

Constant Spacetime Velocity and Time Dilation

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***Abstract:** Spacetime velocity and related time dilation, are presented in a clearer and simpler format. Many example calculations are shown to demonstrate the simplicity of this approach.*

In his landmark 1905 paper, "On the Electrodynamics of Moving Bodies" Albert Einstein presented his theory of "Special Relativity" that was based upon two essential postulates:

1. Relativity: The laws of physics are the same for all observers who are in moving at constant velocity relative to one another.
2. Constant Speed of Light: The speed of light in a vacuum is constant and is the same for all observers, regardless of their relative motion.

This theory lead to several profound changes in our understanding of space and time. One such change was time dilation: an object moving through space experiences time more slowly than a stationary object, so a moving clock ticks slower than a stationary clock. Special Relativity also required that space and time be combined rather than treated separately. Hermann Minkowski was a professor of Albert Einstein's who worked with him on special relativity and is largely credited with introducing the concept of **spacetime**.

The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Henceforth, space by itself and time by itself are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.

(Hermann Minkowski, 1908)

When viewed from the perspective of spacetime rather than just space, a profound reality emerges. **Everything (light and matter) travels at a constant velocity through spacetime, and the magnitude of that velocity is the speed at which light travels in vacuum (c).**

This very profound fact is often missed because of the way this subject is typically presented. Mathematical rigour is needed for many complex calculations, but can obscure important relationships, and is simply unnecessary when calculating effects as fundamental as time dilation.

Motion in spacetime is calculated by combining the motions in each of the three spacial dimensions (x, y, z) plus time. The three spacial dimensions are easy to combine, but how do you combine distance in space with distance in time? If distance in space is measured in meters, and distance in time is measured in seconds, the time distance must be multiplied by a constant that has units of meters/second, so the seconds cancel. The constant designated "c" (conventionally called the speed-of-light) provides this conversion. The constant c is generally shown in units of meters/second, so it relates distances measured in meters to distances measured in seconds. The constant c can however have any units of space/time, and in the examples that follow, the units of c will be in light-years/year, which also gives c a magnitude = 1.

The spacetime interval (ΔS) is calculated using what is called the "four-vector" consisting of the changes (represented by " Δ ") in the three spacial dimensions and the one time dimension.

$$\Delta S = \sqrt{(\Delta x)^2 - (\Delta y)^2 - (\Delta z)^2 + (c \Delta t)^2}$$

The statement that all entities (light and matter) travel at a constant velocity through spacetime and the magnitude of that velocity = c , can be derived from the above equation by dividing both sides by Δt (the change in time):

$$\frac{(\Delta S)}{(\Delta t)} = \sqrt{\left(\frac{\Delta x}{\Delta t}\right)^2 - \left(\frac{\Delta y}{\Delta t}\right)^2 - \left(\frac{\Delta z}{\Delta t}\right)^2 + c^2}$$

For a single object, there is no relative motion in space so all spacial terms (Δx , Δy & Δz) = 0.

$$\frac{(\Delta S)}{(\Delta t)} = \sqrt{c^2} = c \quad \textbf{Everything moves through spacetime at speed = c.}$$

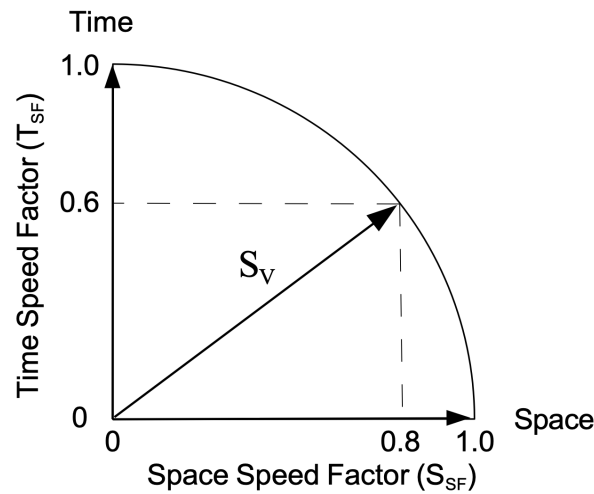


Figure 1: Spacetime Velocity (S_v)

(The convention in physics is to draw time on the vertical axis.)

All spacial directions are equivalent regarding the relationship between motions in space and in time, so the relationship is clearer if the three dimensions of space are reduced to a single value. Motion through time is unidirectional (always forward) and only the magnitude of motion through space is significant, so they can both be reduced to simple scalar values (no direction) that are orthogonal components of spacetime motion. Scaling the space and time speeds, to factors of c , also increases overall clarity.

Spacetime motion is typically represented by the letter "S" but the Spacetime Velocity diagram uses " S_v " to emphasis that it is a vector with space and time factors as shown. All spacetime velocity (S_v) vectors have the same magnitude = c , so they all end somewhere on the arc with radius = c . Example speed factors of 0.8 through space and 0.6 through time, are chosen because they are located roughly midway on the arc, and are exact solutions (no additional digits required).

From Special Relativity

$$t = \frac{T}{\sqrt{1 - v^2/c^2}} \quad (\text{Also called the } \textit{time dilation} \text{ equation.})$$

Where:

- t = time observed by stationary observer (*Special Relativity calls this "coordinate time".*)
- T = time experienced by traveller (*Special Relativity calls this "proper time".*)
- v = speed of traveller relative to stationary observer

Rearranging for T (time experienced by traveller): $T = t \sqrt{1 - v^2/c^2}$

Since $c = 1$ in units of light-years / year: $T = t \sqrt{1 - v^2}$

With v in units of c , $v = \text{Space Speed Factor } (S_{SF})$: $T = t \sqrt{1 - S_{SF}^2}$

For $t = 1$, T becomes the Time Speed Factor (T_{SF}): $T_{SF} = \sqrt{1 - S_{SF}^2}$

(*This is just Pythagorean math with S_v the hypotenuse = 1, and T_{SF} and S_{SF} the two sides.*)

Example Calculations:

1. If $v = S_{SF} = 0.8c$ the time speed factor (T_{SF}) will be :

$$T_{SF} = \sqrt{1 - S_{SF}^2} = \sqrt{1 - 0.8^2} = \sqrt{1 - 0.64} = \sqrt{0.36} = \mathbf{0.6}$$

If a stationary observer measures an elapsed time of 1 year, the traveller will measure 0.6 years. Spacetime Velocity (S_v) = (0.8, 0.6) as shown in Figure 1.

2. If $v = S_{SF} = 1.0c$ (for light) the spacetime velocity vector (S_v) is horizontal so:

$$T_{SF} = \sqrt{1 - S_{SF}^2} = \sqrt{1 - 1^2} = \sqrt{1 - 1} = \sqrt{0} = \mathbf{0}$$

Spacetime Velocity (S_v) = (1, 0), and **no time** is experienced by the traveller (light).

3. If $v = S_{SF} = 0.001c$ (Approximate speed of Earth orbiting the Milky Way galaxy.)

$$T_{SF} = \sqrt{1 - S_{SF}^2} = \sqrt{1 - 0.001^2} = \sqrt{1 - 0.000001} = \sqrt{0.999999} \approx \mathbf{0.9999995}$$

Spacetime Velocity (S_v) = (0, 0.9999995) so Earth is moving through time at almost maximum speed. A truly stationary object would travel through time at maximum speed, but only have a time speed factor 0.0000005 greater than Earth.

(*The solar system orbits the Milky Way galaxy at approximately 230,000 m/s, which is very fast on the human scale, but $230,000 / 299,792,458 = 0.00076c$, so almost stationary on the light speed scale.*)

Gravitational Time Dilation

Time dilation also occurs due to gravity. Why does gravity cause time to pass more slowly than it does in a non-gravitational environment ?

"The River Model of Black Holes" (Hamilton and Lisle, Aug. 2006) proposes that space can be considered to "flow" into a massive object (planets, stars, moons, etc.), the way water flows in a river. (This is not what is actually happening but it provides a very useful way of thinking about objects in a gravitational field. In a similar way, it is easier to think of gravity as "Newtonian" when calculating rocket trajectories to Earth orbit or the moon.) In the "River Model", a stationary object on the surface of a massive object is experiencing the equivalent of movement through space because space is "flowing" past the object. Because velocity through spacetime is a constant, any motion through space must result in slower motion through time. Consequently objects in a gravitational field must travel through time slower than they would when not in a gravitational field. That reduction in speed through time is the cause of gravitational time dilation.

The equation for escape velocity (V_E) is: $V_E = \sqrt{2 G M / r}$

Where:

- G = the gravitational constant
- M = the mass of the object (planet, star, moon, etc.)
- r = the distance from the centre of mass of the object to its surface.

The speed at which space is flowing past an object on the surface of a massive object is equal to the escape velocity from that object. Escape velocity from the Sun is stated (Wikipedia: "Escape Velocity", Sep. 2026) as 617,700 meters/second, and $617,700 / 299,792,458 = 0.002c$. For the surface of the Sun, the time speed factor (T_{SF}) will be:

$$T_{SF} = \sqrt{1 - S_{SF}^2} = \sqrt{1 - 0.002^2} = \sqrt{1 - 0.000004} = \sqrt{0.999996} = \mathbf{0.999998}$$

A reduction of **0.000002**

The stated time dilation (Wikipedia: "Gravitational Time Dilation", Sep. 2026) for the sun is given as 66.4 seconds/year.

One year = 31,536,000 seconds, and $66.4 / 31,536,000 = \mathbf{0.000002}$

An exact match.

The (so-called) Twin Paradox of Special Relativity *(There is no paradox just confusion.)*

Example: From Wikipedia: "Twin Paradox", Sep. 2026

Consider a space ship travelling from Earth to the nearest star system: a distance $d = 4$ light years away, at a speed $v = 0.8c$ (i.e., 80% of the speed of light).

To make the numbers easy, the ship is assumed to attain full speed in a negligible time upon departure (even though it would actually take about 9 months accelerating at 1 g to get up to speed). Similarly, at the end of the outgoing trip, the change in direction needed to start the return trip is assumed to occur in a negligible time. ...

(A very lengthy section of complex formulae and explanations deleted. If interested in the details check out the Wikipedia page.)

... the round trip will take $t = 2d/v = 10$ years in Earth time ...

(Another very lengthy section of complex formulae and explanations deleted.)

... the travellers will have aged only $0.6 \times 10 = 6$ years when they return.

The same calculation using constant spacetime velocity is trivial, and the Wikipedia example conveniently uses the same values (0.8 and 0.6) as the example shown in Figure 1.

$$T_{SF} = \sqrt{1 - S_{SF}^2} = \sqrt{1 - 0.8^2} = \sqrt{1 - 0.64} = \sqrt{0.36} = 0.6$$

If the ship is travelling at $0.8c$ through space, it is travelling at a speed factor of $0.6c$ through time. If the stationary observer (on Earth) measures elapsed time of **10 years**, the traveller (on the ship) will measure 0.6×10 years = **6 years**.

Simple calculation, no complex formulae or explanations required, and **exactly** the same answer.

Alice and Bob (A thought experiment providing a different view of the "Twin Paradox".)

Imagine that two twins named Alice and Bob, are on a very large space ship in intergalactic space. The ship is called the "RSO" (Relatively Stationary Observer). They each board a small ship and head off in opposite directions. To make the numbers easy, they get up to a velocity of $0.1c$ relative to RSO immediately. (It would actually take about 5 weeks at an acceleration of 1G to reach a velocity of $0.1c$.) They stay at that velocity for one year then transmit their status to the RSO. After 1 year at $0.1c$ Alice and Bob are 0.1 light-years away from RSO, so transmissions from Alice and Bob will take 0.1 year, or about 37 days, to reach RSO. However, Alice and Bob are now travelling $0.1c$ faster than RSO so they should experience time dilation relative to RSO:

$$T_{SF} = \sqrt{1 - S_{SF}^2} = \sqrt{1 - 0.1^2} = \sqrt{1 - 0.01} = \sqrt{0.99} = 0.99498$$

365 days / 0.99498 is about 367 days for Alice and Bob, about 2 days more. So RSO expects to hear from Alice and Bob in 367 days plus signal travel time of 37 days = 404 days RSO time. But RSO hears from Bob 2 days earlier than expected, and from Alice 5 days later than expected. Something is wrong.

It turns out that RSO is actually travelling at $0.1c$ absolute, in the same direction that Alice went. Alice actually increased her speed from $0.1c$ until she reached an absolute speed of $0.2c$, so her clock slowed down more than it would have at $0.1c$. Bob actually slowed down from $0.1c$ until he reached an absolute speed of $0c$, so Bob's clock sped up more than it would have at $0.1c$.

Bob has $S_{SF} = 0c$, so he has no time dilation and 1 year is exactly 365 days.

RSO has $S_{SF} = 0.1c$, so $T_{SF} = \sqrt{1 - S_{SF}^2} = \sqrt{1 - 0.1^2} = \sqrt{1 - 0.01} = \sqrt{0.99} = \mathbf{0.99499}$
 1 year for Bob is 0.99499 years on RSO, about 363 days, which is about 2 days less than Bob.

Alice has $S_{SF} = 0.2c$, so $T_{SF} = \sqrt{1 - S_{SF}^2} = \sqrt{1 - 0.2^2} = \sqrt{1 - 0.04} = \sqrt{0.96} = \mathbf{0.97979}$
 1 year for Bob is 0.97979 years for Alice, about 357.6 days, which is about 7 days less than Bob, and about 5 days less than RSO.

If the "Twin Paradox" was played-out on the RSO:

- If Bob stayed on the ship and Alice travelled away, **she would return younger**. She would be travelling through space **faster** than RSO, so **her clock would slow down**. This is the situation when a twin is leaving Earth. Because Earth is so very close to being stationary, the travelling twin is always travelling through space faster than Earth.
- If Alice stayed on the ship and Bob travelled away, **he would return older**. He would be travelling through space **slower** than RSO, so **his clock would speed up**.

Motion through space is relative but **motion through spacetime is absolute**.

Absolutely Stationary Space

Albert Einstein said in his 1905 paper, "On the Electrodynamics of Moving Bodies" that:

The introduction of a "luminiferous ether" will prove to be superfluous inasmuch as the view here to be developed will not require an "absolutely stationary space" provided with special properties ...

He clearly knew that an "**absolutely stationary space**" was needed, but as he points out, it does not require any "special properties".

Summary

Everything in the universe travels at a constant velocity through spacetime. Time dilation is a simple consequence of constant velocity through spacetime: if an object travels faster through space, it must travel slower through time. And while motion through space is relative, motion through spacetime is absolute.