Does Time Dilation Reveal a Variable Speed of Light?

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Abstract

A reexamination of the well-known Hafele-Keating time dilation experiment reveals an overlooked assumption in standard interpretations. The time interval measurements for all clocks began and ended simultaneously in the laboratory, implying that their measured intervals should be identical. This raises questions about the conventional view that these intervals differ in duration due to motion. A deeper analysis revealed a fundamental issue: applying the same standard seconds to all intervals disregards the fact that moving clocks tick at a slower rate. This implies that the duration of a time unit on a moving clock is longer than a standard second. To resolve this inconsistency, we introduce the concept of variable time units. We further propose modifying the time dilation formula by defining time intervals in terms of discrete clock ticks rather than fixed-duration units, demonstrating that the ratio of time units follows directly from the ratio of clock ticks. However, adopting variable time units leads to the inevitable conclusion that the speed of light must also be variable, contradicting Einstein's postulate of its invariance. From this perspective, while the Hafele-Keating experiment is widely regarded as empirical confirmation of Einstein's theory of relativity, a closer analysis suggests an alternative interpretation that questions the assumption of a universally constant speed of light.

Contents

1 Introduction

In this paper, we will discuss time dilation caused by motion, rather than the gravitational effects of time dilation. Our focus will be on the kinematic aspect of time dilation as described by special relativity[1][2][3].

Time dilation [4] is a relativistic effect in which the passage of time for a moving observer or any physical system (e.g., an object or clock) appears slower relative to a stationary observer or system.

In this context, a clock moving at a certain velocity relative to an inertial frame ***ticks at a slower rate*** *compared to a clock at rest in that frame.*

Mathematically, time dilation is described by the equation:

$$t = \frac{\tau}{\sqrt{1 - \frac{v^2}{c^2}}} \qquad (1)$$

Here:

- t represents the time interval for an observer (clock, object) in motion,
- τ is the proper time for an observer (clock, object) at rest,

- v is the relative velocity between them,
- c is the speed of light.

The relativistic factor γ:

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

Therefore:

$$t = \gamma \cdot \tau \tag{3}$$

For $v > 0$, it holds that $\gamma > 1$.

In the time dilation formula, **both time intervals are expressed using the same standard time units (one second)**. To emphasize this, we can also write the time dilation equation as:

$$t(s) = \gamma \cdot \tau(s) \tag{4}$$

Expressing time intervals in the same units is expected since, in physics, one second is strictly defined.

Potential inconsistency in the use of the same time units

However, we argue that, in the case of time dilation, expressing both time intervals (t and τ) in the same time units, or more precisely, with the same duration of time units, is not physically correct. *The clocks that measured these time intervals operated at different rates, which inevitably affected the duration of the time units they displayed.*

If we define the time unit in terms of clock ticks (i.e., one tick = one time unit), then it is physically justified to say that the time unit differs for different clocks that measure time intervals during time dilation.

Thus, time dilation can be understood not only as an extension of the time interval but also as a change in the duration of the time unit itself.

We will confirm this by analyzing the well-known Hafele-Keating experiment[5], which provided empirical evidence for time dilation.

2 A critical analysis of the Hafele-Keating experiment and its implications

2.1. The Hafele-Keating experiment proves time dilation

The Hafele-Keating experiment was conducted using three atomic clocks to test time dilation as predicted by the theory of relativity. One clock remained on Earth (the reference clock), while the other two traveled aboard an airplane, one moving in the direction of Earth's rotation and the other in the opposite direction.

This experiment confirmed the predictions of both special and general relativity:

- Moving clocks measure time differently compared to a stationary clock.
- Time dilation depends not only on the velocity of motion (special relativity) but also on gravitational potential (general relativity).

2.2. Simplified principle of the Hafele-Keating experiment

Figure 1 illustrates the simplified principle of the Hafele-Keating experiment.

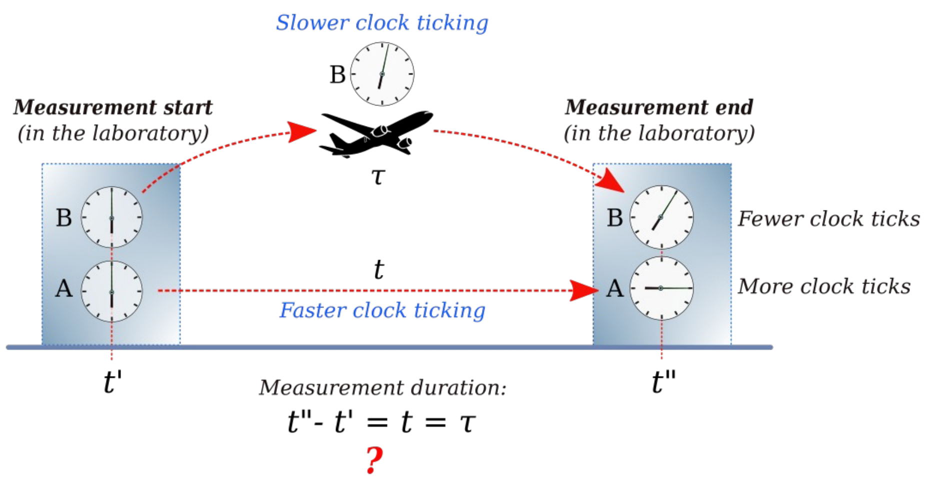

Figure 1

In this section, we will focus on clock A, which remained on Earth (the stationary clock), and only one of the traveling clocks, clock B (the moving clock). Furthermore, we will consider only kinematic time dilation, while ignoring the effects of gravitational time dilation.

The illustration includes all phases of the measurement of time intervals (t and τ):

1. Start of measurement (left side of the figure):

    - Two synchronized clocks (A and B) are placed on Earth.
    - ***The measurement on both clocks begins simultaneously at moment t' within the laboratory reference frame on Earth.***
    - Clock A measures the time interval t, while clock B measures the time interval τ.

2. Motion phase of clock B (middle section of the figure):

    - After the start of measurement, clock B travels aboard an airplane (moving clock), while clock A remains on Earth (stationary clock).
    - Due to its higher speed, clock B experiences relativistic time dilation. Since its speed is greater than that of clock A throughout the journey, time passes more slowly for it during the entire flight.
    - As a result of slower time passage, clock B ticks at a slower rate compared to clock A, which remained stationary on Earth during the entire measurement.

3. End of measurement (right side of the figure):

    - Once clock B returns to Earth, ***the measurement ends simultaneously for both clocks, again within the laboratory frame, at moment t''.***
    - Clock B is then compared to the reference clock A.
    - Clock B (the traveling clock) displays fewer clock ticks than clock A, which remained stationary on Earth.
    - The comparison of time intervals, assuming *both clocks use the same time units*, shows that the time interval τ measured by the traveling clock B was shorter than the time interval t of the stationary clock A on Earth, meaning $t > \tau$. ***However, we challenge this conclusion, as it does not align with the logic of measurement in this case, which we explain in the rest of the paper.***

2.3. The simultaneous start and end of measurement

In the Hafele-Keating experiment, both clocks started measuring simultaneously at time t' and finished simultaneously at time t''. This means that the total duration of the experiment is:

$$\Delta t = t'' - t' \qquad (5)$$

Since the measurements on the stationary clock A and the moving clock B lasted exactly as long as the experiment itself, we can express this as:

$$\Delta t = t'' - t' = t = \tau \qquad (6)$$

This result contradicts the classical interpretation of the experiment, which assumes $t > \tau$. *It also does not align with the time dilation formula* (3)*, which clearly shows a difference in time intervals at high speeds due to the relativistic factor* γ.

The principle of comparing time intervals

However, it is evident that comparing time intervals is only meaningful if both measurements start and end simultaneously. We refer to this as the **principle of comparing time intervals**. If one measurement starts or ends earlier or later than the other, a direct comparison of time intervals is not possible.

Although in the example of measuring time intervals, the classical interpretation of time dilation assumes different time intervals (t *and* τ*), the principle of comparing time intervals requires them to be equal (*$t = \tau$*).*

This apparent contradiction can be resolved by introducing **variable time units**.

2.4. Time dilation implies variable time units

Time frames:

> *For clocks A and B, we can state that they experienced different flows of time, that is, they were in different* ***time frames***[7]. *We will consider a time frame as a limited part of space in which the corresponding flow of time is defined.*

As shown in Figure 2, due to the motion of clock B, time progresses more slowly for it, while for the stationary clock A, time flows faster. As a result of this slowdown, clock B ticks at a slower rate than clock A, meaning that **each time unit on clock B lasts longer than on clock A**.

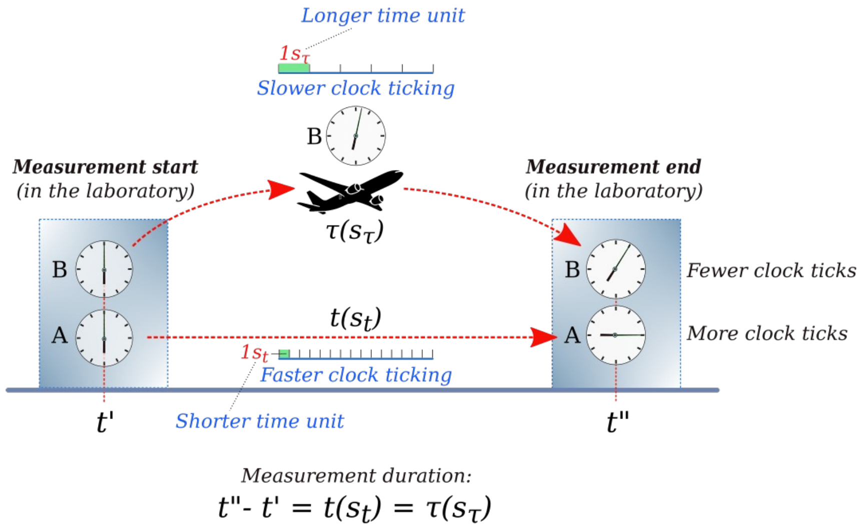

Figure 2

Standard second is a local second

The standard second is defined as the duration of 9,192,631,770 oscillations of radiation corresponding to the transition between two hyperfine energy levels of the ground state of a cesium-133 atom.

This definition is based on measurements conducted under Earth's gravitational conditions, meaning that the duration of the standard unit of time depends on the local gravitational potential. Consequently, the standard second is actually a local second, defined within Earth's specific gravitational dilation.

Time units measured under different conditions of gravitational or kinematic dilation may therefore be longer or shorter than the standard second.

Variable units of time

Thus, using the same unit of time (the standard second) for measuring time intervals under different dilation conditions does not provide a correct physical picture. *For an accurate description of time dilation, it is necessary to introduce variable units of time.*

This is not a standard practice in physics. However, in this case, where time intervals can "stretch," this stretching must also apply to time units, especially since **time units themselves are time intervals**.

To distinguish between constant and variable time units, we introduce indexed notation:

1 s_t – one second of clock A (at rest)

1 s_{τ} – one second of clock B (in motion)

Now, we can refine equation (6) to:

$$\Delta t = t'' - t' = t(s_t) = (s_{\tau}) \qquad (7)$$

where:

- $t(s_t)$ represents the time interval of clock A, expressed in time units $1s_t$
- $t(s_{\tau})$ represents the time interval of clock B, expressed in time units $1s_{\tau}$

When measuring time dilation, the measured time intervals t and τ remain the same, but their respective time units s_t and s_{τ} differ in duration:

$$t(s_t) = \tau(s_{\tau}) \qquad (8)$$

2.5. Example: Time intervals, clock ticks, and time units

This example of time dilation measurement serves to mathematically and graphically justify the introduction of variable time units as a necessary component for accurately describing the physical reality of time dilation.

The chosen values are simplified for graphical representation and do not correspond to the exact numerical results of the Hafele-Keating experiment, but they align with its fundamental logic.

Let’s assume that clocks A and B register the following number of ticks:

- $n_t = 15\ ticks$ – clock A (at rest, faster clock)
- $n_{\tau} = 5\ ticks$ – clock B (in motion, slower clock)

The graphical representation in Figure 3 illustrates the relationship between the ticks recorded by clocks A and B.

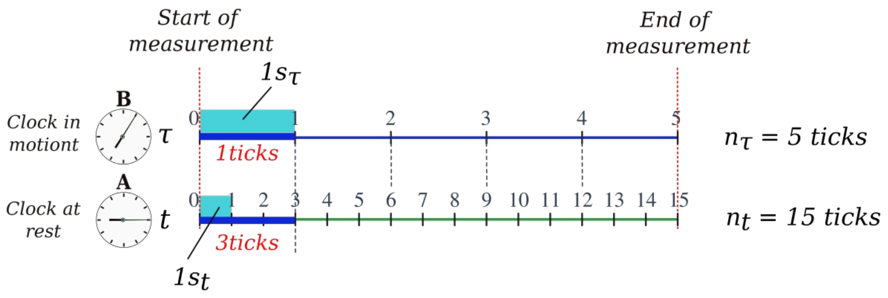

Figure 3

By substituting these time intervals into equation (8), we obtain the relationship between the time units of clocks A and B:

$$n_t \cdot 1s_t = n_\tau \cdot 1s_\tau$$

Since the number of clock ticks and time unit duration are inversely proportional, we can express this as:

$$\frac{s_\tau}{s_t} = \frac{n_t}{n_\tau} \tag{9}$$

Substituting the measured tick counts:

$$\frac{s_\tau}{s_t} = \frac{15}{5} = 3$$

The value 3 corresponds to the relativistic factor γ:

$$\gamma = 3$$

Thus, the time unit of the moving clock is related to the stationary clock's time unit by:

$$s_\tau = \gamma \cdot s_t \tag{10}$$

Fundamentally, when measuring time intervals, we count clock ticks and then multiply these counts by the standard unit of time (one second). However, in this example with variable time units, the clock ticks are multiplied by its local time units.

The corresponding time intervals are:

$$t(s_t) = nt \cdot 1s_t \tag{11}$$

$$\tau(s_\tau) = n_\tau \cdot 1s_\tau \tag{12}$$

By substituting values, we obtain:

$$t(s_t) = 15 \cdot 1s_t = 15s_t \tag{13}$$

$$\tau(s_\tau) = 5 \cdot 1s_\tau = 5s_\tau \tag{14}$$

Although the time intervals appear different, they have the **same total duration** (as illustrated in Figure 4), but their time units differ.

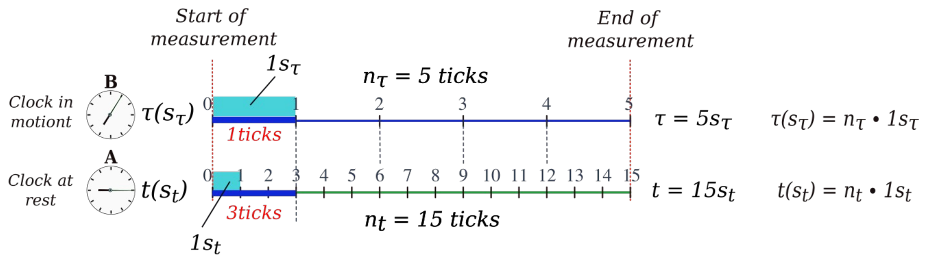

Figure 4

This can be verified by expressing both intervals in the same time unit. We choose the s_t time unit of clock A, which is at rest on Earth.

Since from equation (10):

$$s_\tau = 3s_t \quad \Rightarrow \quad s_t = \frac{s_\tau}{3}$$

Substituting this into equation (13):

$$t(s_\tau) = 15(\frac{s_\tau}{3}) = 5s_\tau$$

From equation (14), we already have:

$$\tau(s_\tau) = 5s_\tau$$

Once both time intervals are expressed in the same time unit, it becomes clear that their durations are identical, ***which aligns with the principle of comparing time intervals****.*

2.6. Incorrect use of time units in time dilation

In the Hafele-Keating experiment, the measurements of time intervals (t and τ) were expressed in the same time units, using the standard second (s), which is defined by the time dilation conditions on Earth. The same principle of expressing time intervals is applied to the time dilation relation (1).

However, this approach neglects the fact that time units have different durations in different time frames, *which can lead to misinterpretations and theoretical inconsistencies in time dilation analysis.*

We can better understand this issue with a concrete example.

Let's express both time intervals (t and τ) in a time unit (s_t), without applying the time unit conversion from equation (10).

$$t(s_t) = 15s_t$$

$$\tau(s_t) = 5s_t$$

This effectively assumes that clocks A and B tick at the same rate, which is **fundamentally incorrect**, as they are influenced by different time flows, causing them to tick at different rates.

This case of time intervals is illustrated in Figure 5.

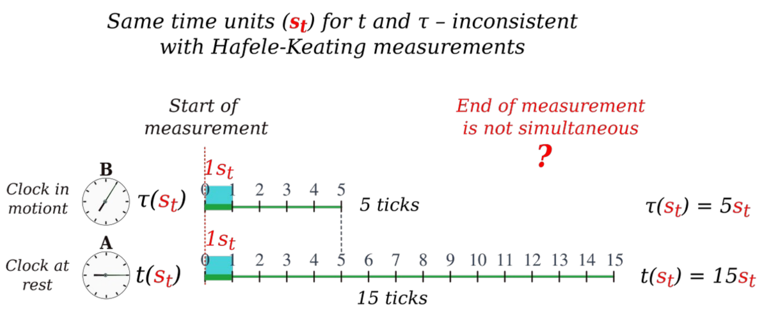

Figure 5

Although the measurement of both time intervals starts at the same time, *the diagram clearly shows that the end of the measurement is not simultaneous*. **This discrepancy violates the fundamental principle of comparing time intervals,** which requires that both the start and the end of the measurement be simultaneous.

This represents a significant deviation from physical reality. Consequently, an alternative approach is necessary for describing time intervals in time dilation measurements. This requires not only the introduction of variable time units (as previously discussed), but also a revision of the time dilation formula (1).

2.7. Correction of the time dilation formula

The standard time dilation equation (1) does not provide an accurate physical representation because it assumes a universal time unit (s) for both time intervals (t and τ). As clearly demonstrated in the previous chapter, this approach is incorrect since the clocks measuring these intervals operate within different time flows (time frames), meaning they use different time units.

To achieve a more precise physical representation of measurements in time dilation, we propose substituting time intervals in equation (1) with the number of clock ticks (n_t i n_τ) :

$$n_t = \frac{n_\tau}{\sqrt{1 - \frac{v^2}{c^2}}} \qquad (15)$$

where represents the number of ticks recorded by clock A (stationary), and represents the number of ticks recorded by clock B (moving).

Additionally, from equation (2), we obtain:

$$n_t = \gamma \cdot n_\tau \qquad (16)$$

When measuring time dilation, we record the number of clock ticks but lack immediate information about the time frames in which the clocks operated. As a result, we cannot directly determine which time units correspond to which time interval. Only after reading the number of clock ticks and applying relation (9) can we correctly establish the relationships between time units. Knowing these relationships enables the calculation of other time interval-related quantities.

3 Variable speed of light

3.1. The speeds *v* and *c* in the formula for time dilation

When examining equation (15) for time dilation, one may ask in which time units (s_t or s_τ) the relative velocity v and the speed of light c should be expressed.

In this equation, the ratio $\frac{v}{c}$ appears. Since both the velocity v and the speed of light c are expressed in the same length units and time units, these units cancel out.

As a result, velocities can be expressed in either s_t or s_τ without altering the ratio. The crucial requirement is that both v and c are expressed in the same time units.

If the speeds are expressed in time units s_t (corresponding to the time frame of clock A at rest), then equation (15) takes the form:

$$n_t = \frac{n_\tau}{\sqrt{1 - \frac{v^2(\frac{m}{s_t})}{c^2(\frac{m}{s_t})}}}$$

Alternatively, if the time frame of clock B (in motion) is chosen, the velocities will be expressed in time units s_τ:

$$n_t = \frac{n_\tau}{\sqrt{1 - \frac{v^2(\frac{m}{s_\tau})}{c^2(\frac{m}{s_\tau})}}}$$

3.2. Variable units of time also imply a variable speed of light

Since the speed of light can be expressed in different time units, depending on the time frames through which it passes, an intriguing idea arises: its numerical value is set by the time unit of the corresponding time frame. For example:

$$c(t) = 3 \cdot 10^8 \, \frac{m}{s_t}$$

$$c(\tau) = 3 \cdot 10^8 \, \frac{m}{s_\tau}$$

In this example, the speed of light is expressed using two different time units (t and τ), which

In this example, the speed of light is expressed using two different time units (t and τ), each with a different duration due to variations in local time flow. If we assume that the unit of length (meter) remains invariant across all reference frames, then the speed of light depends only on the corresponding local time unit.

Therefore, when observers measure the speed of light within their local time frame, they obtain the following result:

$$c = 3 \cdot 10^8 \, \frac{m}{local\, time\, unit}$$

However, in different time frames, depending on the flow of time, local time units vary (being longer or shorter), and as a result, the speed of light itself differs between time frames.

If observers are unaware of the variability of time units, they will assume that the speed of light is constant everywhere in the universe.

3.3. Why does every observer measure the same speed of light?

We assume that all motion within a time frame is determined by the flow of time within that frame. This applies to the motion of all objects, the rate of chemical processes, the ticking of clocks, and other temporal phenomena.

We also assume that the speed of light depends on the passage of time: in a slower flow of time, light moves more slowly, while in a faster flow of time, it moves more quickly. However, this seems to contradict the well-established fact that all observers measure the same speed of light. This leads to a fundamental question:

Why does every observer measure the same speed of light, regardless of their motion or reference frame?

From the perspective of the time frames introduced here, we can reformulate this question as:

Why does every observer measure the same numerical value for the speed of light within their local time frame?

The answer: proportional influence of time flow

We will seek the answer in the proportional influence of the passage of time on both the clock and light.

When an observer measures the speed of light, they do so using a clock whose time units are determined by the local flow of time in their own time frame. However, for the observer to measure light, the light itself must exist within the observer's time frame. This implies that light, like any other physical process within that frame, is subject to the same local flow of time, which determines its speed.

This *proportional adjustment between the speed of light and the rate at which the observer's clock ticks* ensures that the measured speed of light is always:

$$c = 3 \cdot 10^8 \, \frac{m}{\text{observer's local time unit}}$$

Since both the clock and light are equally affected by the same flow of time, this necessarily ensures proportionality and the constancy of the speed of light within local time frames.

Implications: The speed of light in a vacuum is not universally constant

However, when comparing the measured speeds of light across different time frames, *it becomes evident that the speed of light is not universally constant and does not conform to Einstein's postulate of the constancy of the speed of light.*

4 Conclusion

The theory of relativity is based on Einstein's postulate of the constancy of the speed of light. The Hafele-Keating experiment is often cited as empirical evidence supporting this theory. However, as demonstrated in this work, a detailed analysis of the experiment reveals conclusions that deviate from the classical interpretation of relativity, particularly regarding the assumption of the universal constancy of the speed of light.

By analyzing the Hafele-Keating experiment, we identified an inconsistency in the representation of time due to the use of the same time units when describing time dilation. Our findings indicate that a physically accurate representation of time intervals in the context of time dilation is only possible by introducing variable time units. However, it has been shown that this may also have implications for the speed of light. Since the speed of light can also be expressed in terms of variable time units, this naturally leads to the concept of a variable speed of light.

Taking into account the proportional effect of the flow of time on both clocks and light, a remarkably simple explanation emerges as to why every observer measures the same speed of light within their local time flow.

While Einstein postulated the constancy of the speed of light, this explanation suggests that such a postulate may not have been necessary. The observed constancy of c is visible only within the observer's local time frame, where the flow of time proportionally affects both the ticking rate of the clock used to measure the speed of light and the speed of light itself.

At the same time, the observer is also subject to the same time flow, which suggests a proportional slowing down or speeding up of all the observer's functions, depending on the time frame transition. Consequently, *the observer is unable to perceive any changes in the speed of light when transitioning from one time frame to another.*

However, when different time units corresponding to different time flows are taken into account, it becomes evident that the speed of light is not universally constant.

Furthermore, this concept of a variable speed of light eliminates the need for length contraction as required in relativity. The unit of length (m) can be considered invariant, regardless of the observer's motion.

This work suggests the possibility of a simplified and logically consistent physical interpretation related to time dilation and the speed of light, compared to the standard descriptions within the theory of relativity.

However, further research is required to refine and validate this approach.

5 *References*

[1] Einstein, A. (February 2004). Relativity: the Special and General Theory by Albert Einstein. Project Gutenberg. https://www.gutenberg.org/ebooks/5001

[2] Einstein, Albert, 1916. The Foundation of the General Theory of Relativity (Die Grundlage der allgemeinen Relativitätstheorie). Annalen der Physik 49 (7): 769–822.

[3] Robert Resnick, Introduction to Special Relativity, (John Wiley, New York, 1968)

[4] Time dilation. In Wikipedia. https://en.wikipedia.org/wiki/Time_dilation

[5] Hafele, J. C.; Keating, R. E. (July 14, 1972). "Around-the-World Atomic Clocks: Predicted Relativistic Time Gains". Science. 177 (4044): 166–168.

[6] Hughes, R. J., Clendenin, J. C., & Schaeffer, E. L. L. (1969). "Relativistic Time Dilation Observed in Muons." *Physical Review Letters*, 23(11), 679-683. DOI: 10.1103/PhysRevLett.23.679

[7] Špigel, B. (2023, December). Introduction to the Theory of Time Frames: (2) Time Frames and Time Transformations. *viXra.org*. https://vixra.org/pdf/2312.0130v1.pdf

[8] Špigel, B. (2024, February). Theory of Time Frames: Variable Speed of Light. *viXra.org*. https://vixra.org/pdf/2312.0130v1.pdf

[9] Špigel, B. (2024, February). Acceleration History Breaks Symmetry Principle and Resolves the Twin Paradox. *viXra.org*. https://vixra.org/pdf/2410.0108v1.pdf