Consider two twins. One sets out at the age of 25 on a spaceship from Earth at a speed of $0.99c$ where c is the speed of light. The Earthbound twin goes on about her/his business accumulating the normal accouterments of advancing age (gray hair, drooping body parts, *etc.*). After twenty years have passed for the Earthbound twin, the spacefaring one returns. When they finally meet the voyager is NOT twenty years older! She/He looks only a few years older than when she/he left and shows few signs of age. How much has she/he aged during the journey?

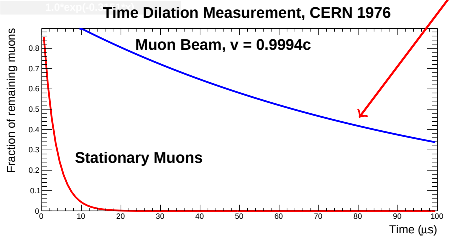
Time Dilation 3

Electrons at the speed of light.

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			
Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	−1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	−1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	−1

Quarks spin = 1/2			
Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	−1/3
c	charm	1.3	2/3
s	strange	0.1	−1/3
t	top	175	2/3
b	bottom	4.3	−1/3

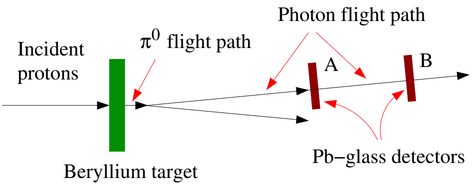


Muon half-life: $2.2 \times 10^{-6} s$

1. Physics is the same in all inertial reference frames (hopefully).

1. Physics is the same in all inertial reference frames (hopefully).
2. The speed of light is the same in all inertial reference frames.

1. Get on a very fast train. - At CERN in 1964 T. Alvager *et al.* created a beam of π^0's moving close to the speed of light ($0.99975c$) by hitting a beryllium target with a high-energy proton beam.
2. The π^0's almost immediately decayed into particles of light called photons ($t_{1/2} = 8.64 \times 10^{-17}\ s$).
3. The photons were measured at different, known locations downstream from the target.
4. $c' = (2.9977 \pm 0.0004) \times 10^8\ m/s$ versus $2.99792458 \times 10^8\ m/s$.



Alvager et al, CERN, 1964

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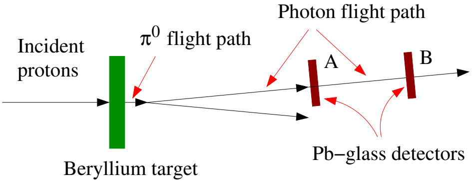

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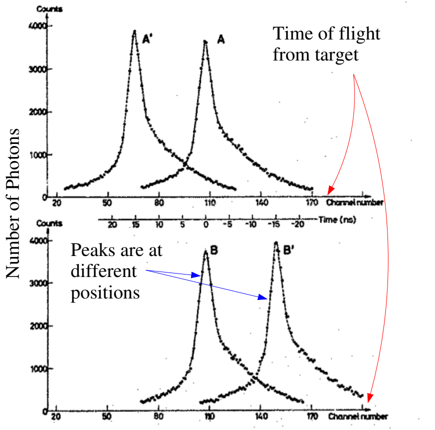


Fig. 1. The experimental arrangement and typical time spectra of the γ rays, recorded in the four detector positions A, A', B, B'. Channel width 0.35 nsec. The measuring time for 100 000 counts in the peak was about 10 min.

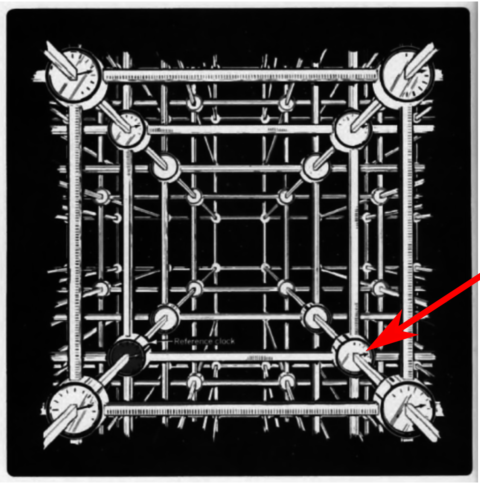
T.Alvager *et al.*, Phys. Lett. 12, 260 (1964)

1. In 1971 Hafele and Keating at the old National Bureau of Standards (now National Institute for Standards and Technology) took four cesium-beam atomic clocks aboard commercial airliners and flew twice around the world, first eastward, then westward, and compared the clocks against those of the United States Naval Observatory.

	nanoseconds gained			
	predicted			measured
	gravitational (general relativity)	kinematic (special relativity)	total	
eastward	144 ± 14	-184 ± 18	-40 ± 23	-59 ± 10
westward	179 ± 18	96 ± 10	275 ± 21	273 ± 7

2. Mountaintop muon decay measurements.
3. GPS and many others.

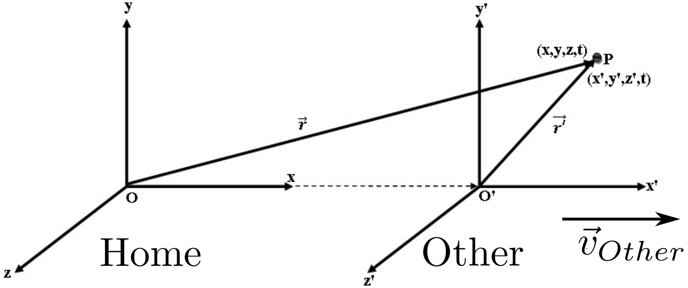
Inertial Frames - 1



$$(t, x, y, z)$$

$$\vec{v}_{Home} = 0$$
$$\vec{v}_{Other} = \text{constant}$$

The coordinates (t, x, y, z) describe the spacetime position P of an event in the *Home* frame. The *Other* frame is aligned with the x axis of the *Home* frame and is moving at a velocity $\vec{v}_{Other}$. The coordinates (t', x', y', z') describe the spacetime position P of the same event in the *Other* frame. Assume the clocks both start at the same moment and the origins coincide at that moment. How are (t, x, y, z) and $\vec{v}$ in *Home* related to (t', x', y', z') and $\vec{v}'$ in the *Other* frame in Galilean Relativity?



Galilean
$x' = x - vt$
$y' = y$
$z' = z$
$t' = t$
$v'_x = v_x - v_O$
$v'_y = v_y$
$v'_z = v_z$

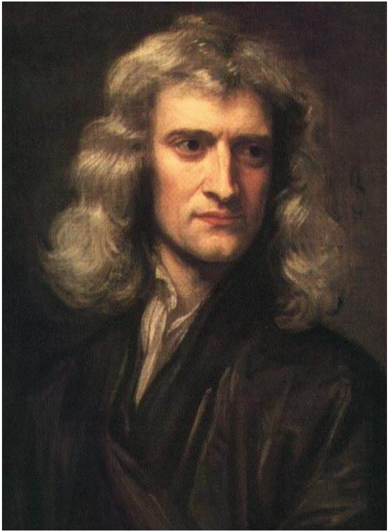
primes refer to the frame moving with velocity v_O.

v_O - velocity of moving/Other/B frame.

v_i - i^{th} component of the velocity in the stationary/Home/A frame.

v'_i - i^{th} component of the velocity in the moving/Other/B frame.

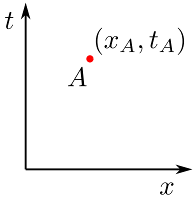
Newtonian or absolute time (1) exists independently of any perceiver, (2) progresses at a consistent pace throughout the universe, (3) is measurable but imperceptible, and (4) can only be truly understood mathematically. Absolute time and space were independent and separate aspects of objective reality, and not dependent on physical events or on each other. It is universal, *i.e.* the same for everyone everywhere in the universe.



1. Inertial frame of reference - coordinates moving at a constant $\vec{v}_{Other}$.
2. Synchronized clocks in an inertial frame - A light flash is emitted at clock A at time t_A and received at clock B (in the same frame) at a later time t_B.
3. The distance between the clocks is $c(T_B - T_A)$.

Spacetime Diagrams

1D spacetime



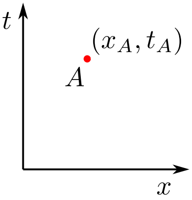
What is the world-line of a stationary point?

Describe the motion shown here.

What is the world-line of a point with constant $\vec{v}$?

Spacetime Diagrams

1D spacetime



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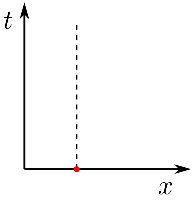

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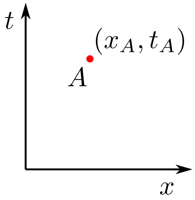

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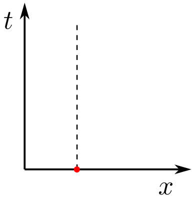

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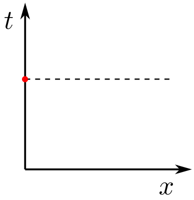

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Spacetime Diagrams

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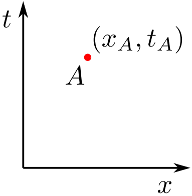

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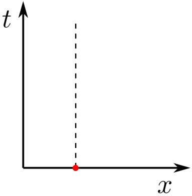

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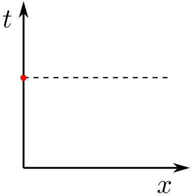

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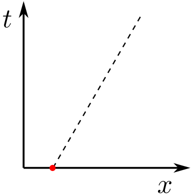
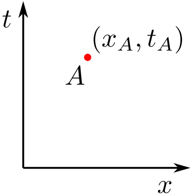


What is the world-line for a photon in the $+x$ direction?

Spacetime Diagrams

1D spacetime



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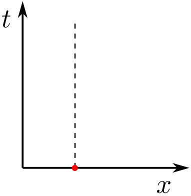

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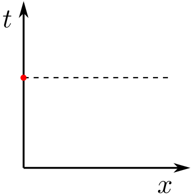

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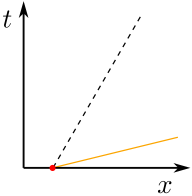
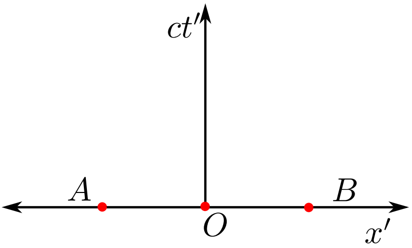


What is the world-line for a photon in the $+x$ direction?

The coordinate time Δt is the time difference between two events A and B with two clocks at rest in an inertial frame located at the positions of the two events.



Consider two light pulses from the origin at $t' = 0$ sent towards clocks at $\pm x'$. This is in the Other frame.

What will the worldlines of the clocks look like in the Other frame?
What will the worldlines of the light pulses look like in the Other frame?
What is $\Delta t'$ in this frame?

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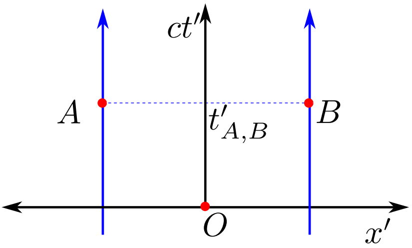

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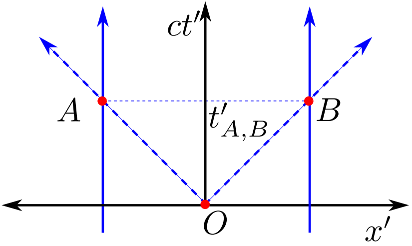

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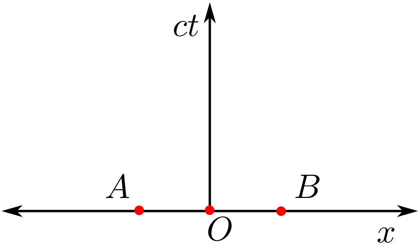

Consider the same light pulses from the origin at $t' = 0$ in the Other frame.

You're now in the Home frame and the Other frame is moving in the positive x direction.

What will the worldlines of the clocks look like in the Home frame?
What will the worldlines of the light pulses look like in the Home frame?
Where do we put the clocks in the Home frame when they reach $\pm x'$?
What is Δt in this frame? Is $\Delta t = \Delta t'$?

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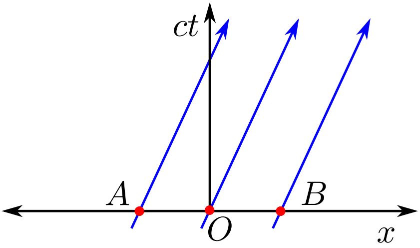

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Defining Coordinate Time - 5 24

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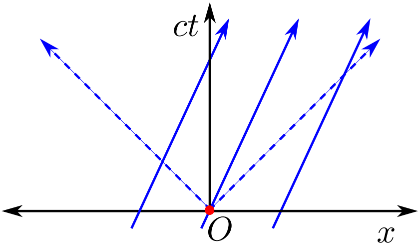

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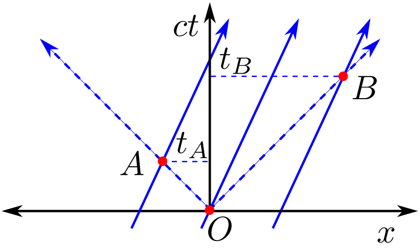


Consider the same light pulses from the origin at $t' = 0$ in the Other frame.

You're now in the Home frame and the Other frame is moving in the positive x direction.

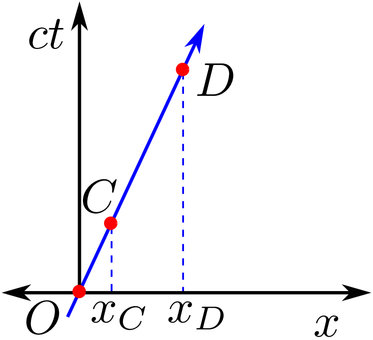
What will the worldlines of the clocks look like in the Home frame?
What will the worldlines of the light pulses look like in the Home frame?
Where do we put the clocks in the Home frame when they reach $\pm x'$?
What is Δt in this frame? Is $\Delta t = \Delta t'$?

Defining Coordinate Time - 6 26

The time interval Δt is messed up, what about the space interval Δx?

Defining Coordinate Time - 6

The time interval Δt is messed up, what about the space interval Δx?



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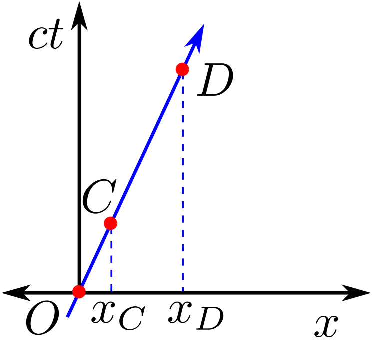
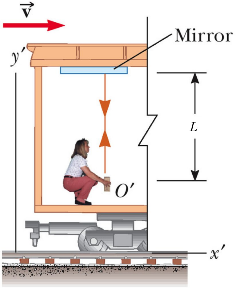
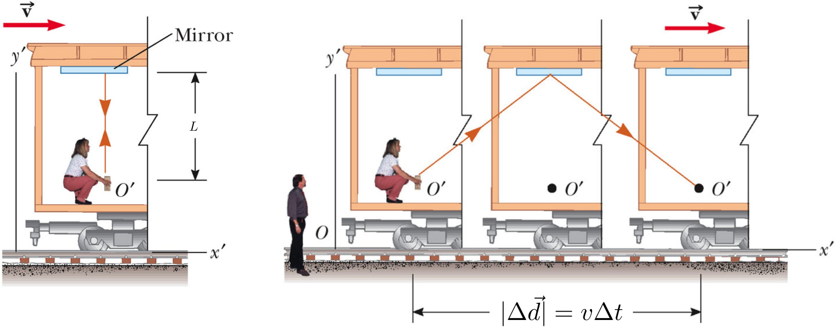
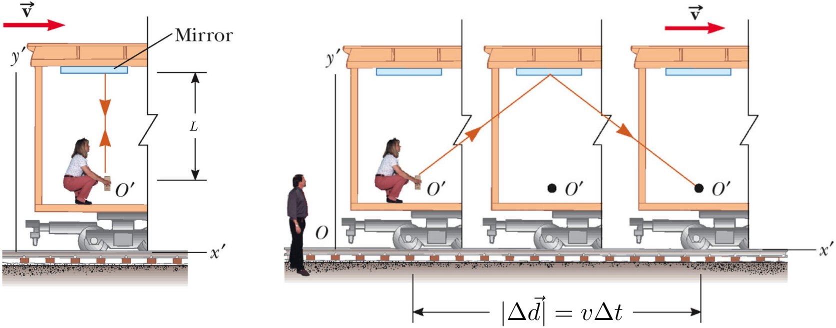


Consider two events that occur at the origin in the Other frame at different times. Both events occur at $x' = 0$ in the Other frame, but they will be in different locations in the Home frame. The Home frame is shown here. What is Δx in this frame? Is $\Delta x = \Delta x'$?

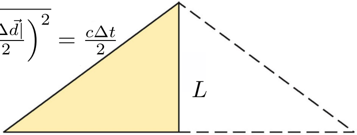


$\vec{v}$
Mirror
y'
L
O'
x'


$\vec{v}$
Mirror
y'
L
O'
x'
$\vec{v}$
y'
O'
O'
O'
O
x'
$|\Delta\vec{d}| = v\Delta t$



$$L_{Home} = \sqrt{L^2 + \left(\frac{|\Delta\vec{d}|}{2}\right)^2} = \frac{c\Delta t}{2}$$

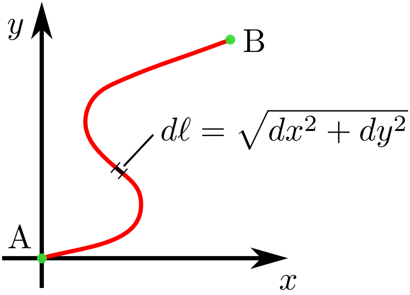


$$\frac{|\Delta\vec{d}|}{2} = \frac{v\Delta t}{2}$$

Consider two twins. One sets out at the age of 25 on a spaceship from Earth at a speed of $0.99c$ where c is the speed of light. The Earthbound twin goes on about her/his business accumulating the normal accouterments of advancing age (gray hair, drooping body parts, *etc.*). After twenty years have passed for the Earthbound twin, the spacefaring one returns. When they finally meet the voyager is NOT twenty years older! She/He looks only a few years older than when she/he left and shows few signs of age. How much has she/he aged during the journey? What does her/his worldline look like?

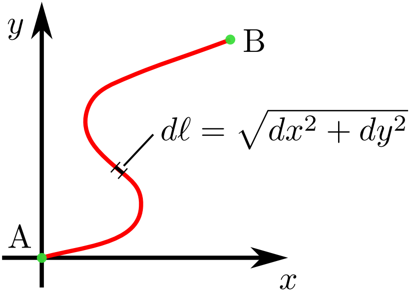
In the Home frame two events are observed to occur with a spatial separation $\Delta d = 360\ cm = 12\ ns$ and a coordinate time separation of $\Delta t = 24\ ns$. (a) An inertial clock travels between these events so it is present at both events. What time interval does this clock measure? (2) What is the speed of the clock in the Home Frame?

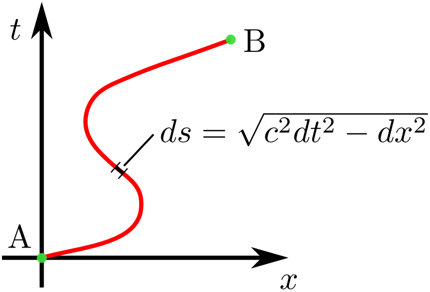
In the reference frame of the solar system two events are separated by 5.0 h of time and by $|\Delta\vec{d}| = 4\ h$ in space. What is the spacetime interval between these events?



$$\Delta\ell_{AB} = \int_{path} \sqrt{dx^2 + dy^2}$$

Defining A Pathlength - Proper Time





$$\Delta \ell_{AB} = \int_{path} \sqrt{dx^2 + dy^2} \qquad \Delta s_{AB} = \int_{path} \sqrt{c^2 dt^2 - dx^2}$$

The proper time between event A and event B is measured in the frame moving with the clock and in SR and SI units it is

$$\Delta s_{AB} = \int_{t_A}^{t_B} \sqrt{1 - \frac{v^2}{c^2}} c dt \ (SI \ units)$$

$$\Delta \tau_{AB} = \int_{t_A}^{t_B} \sqrt{1 - v^2} dt \ (SR \ units)$$

This equation describes how to use measurements in an inertial frame to determine the proper time between any two events A and B along an arbitrary worldline. The limits t_A and t_B are the times of the events A and B respectively, dt is the coordinate time differential, and $\vec{v}(t)$ is the clock speed all measured in the same inertial frame.

Example: A spaceship leaves Earth (event A) at a speed $v = 0.999c$ where c is the speed of light. It travels to the star Polaris at a distance $\Delta x = 434 \ ly$ away where $1 \ ly = 1 \ yr \times c$ is one light-year (the distance light travels in one year). Arriving at Polaris is event B. What is the proper time between leaving the Earth and arriving at Polaris?

Summary of Time Measurements

	Coordinate Time	Proper Time	Spacetime Interval
Definition	Time between two events in an inertial frame measured with synchronized clocks	Time between two events measured by the same clock at both events.	Time between two events measured by the same, inertial clock at both events.
Equation	Δt	$\Delta s_{AB} = \int_{t_A}^{t_B} \sqrt{1 - \frac{v^2}{c^2}}\, c dt$	$\Delta s^2 = c^2 \Delta t^2 - \Delta d^2$
Frame independent?	No	Yes	Yes
Geometric analog	coordinate difference	pathlength	distance

The proper time between event A and event B is measured in the frame moving with the clock and in SR and SI units is

$$\Delta s_{AB} = \int_{t_A}^{t_B} \sqrt{1 - \frac{v^2}{c^2}} c dt \ (SI \ units)$$

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which describes how to measure the proper time in an inertial frame between any two events A and B along an arbitrary worldline. The limits t_A and t_B are the times of A and B, dt is the coordinate time differential, and $\vec{v}(t)$ is the clock speed all measured in the same inertial frame.

Defining Proper Time - 2

The proper time between event A and event B is measured in the frame moving with the clock and in SR and SI units is

$$\Delta s_{AB} = \int_{t_A}^{t_B} \sqrt{1 - \frac{v^2}{c^2}} c dt \ (SI \ units)$$

$$\Delta \tau_{AB} = \int_{t_A}^{t_B} \sqrt{1 - v^2} dt \ (SR \ units)$$

which describes how to measure the proper time in an inertial frame between any two events A and B along an arbitrary worldline. The limits t_A and t_B are the times of A and B, dt is the coordinate time differential, and $\vec{v}(t)$ is the clock speed all measured in the same inertial frame.

Suppose the speed of a spaceship relative to an inertial frame fixed to the Sun is given by $|\vec{v}| = v = |\vec{a}|t = at$ where $a = 9.8 \ m/s$. Where would the proper time be measured? How long does it take to accelerate from rest to $v_f = 0.5c$ in the frame of the Sun? How long does it take to accelerate from rest in the spaceship frame?

Consider two twins. One sets out at the age of 25 on a spaceship from Earth at a speed of $0.99c$ where c is the speed of light. The Earthbound twin goes on about her/his business accumulating the normal accouterments of advancing age (gray hair, drooping body parts, *etc.*). After twenty years have passed for the Earthbound twin, the spacefaring one returns. When they finally meet the voyager is NOT twenty years older! She/He looks only a few years older than when she/he left and shows few signs of age. How much has she/he aged during the journey? What does her/his worldline look like?

Consider

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1. In the problem we found the Earthbound twin (EB) aged 20 years.

The Paradox of the Twins Paradox - 1 44

Consider

1. In the problem we found the Earthbound twin (EB) aged 20 years.
2. The Spacefaring twin (SF) aged just 2.8 years.

The Paradox of the Twins Paradox - 1 45

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3. EB took a relativity course in college and expects SF be younger upon arrival.

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4. From SF's frame it appears the Earth receded from the spaceship and then returned. SF expects EB to be much younger.

The Paradox of the Twins Paradox - 1

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5. The first postulate says performing the same measurement in inertial frames should give you the same result.

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6. Is one twin older than the other when they are reunited or are they the same age?

The Paradox of the Twins Paradox - 1 49

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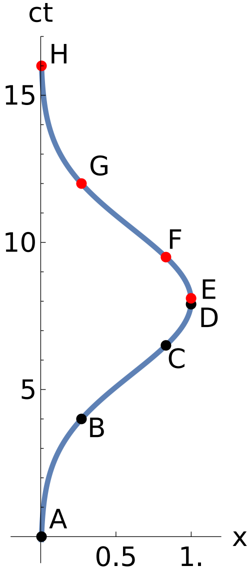
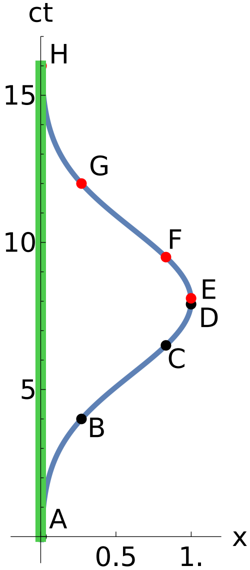
6. Is one twin older than the other when they are reunited or are they the same age?

SF was not in an inertial frame during the entire trip. She/he had to accelerate to turn around and return.



A	spaceship leaves
B	reaches cruising speed
C	starts decelerating
D	reaches turn-around point
E	starts return trip
F	reaches cruising speed
G	starts decelerating
H	return

Blue	Spacefaring
Green	Earthbound



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