Time dilation: Impact on Global Positioning System (GPS)

Time is a fascinating physical quantity. It is generally believed to flow continuously and uniformly without stoppage since the beginning of the universe nearly 14 billion years ago. But is it? Is time independent of any other physical characteristics of the universe? The answer may surprise many. Time is not an immutable physical quantity; it is very much influenced by the happenings around it. Time to you is not the same as time to me. Time on the sun ticks slower than on earth. Your head is older than your toes. And the best anti-ageing technique is to live aboard a very fast spaceship.

It is true that these effects of time speeding up or slowing down are very small to be observed in our daily life. Hence, I choose to demonstrate a commonly used service by us where these effects on time are observed. This service is the Global Positioning Service (GPS). Every time we use Google Maps or an equivalent service, the device figures out, using GPS satellite signals, where it is located on the surface of the earth with very high precision.

How does the GPS system work? Thirty-two satellites are orbiting at around 20,000 km from the surface of the earth. Each satellite sends signals which are received by the device and after some computations based on when the signal originated and when it was received from at least four satellites, the device can calculate its own precise coordinates (latitude and longitude).

However, to be accurate the clock on the satellite should be running at the same speed as clocks on the earth. This is because each signal has an embedded time of origin which is used to compute the distance it is from the receiver. If the clock on board the satellite is for some reason fast or slow, then an error can creep in resulting in giving wrong position.

Every GPS satellite does have an atomic clock on board which is a very stable and a precise device and has an error of at most 1 second per 100 million years. Therefore, there can be no error due to the quality of device on board. However, as Einstein postulated in his theory of relativity, the passage of time is influenced by two aspects. Firstly, the speed of the body and secondly, the distance the body is from a very heavy body. As speed increases, time slows down and as the body moves further away from a heavy body (like earth), time speeds up.

So, on each satellite, due to it traveling at a very high speed of 3.9km/sec, time slows down by about 7.3 microseconds per day. A microsecond is a millionth of a second. This phenomenon is called kinetic time dilation. However, due to the satellite being 20,000km above the surface of the earth, time speeds up due to less gravity. This phenomenon is called gravitational time dilation. This results in the satellite gaining 45.7 microseconds per day. Combine the effect of these two, kinetic and gravitational time dilation, a GPS satellite atomic clock falls behind a similar clock on earth by 38.4 microseconds per day.

Now, we may think 38 millionths of a second is so tiny that it does not matter. However, signals travel at the speed of light and light travels at 300 meters every microsecond. So, an error of 38.4 microseconds would mean 11.5km in terms of distance and you would agree that such an error would make GPS an unusable service.

To compensate for time dilation effect, clocks on the satellite are calibrated to operate at a slightly lower frequency than those of earth. Time dilation, therefore, is not just an abstract concept but is very real and our daily lives would be impacted if we were to ignore it.

To show this phenomenon, I have here three exhibits

1. GPS satellites in orbit: A scaled model of earth and the GPS satellites around it. At any point on earth there are at least four satellites, minimum, which are in line of sight and transmitting signals.
2. Gravitational time dilation: A tall tower with a clock on top and a clock on the bottom. Since the bottom clock is closer to the center of the earth it experiences more gravitational force and hence it moves slower than the clock on top which moves faster.
3. Kinetic time dilation: A moving train which shows that time moves slower on a moving object than on a stationary one.

Exhibit 1: Globe with the satellites in orbit

- Global Positioning System (GPS)
    - 32 satellites in orbit
        - Altitude: 20,180 km from earth's surface. This is a scaled model where the orbital sphere has a radius which is slightly over 4 times than that of earth.
        - Velocity: 3.9 km/sec or 14,040 kmph
    - Minimum 4 satellites to locate the position of a receiver (phone, watch, etc.)
    - Each satellite has an atomic clock on board.
    - Each satellite sends the signal to the GPS receiver. The time taken for the signals, which travel at speed of light, to traverse is used to compute the position of the receiver in 3-d space.
    - Accuracy: 30-500cm
    - Errors due to time dilation
        - Time dilation due to speed of satellite or kinetic time dilation
            - The relative difference of speed of the satellite compared to an observer on the surface of earth is 3.9 km/sec.
            - **The faster you travel, the slower time passes.**
            - This results in the time on the satellite to slow down by around 7.3 microseconds per day or 1 sec slower for every 377 years.
        - Time dilation due to gravity or gravitational time dilation
            - Since the satellite is away from earth, which is a massive object, the gravitational force is lower on it compared to an observer on earth. This causes time to go faster on the satellite.
            - **The farther away you are from a heavy object, the faster time passes.**
            - These satellites orbit earth at 20,180 km above the surface. Hence the time speeds up by 45.7 microseconds per day or 1 second faster for every 60 years.
        - The combined impact of the above two is that the atomic clock on the GPS satellite is faster by 38.4 microseconds per day or 1 second faster for every 71 years.

- Given the speed of light is 300 meters per microsecond. An error of 38 microseconds in a day would mean a spatial error of over 11 km will creep into the system every day unless corrected.

Error due to	Amount ('-' indicates slower time and '+'indicates faster time) {microseconds per day}	Notes
Kinematic time dilation	-7.3	Relative velocity of 3,900 m/s
Gravitational time dilation	+45.7	Orbital height of 20,180 km
Total time dilation	**+38.4**	

To compensate for this time dilation error, clocks on the satellites are calibrated to function at a slightly lower frequency at 10.22999999545 MHz instead of 10.23 MHz

Exhibit 2: A tall tower with a faster clock on top and a slower clock on top.

- Gravitational time dilation
  - Time slows down near massive objects like earth, sun, black hole, etc.
  - One earth year on the sun is 67 seconds slower because the sun's mass is 333,000 times more than earth.
  - One earth year on the known most massive black hole, TON 618, would be 19 days slower. (TON 618 mass is 66 billion times that of sun).
  - The center of earth is estimated to be 2.5 years younger than the surface of the earth. (https://iopscience.iop.org/article/10.1088/0143-0807/37/3/035602)
  - The center of sun is estimated to be 40,000 years younger than the surface of the sun. (https://iopscience.iop.org/article/10.1088/0143-0807/37/3/035602)

$$\Delta t' = \Delta\sqrt{\frac{1-2GM}{rc^2}}$$

where:

- Δt' - Time interval affected by gravity;
- Δt - Time interval uninfluenced by gravity (in a reference frame in an infinite distance from any mass);
- M - Mass of an object causing the gravitational dilation;
- G - Gravitational constant ($G = 6.6743 \times 10^{-11}\ \mathrm{Nm^2/kg^2}$);
- r - Distance from the center of an object causing the gravitational dilation; and
- c - The speed of light in a vacuum ($c = 299,792,458\mathrm{m/s}$).

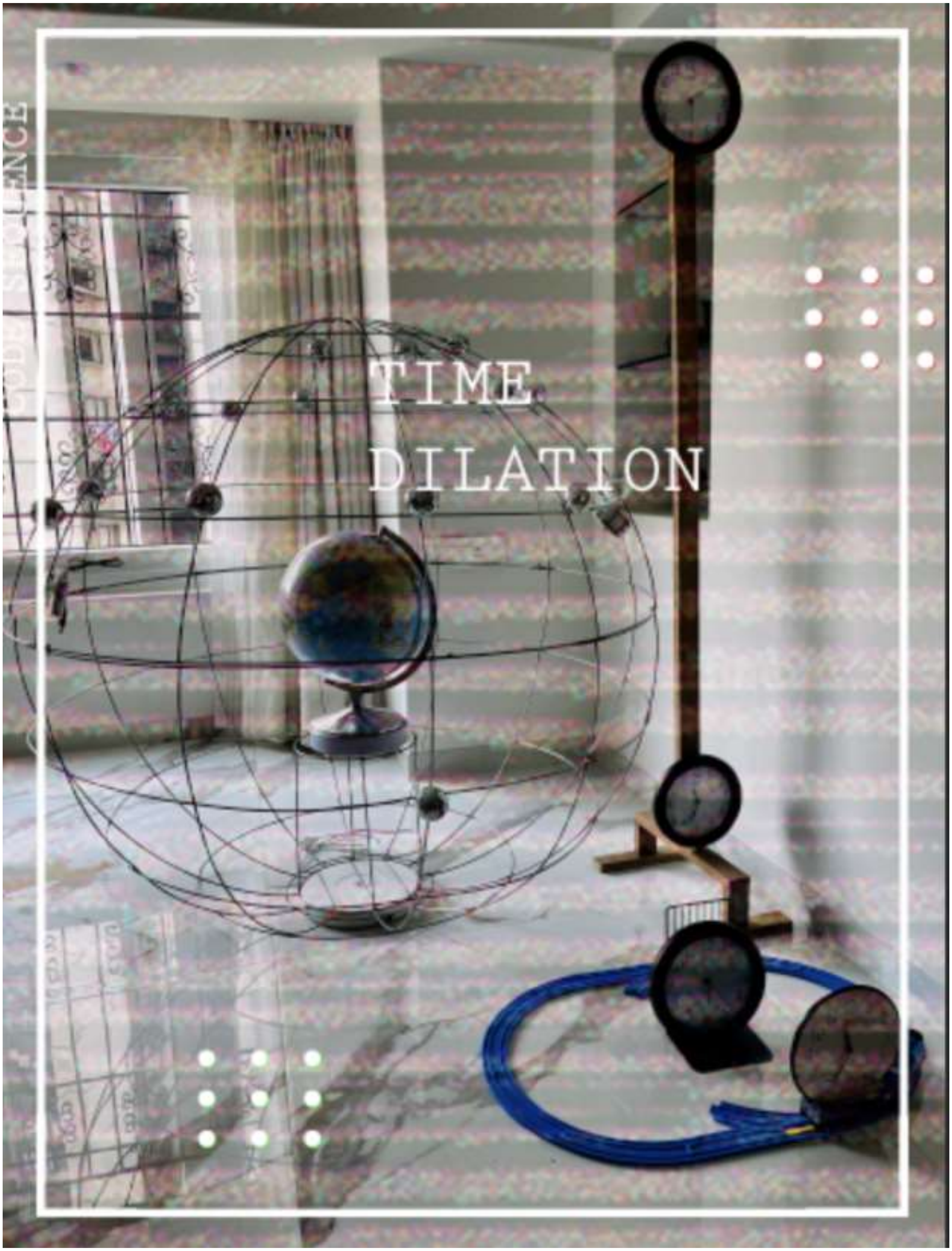

TIME
DILATION

Exhibit 3: Train with a faster clock in it and a slower clock kept stationary

- Kinematic time dilation
  - If you move at a very high speed, time begins to slow down. Obviously, you don't move in slow motion – from the perspective of the person who is moving at high-speed time passes as usual. However, from the perspective of the stationary person time passes slower for the body at high speed.
  - A famous thought experiment of twin astronauts is a good example that makes time dilation easier to understand. Imagine that one of the twins stays at home on Earth, and the other one gets on a high-speed rocket. He spends some time traveling through space and returns home after what he thought was a few years. To his surprise, he finds that his twin, who stayed back, has aged much more and is now an older man.
  - If one is travelling at 10% of speed of light, then an earth year will be longer by 44 hours. At 28% of speed of light then an earth year will be longer by 287 days.

$$\Delta t' = \gamma \Delta t = \frac{\Delta t}{\sqrt{1 - v^2/c^2}}$$

where:

- $\Delta t'$ – Time that has passed as measured by a stationary observer (relative time);
- γ – Lorentz factor;
- Δt – Time that has passed as measured by the traveling observer;
- v – Speed of the traveling observer; and
- c – Speed of light (299,792,458 m/s).

Time Trivia

-During Kargil War, USA degraded the GPS system by a program called selective availability which made the system unusable by Indian military. Hence, India launched its own system called NavIC.

Present atomic clocks, based on cesium atoms, have an accuracy of being accurate to the extent of 1 sec in 100 million years. Your quartz watches maybe accurate to within about 15 seconds per month. The next generation atomic clock, strontium atomic clock, is so accurate that it would not have lost a second had it started at the moment of Big Bang. This means that a height of 2 cm on earth can be measured using this clock as a sensor and using the principle of gravitational time dilation.

While standing your head is 1.6m farther from earth's surface than your feet, every year your head ages faster than your feet by 0.0000000055 seconds or 5.5 nano seconds. *Your head is older than your feet.*

If you have cumulatively spent one year traveling in a car all your life then you are 49 nano seconds younger than you would have been had you never traveled. An average pilot in a year is younger by 691 nanoseconds.

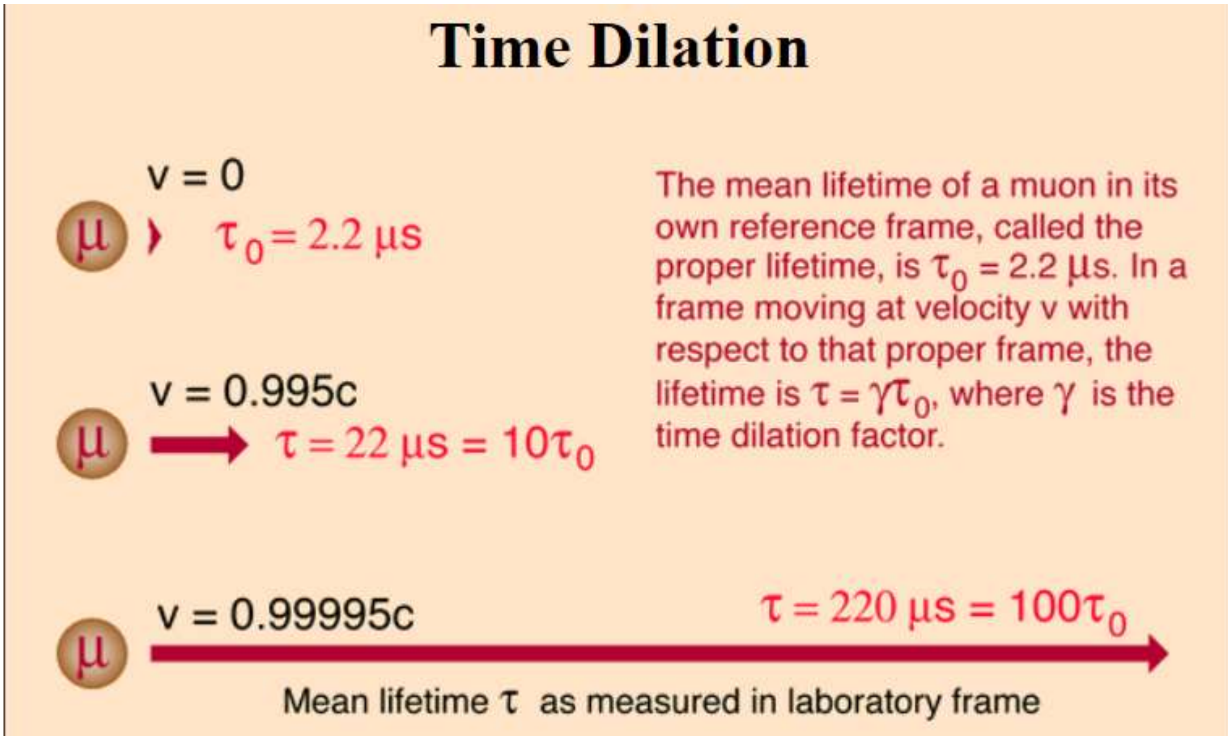
Time runs slower on ISS (International space station) by around 0.01 seconds per year.

Earth's core is 2.5 years younger than its surface.

Your time is different than my time.

For Deep Space Navigation, NASA is developing a clock which can be accurate and not rely on ground stations on Earth, as GPS satellites do, because time it will take for the signal to travel back and forth will be very long.

Muons are 2nd generation leptons which are formed when cosmic rays hit earth's atmosphere. The lifetime of muons is about 2.197 microseconds and sometimes travel at near the speed of light. According to Classical Mechanics, muons travelling at nearly the speed of light will take approximately 50 microseconds to reach sea level which is 25 times longer than muon lifetimes. Muons can, however, be detected at sea level at a rate far greater than classical predictions. This is due to time dilation.



Speed kills. Very high speed though makes you near immortal!

Best anti-ageing technique – Travel aboard a very fast spaceship and stay away from any planetary bodies.

What time is it?

A simple question … eh?

Well … maybe…actually no.

Time based on earth's rotation. That is called UT1 time. Radio telescopes intercept signals from quasars to register the moment a fixed star passes a location's longitude.

Time based on oscillation of Cesium-133 atoms i.e., 9,192,631,770 times per second. This is called TAI or International Atomic Time. It has nothing to do with earth's rotation.

We neither use UT1 or TAI!

We use UTC time or Coordinated Universal Time. This comes about by finding a way to use TAI and adjust it based on earth's rotation. While earth is supposed to spin exactly once every 24 hours, it does not. It is slowly slowing down.

UTC – Time at Greenwich Mean Time (GMT)

TAI – UTC + 37 seconds (synchronized in 1958; earth slowing down means TAI is ahead of UTC)

GPS time – UTC + 18 seconds. (GPS synchronized with UTC in 1980, unadjusted by leap seconds)

Conversion between TAI, UTC, and GPS

	From			
To		TAI	UTC	GPS
	TAI	-	+37*	+19
	UTC	-37*	-	-18*
	GPS	-19	+18*	-

And UT1 time is not really time as it keeps tally of earth's rotations and revolutions.

For further information on GPS

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The Cathedral & John Connon School

https://www.gps.gov/students/

links to my exhibits:

Time Dilation and GPS: https://youtu.be/Hxa7qx5PEzc

GPS Satellites: https://youtu.be/vpsAv4j7UWU

Gravitational Time Dilation: https://youtu.be/JD0dkow_uJ0

Kinematic Time Dilation: https://youtu.be/CdVVYn5VPW0