QUANTUM SPACETIME FABRIC.

Muga, G., Mayato, R. S., & Egusquiza, I. (Eds.). (2007). *Time in quantum mechanics* (Vol. 734). Springer Science & Business Media.

Newman, A. (2021). The Rates of the Passing of Time, Presentism, and the Issue of Co-Existence in

Special Relativity. *Foundations of Physics*, *51*(3), 1-19.

Newton, I. (1934). Principia mathematica. *Book III*, *Lemma V*, *Case*, *1*, 1687.

Novikov, I. (1997). Black holes. In *Stellar Remnants* (pp. 237-334). Springer, Berlin, Heidelberg.

Penrose, R. (1979). Singularities and time-asymmetry. In *General relativity*.

Peres, A., & Terno, D. R. (2004). Quantum information and relativity theory. *Reviews of Modern Physics*, *76*(1), 93.

Reinhardt, S., Saathoff, G., Buhr, H., Carlson, L. A., Wolf, A., Schwalm, D., ... & Gwinner, G. (2007). Test of relativistic time dilation with fast optical atomic clocks at different velocities. *Nature Physics*, *3*(12), 861-864.

Savitt, S. (2011). Time in the special theory of relativity.

Sklar, L. (1981). Time, reality, and relativity. *Reduction, Time, and Reality*, 129-142.

Thorne, K. (1995). *Black Holes & Time Warps: Einstein's Outrageous Legacy (Commonwealth Fund Book Program)*. WW Norton & Company.

Thorne, K. (2020). One Hundred Years of Relativity. From the Big Bang to Black Holes and Gravitational Waves”. *Einstein Was Right. The Science and History of Gravitational Waves*, 19-46.