A Unified Geometric Interpretation of Time Dilation in Special and General Relativity

K. Sethuraman

Email: ksethur83@gmail.com

ORCID: *https://orcid.org/0009-0007-5903-4212*

Independent Researcher, India

February, 12,2026

Abstract:

Time dilation in Special Relativity (SR) and General Relativity (GR), discovered by Albert Einstein, is conventionally introduced through distinct mechanisms: relative velocity in SR and gravitational potential in GR. In contrast, this paper proposes a unified conceptual framework for interpreting time dilation in both SR and GR based on a single geometric principle, illustrated using a common light-clock model. The guiding heuristic is "longer path = slower tick." In SR, relative motion causes the light pulse in a moving light clock to follow a longer diagonal spacetime path between successive reflections, leading to time dilation. In GR, spacetime curvature(geodesics) generated by mass–energy causes the light pulse to follow a longer curved path between equivalent clock events, likewise resulting in time dilation. Rather than interpreting gravitational time dilation solely through abstract expressions involving gravitational potential, this approach emphasizes a geometric interpretation in which time dilation arises from the increased spacetime path length traversed by the light pulse in curved spacetime. This interpretation is consistent with the experimentally verified Shapiro time delay, which demonstrates that a light pulse requires additional propagation time when passing through regions of strong gravitational curvature near a massive body. This framework is intended as a heuristic and interpretive aid and it does not replace the full tensorial formulation of SR and GR or their quantitative predictions derived from the Einstein field equations.

Introduction:

Time dilation is an important concept; it reveals that time is not stable and can slow down or speed up depending on the observer's motion and the presence of gravity. To sum up, time is not constant; it is flexible. According to Special Relativity (SR), a moving clock runs slower than a stationary one, just as, according to General Relativity (GR), a clock placed in a strong gravitational field runs slower than a clock placed in a weaker gravitational field. Although there is solid scientific evidence supporting these results, it is difficult for students to understand relativistic effects because SR and GR are introduced through different phenomena: Minkowski geometry and Lorentz transformations in SR, and spacetime curvature or gravitational potential in GR. As a result, many students find time dilation difficult to visualize and to understand intuitively.

This paper proposes a unified geometric and pedagogical interpretation of time dilation in both Special and General Relativity using a single physical concept, expressed as "slower time corresponds to a longer light path per clock tick"; in Special Relativity this path lengthening arises from diagonal propagation due to relative motion, while in General Relativity it arises from curvature of spacetime, and in both cases the underlying conceptual principle remains the same. This single concept explains relativistic time dilation without modifying Einstein's theory; moreover, the aim of this paper is not to replace existing mathematical formulations and explanations, but to provide a clear, intuitive, and unified conceptual model that makes time dilation more accessible to students and educators.

Special Relativity Time Dilation: Diagonal Light Path:

Light Clock in the Rest Frame:

Consider a frame containing a light clock with two mirrors separated vertically by a fixed distance 'd' in the rest condition, in which a pulse of light travels between the two mirrors; that is, it propagates from the bottom mirror to the top mirror and back to the bottom mirror (one complete up-and-down travel between the mirrors). In this rest case, the light propagates along a straight path; one complete up-and-down light journey is considered as one clock tick. The tick time in the rest case is Tf=2d/c. Here, 'c' is the speed of light, which is taken to be constant.

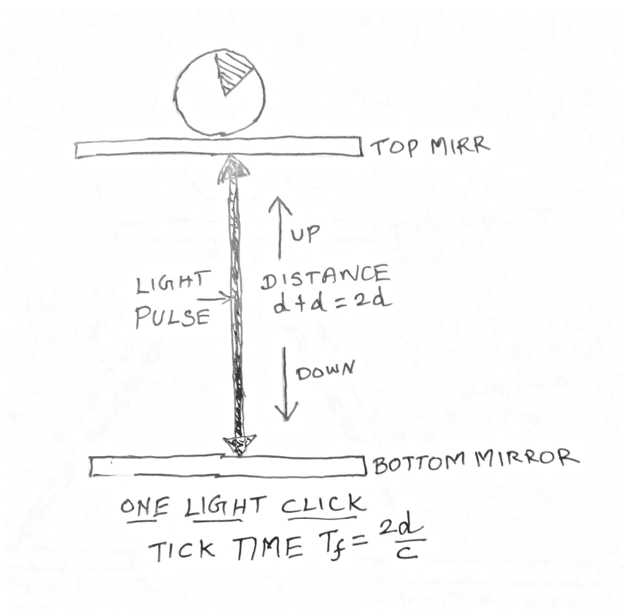

Figure 1: **Light Clock in the Rest Frame**

Light Clock in a Moving Frame:

Consider the same frame with a light clock and two mirrors moving horizontally with a constant velocity 'v'. In this moving condition, the mirrors move sideways while the light pulse is in transit; thus, the light can no longer propagate vertically and instead follows a diagonal path. This occurs because the upper mirror moves sideways continuously, requiring the light pulse to follow a diagonal path in order to meet the upper mirror while maintaining the constant speed of light c. This diagonal light path is geometrically longer than the vertical path, so the light pulse requires more time to complete a round trip between the two mirrors, which corresponds to an increased proper-time interval between successive clock ticks. One clock tick in this moving frame therefore takes more time than in the fixed frame. The tick time in the moving frame condition is also expressed as Tm=2dm/c, but the effective distance 'dm' differs from that in the fixed-frame condition. Tf<Tm high speed - diagonal path - longer - slower tick

Here, 'dm' denote the effective geometric path length associated with the diagonal propagation in the moving frame.

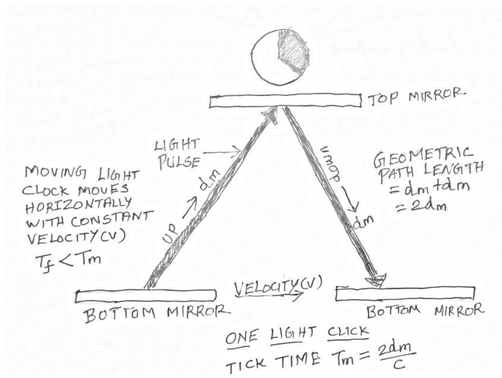

Figure 2: **Light Clock in a Moving Frame**

General Relativity: Gravitational Time Dilation in Curved Spacetime

According to GR, space and time are not separate; together they form spacetime. Spacetime has four dimensions, three of space and one of time, and mass and energy can curve spacetime, with this curvature affecting the motion of objects and the passage of time. This direct consequence of curvature is time dilation. A clock located in a stronger gravitational field runs slower than a clock located in a weaker gravitational field. The Einstein equation expresses how mass and energy shape spacetime. When a smaller object, such as the Earth, comes near the Sun, it moves toward the deepest part of the dimple. It is not being pulled by a force; rather, it follows the shortest and fastest path in the curved fabric of spacetime (geodesics). Stronger gravity stretches the time dimension, slowing the passage of time near a massive object. We can simply say that mass tells spacetime how to curve, and curved spacetime tells objects how to move.

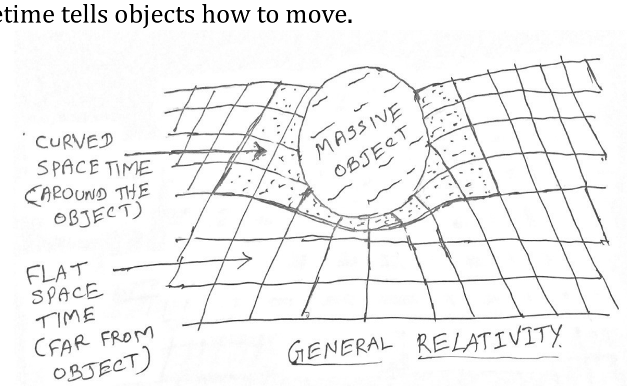

Figure 3: **Gravitational Time Dilation in Curved Spacetime**

Geometric Unification of Time Dilation in SR and GR:

The core of this unifying concept is that both velocity and gravity produce the same physical outcome. They result in the light pulse to traverse a geometrically longer distance than the baseline case (less velocity and gravity) per clock tick, while the speed of light remains the same.

Change in geometry - travel path lengthening - time dilation

A diagonal path arising from motion in Special Relativity and a curved (geodesic) path arising from spacetime curvature due to mass in General Relativity represent parallel geometric effects. The Shapiro time delay provides experimental evidence for spacetime curvature in gravitational fields, indicating that a light pulse follows a longer geometric path, and, since the speed of light is fixed, each clock tick corresponds to a longer proper-time interval. This unification may be summarized by stating that clock ticks correspond to longer proper-time intervals when spacetime geometry requires the light pulse to follow a longer path between successive clock events, whether due to velocity or gravity.

In Special Relativity (SR), the relevant input is high relative velocity, which results in the sideways motion of the destination mirror in a moving light clock. This motion leads to a diagonal geometric path for the light pulse, corresponding to a geometric lengthening of the path between successive clock events, and the final outcome is a slower clock tick. In General Relativity (GR), the corresponding input is a strong gravitational field, which produces curvature of spacetime. This curvature leads to a curved path(geodesic) for the light pulse, again corresponding to geometric lengthening between successive clock events, and the final outcome is likewise a slower clock tick.

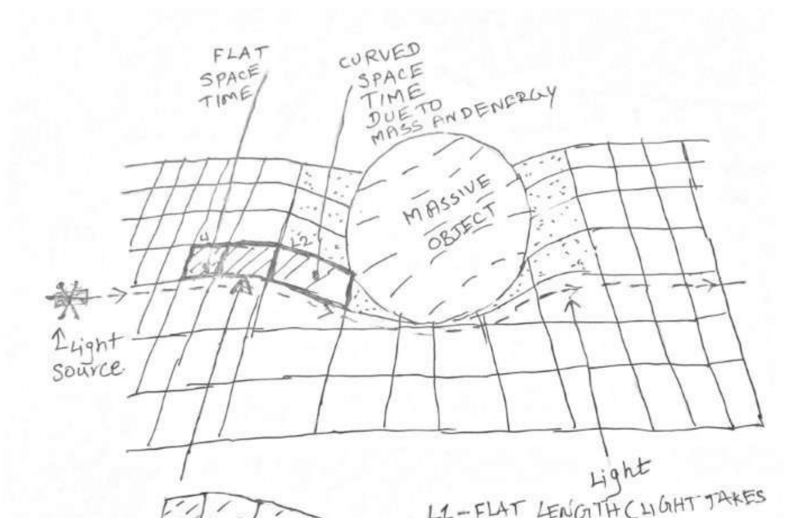

Figure 4: **Geometric Unification of Time Dilation in SR and GR**

Conclusion:

The “longer path = slower tick” model provides students with a clear geometric language for understanding time dilation in both SR and GR without sacrificing intuitive understanding for purely mathematical descriptions. By unifying the diagonal path in SR and the geodesic path in GR, this paper offers students a single accessible principle: clock ticks correspond to longer proper-time intervals when the geometry of spacetime requires the light pulse to follow a longer path, and this unifying concept ultimately allows students to move beyond abstract formulas and gain a deeper visual appreciation of the geometric nature of spacetime.

References :

- Einstein, A. (1905). *On the Electrodynamics of Moving Bodies*. Annalen der Physik, 17, 891–921. — This paper introduced Special Relativity and explained time dilation due to relative motion.
- Einstein, A. (1915). *The Field Equations of Gravitation*. Sitzungsberichte der Preussischen Akademie der Wissenschaften, 844–847. — This work formulated General Relativity, describing gravity as the curvature of spacetime.
- Einstein, A. (1916). The foundation of the general theory of relativity. Annalen der Physik, 49(7), 769–822.eral Relativity, describing gravity as the curvature of spacetime.
- Shapiro, I. I. (1964). *Fourth Test of General Relativity*. Physical Review Letters, 13, 789–791. — This paper experimentally confirmed gravitational time delay, now known as the Shapiro time delay, showing that light takes longer to travel through curved spacetime.
- Taylor, E. F., & Wheeler, J. A. (1992). *Spacetime Physics*. W. H. Freeman, New York. — A widely used textbook providing geometric and conceptual insight into Special Relativity.
- Schutz, B. (2009). *A First Course in General Relativity*. Cambridge University Press, Cambridge. — A standard introductory textbook on General Relativity and spacetime geometry.
