



INTERNATIONAL  
CENTRE *for*  
THEORETICAL  
SCIENCES

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

# A History of Time

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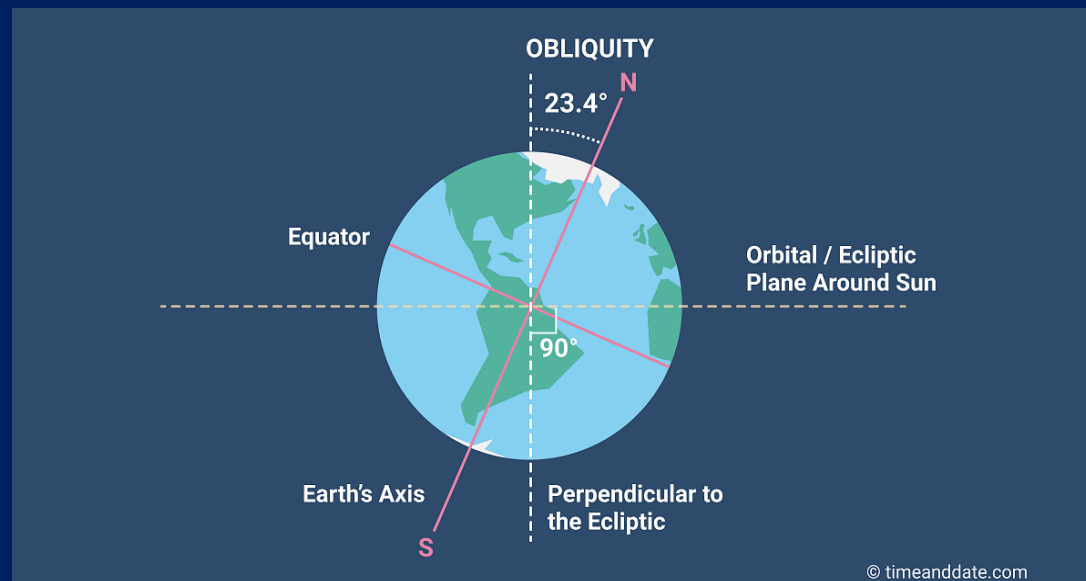


CMI  
27 July 2024

# Time and celestial phenomena-1

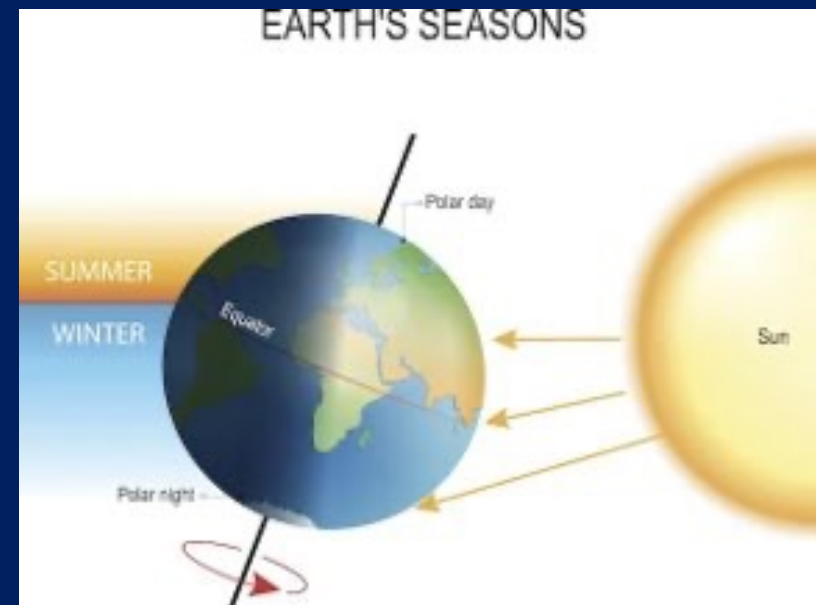
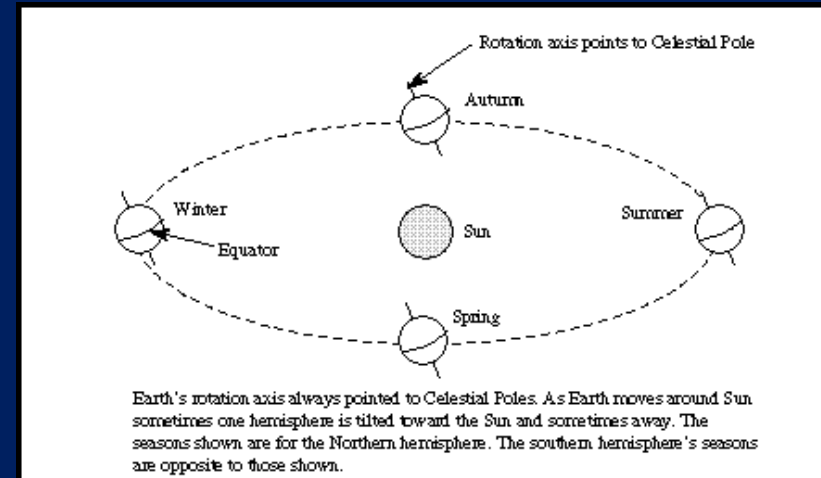
Our awareness of day and night is obvious as the sun appears and disappears daily; this is related to the spinning of the earth on its axis, an explanation that came much later.

Day and night are wired into our genes: there is secretion of melatonin in the evening that induces sleep. Such circadian rhythms are present in animals, plants and other living matter.



# Time and celestial phenomena-2

The awareness of the duration of a year, during the early history of our species, is through the seasons and their manifestation in terms of hot and cold weather, the appearance of fruits and flowers, migratory patterns of birds and animals and, when agriculture came about, a time of sowing seeds and a time for harvest.



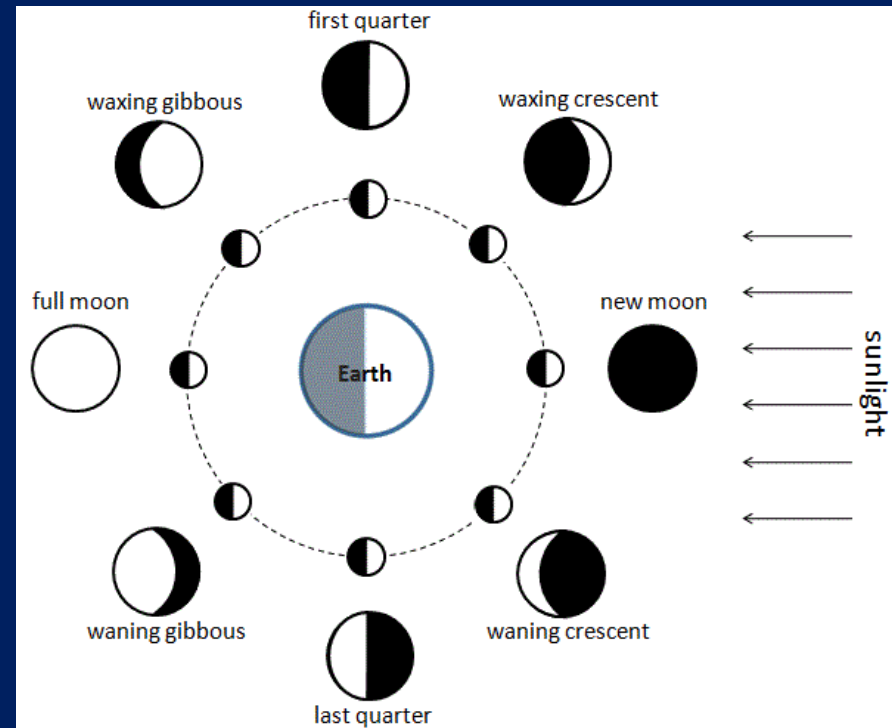
# Time and celestial phenomena-3

The waxing and waning faces of the moon and the rise and ebb of tides, due to its synchronous rotation about its axis and its orbit around the Earth became a natural timekeeper.

A **lunar month** became a natural unit measuring the time between identical faces of the moon.

Early in history, it was our sensory perception of the motion of Earth in the solar system and the visible periodicity of the phases of moon.

The notion of time grew out of the almost periodic cycles of the natural world...and that fact has continued into the modern world.



# Time and celestial phenomena-4

- More sophisticated time keeping devices emerged based on Astronomy. One imperative came from navigation at sea. As the seasons change, the movement of constellations (group of stars) is visible in the night sky. This is due to the orbit of the earth around the sun.
- "The synchronization of celestial and terrestrial changes naturally suggest a causal relationship between them and so observing the motion of constellations and planets became a way of explaining and predicting events on Earth."

(James Vincent. "Beyond Measure: The Hidden History of Measurement").

# Time and celestial phenomena-5

- However, celestial time keeping has inaccuracies built into it because **celestial motions are never perfectly periodic**.
- For example, the length of the year measured between equinoxes is **365.2422**, which over centuries, say five, can grow a difference of  **$0.2422 \times 500 = 121.1$  days!**
- Similarly, the **average length** of a lunar month is 29 days, 12hrs, 44mins and 2.8 secs!

# Terrestrial time keeping devices

Societies also developed various terrestrial time keeping devices e.g., the water clock, the sundial, sandglass and incense clock

These devices are not very accurate timekeepers. E.g., the water clock's measure of time depends on the temperature of water!



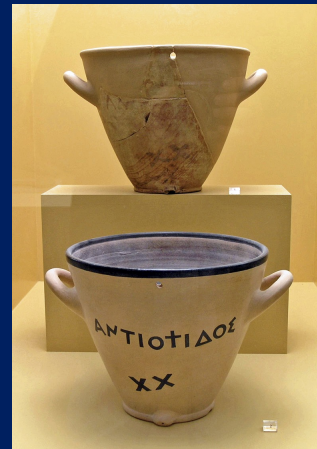
A marine sandglass. It is related to the hourglass, nowadays often used symbolically to represent the concept of time.



An Ancient Egyptian sundial



A limestone Egyptian water clock, 285–246 BC (Oriental Institute, Univ of Chicago)



A display of two outflow water clocks from the Ancient Agora Museum in Athens.



An incense clock; time was measured by means of powdered incense burnt along a pre-measured path

# The Mechanical Clock-1

The **'oscillator and escapement' mechanism** that creates the regular periodic beat of timekeeping was originally developed in countries like China and the middle east. Towards the **end of the 13<sup>th</sup> century** European craftsmen refined this mechanism to create the **first mechanical escapement mechanism that led to the mechanical clock.**



The Gros-Horloge, Rouen  
Normandy, France



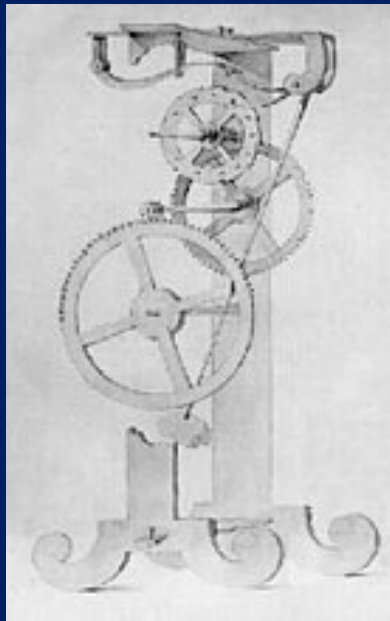
# The Mechanical Clock-2

- “The mechanical clock propelled a new conception of time into the public consciousness, transforming it from a constant flow, embodied in steady emissions of water, sand and mercury to a quantified count: divisible, discrete and measurable”.
- “As with monastic bells, public clocks organized citizens into a cohesive unit, turning what had previously been private lives into communal tides that rose, worked and retired as one” ...
- “The clock is not merely a means of keeping track of the hours, but of synchronizing the lives of men”.

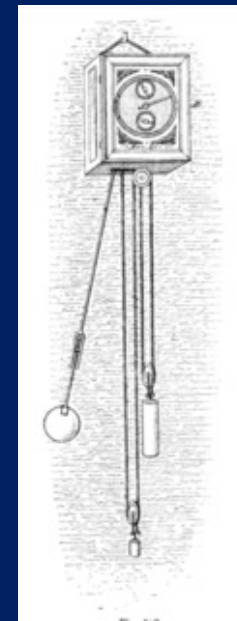
James Vincent: “Beyond Measure: The Hidden History of Measurement”

# The Mechanical Clock-3

The pendulum clock design was conceived by Galileo Galilei around 1637 and the first working model was invented by Christian Huygens and constructed by Salomon Coster in 1656.



Pendulum clock  
conceived by Galileo  
Galilei around 1637.



The first pendulum clock,  
invented by Christiaan  
Huygens in 1656

# The Mechanical Clock & the Growth of the Scientific Method

- The clock, which is a machine, became a symbol of a new way of conceiving the universe: mechanical philosophy.
- “The mechanical philosophers reasoned that if clockwork was able to capture the movement of the stars and bring an elaborate automata to life, who was to say that the natural world did not operate under a similar logic? If nature worked like a machine, then it must rely on observable cause and effect”.
- Galileo Galilei more than any of his contemporaries crystalized the integration of experiment and theory and laid the foundation of the scientific method.
- He died in 1642 the year his successor Isaac Newton was born.

# Quantum Mechanics: The Quartz Clock and the Caesium-133 Standard

- The mechanical clock that worked on the laws of classical mechanics was the standard timekeeper well into the 20th century...till it was replaced by devices that work on Quantum Mechanics!
- The 'Quartz crystal' is piezoelectric and oscillates at a precise frequency: exactly 32768 times each second. This is used as a timekeeper in the quartz clock.
- The most accurate timekeeper is the atomic clock.
- "The second is the duration of 9192631770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the Caesium 133 atom."

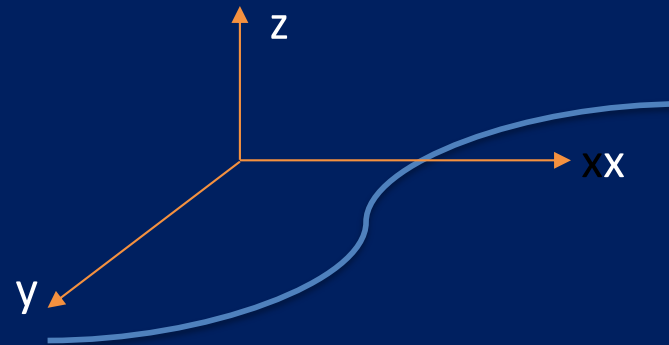
Newtonian Framework of Physics,  
Universal time  
and the  
Law of Universal Gravitation

# Isaac Newton (Principia Mathematica 1687)

Establishes a framework of mechanics:  
All natural processes take place in  
space and time.



Newton formulated the laws of motion in terms of the flow in time of the position of a point particle in 3-dims.



$(x(t), y(t), z(t))$  is a curve; velocity and acceleration are given by time derivatives of the curve. Geometry, Calculus and Mechanics provide a description of motion.

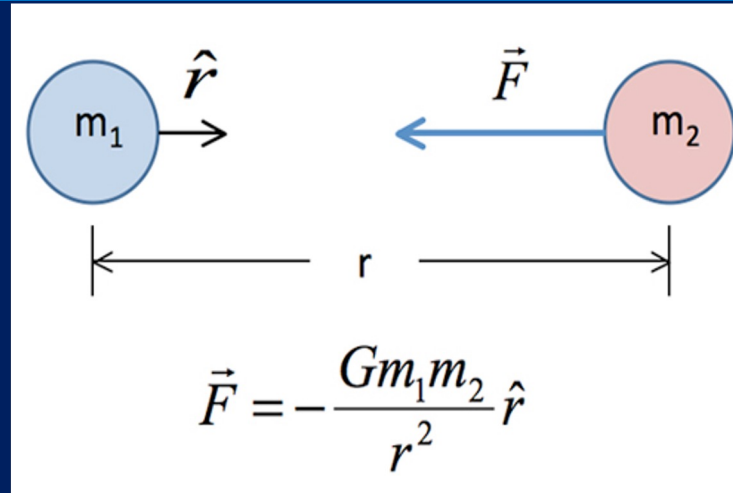
Time is absolute and the same for all observers. Coordinates may be rotated or moved with constant velocity.

Newton's law of motion:

$$\text{Force} = m_i \times a$$

Foundation of ALL classical physics

# Newton's law of Universal Gravitation



- Gravitational force acts instantaneously at a distance
- Always attractive
- Force (on particle 1 due to particle 2) =  $m_{1i} \times a_1$
- Inertial mass  $m_{1i} =$  gravitational mass  $m_1$
- Hence gravitational acceleration does not depend on the mass (Galileo)

In the simple case of 2-bodies leads to the famous elliptical orbits of planets described by Kepler, when the coordinate system is centered at the Sun; he found symmetry in big `data`.

# Newton on the Law of Universal Gravitation

Newton (1692):

"That one body may act upon another at a distance through a vacuum without the mediation of anything else, by and through which their action and force may be conveyed from one another, is to me so great an absurdity that, I believe, no man who has in philosophic matters a competent faculty of thinking could ever fall into it."

Newton (1713):

"I have not yet been able to discover the cause of these properties of gravity from phenomena and I feign no hypothesis. It is enough that gravity does really exist and acts according to the laws I have explained, and that it abundantly serves to account for all the motions of celestial bodies."



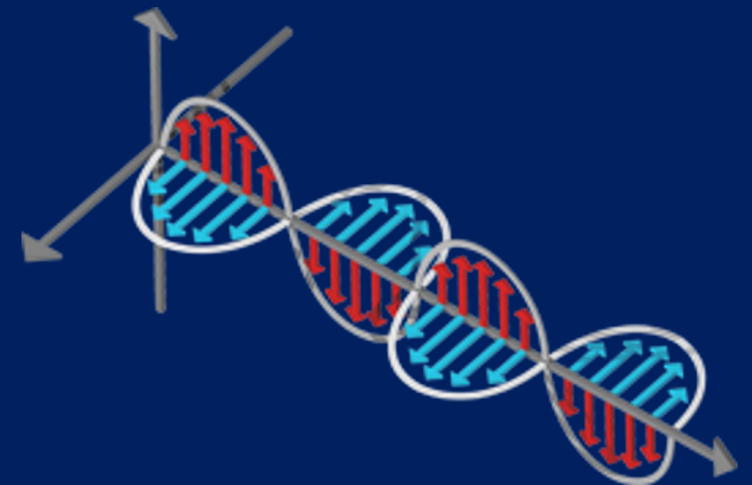
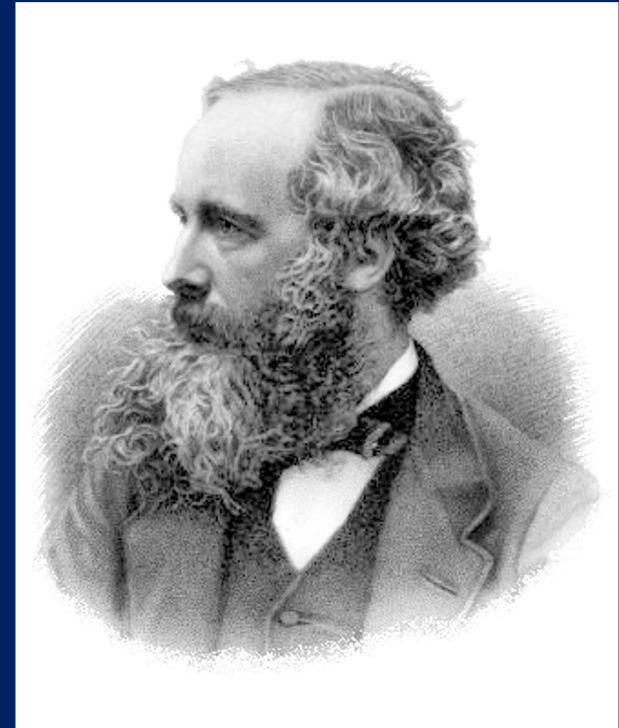
Electricity and Magnetism  
and  
Electromagnetic Waves  
and  
the constancy of the  
Speed of Light

# Electric and Magnetic **Fields** and **Waves**

Michael Faraday had demonstrated that light is polarized by a magnetic field.

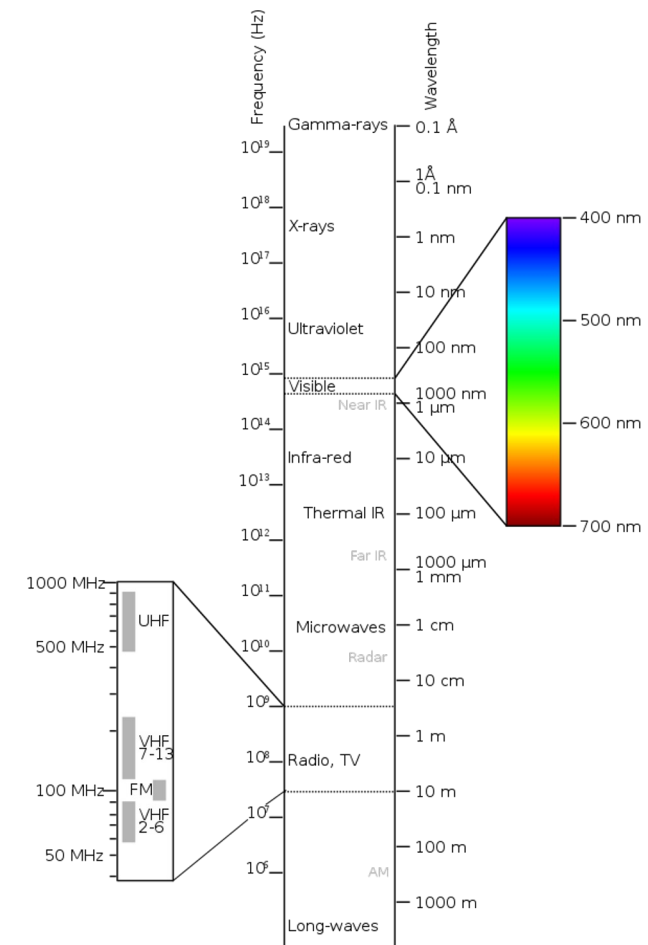
James Clerk Maxwell unified electricity and magnetism, predicted the existence of electromagnetic waves and identified light as an electromagnetic wave of oscillating electric and magnetic fields moving with a speed  $c$  (in vacuum)  
 $c = 3.1 \times 10^5$  kms/sec (1865).

Force between charged particles is not instantaneous. It is transmitted by the electromagnetic field at the speed of light which is finite.



# Experimental tests of Maxwell's theory

- In 1887 Heinrich Hertz demonstrated existence of radio waves that were predicted by Maxwell's theory with properties the same as visible light except the wavelength is  $10^4$  times longer.
- In 1895 Wilhelm Conrad Roentgen made the serendipitous discovery of X-Rays, which are electromagnetic waves of wavelength  $10^{-2}$  times shorter than visible light.



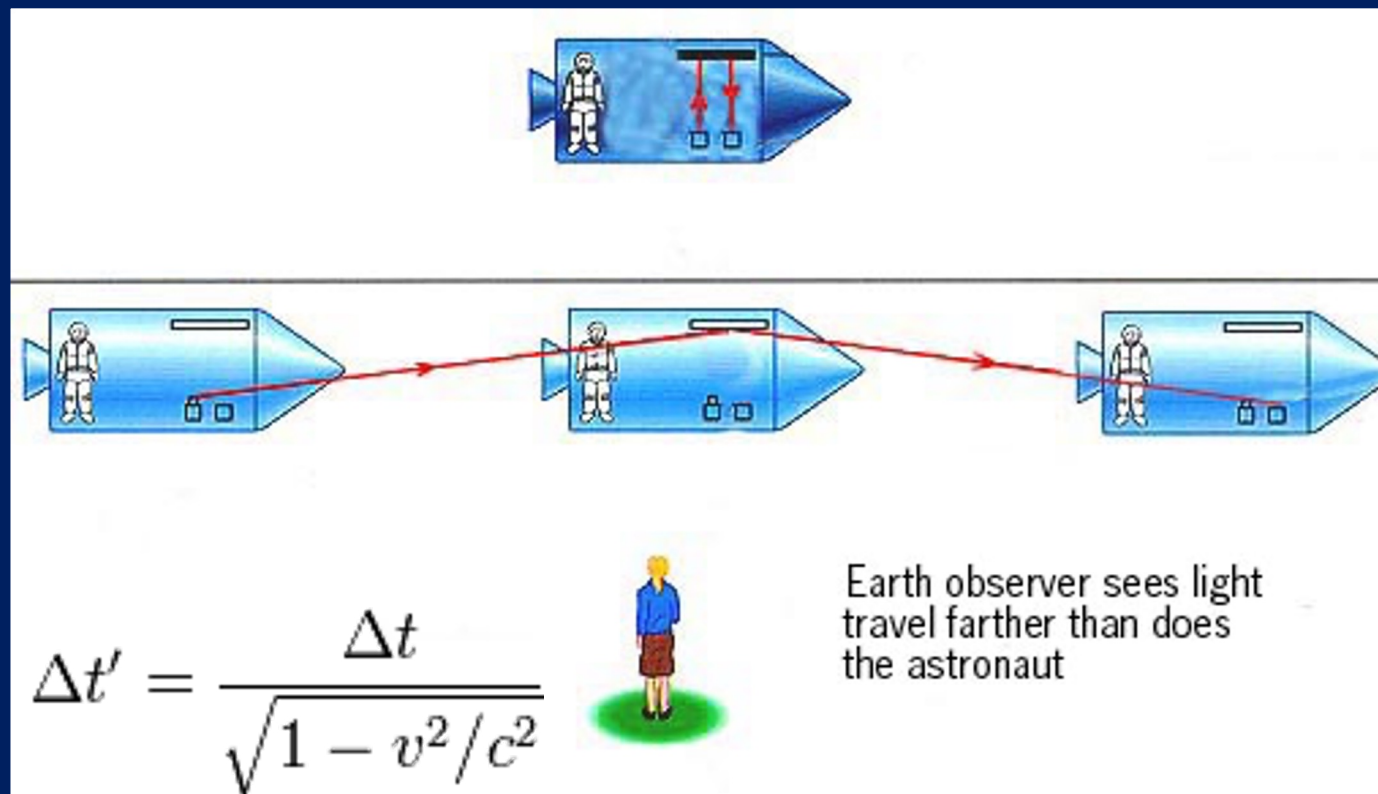
# Lorentz, Poincare, Einstein: Special Relativity (1905)

## Implications of Maxwell's theory

Speed of light is the same whether you run towards it or away from it.

Space and time adjust themselves to ensure this!

Time intervals between events depend on your state of motion; things happen (according to us) more slowly for a moving observer than for us.



# 4-dimensional Space-Time Geometry

Hermann Minkowski (1864-1909)



*“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.”*

Introduced Geometry in Special Relativity

- Time is a 4<sup>th</sup> component of a 4-dim. space-time  $x_4 = ct$ ; a new geometry described by an infinitesimal Lorentz invariant distance

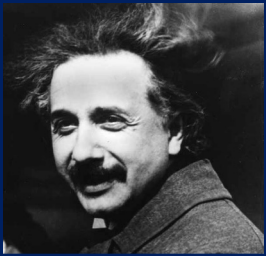
$$ds^2 = (dx_4)^2 - (dx)^2$$

- Recall Euclid's geometry:  
 $ds^2 = (dx_4)^2 + (dx)^2$   
Is the rotational invariant distance.

# General Relativity and Time

# General Relativity-1

Given that the speed of light is the same for observers in relative motion there can be no action at a distance which is simultaneous for all inertial observers in relative motion.



Einstein

Hence Newton's law of gravitation needs to be modified.

Waging one of the great struggles in modern scientific history in 1915 Einstein completed the General Theory of Relativity, which is a theory of gravity in which the force of gravity is not instantaneous. It is communicated at a finite speed  $c$  (the same as the speed of light) by changes in the geometry of space-time.

Here the role of the electromagnetic field is played by the waves of the 'metric' of spacetime.

# Einstein's Two Puzzles/Questions

Newton's law of gravity in conflict with special relativity, and why only special relativity?

- That the force of gravity acts instantaneously is not consistent with Special Relativity!
- Einstein would like to have the force of gravity communicated at the speed of light by a field analogous to the electro-magnetic field of Faraday and Maxwell.
- Special Relativity is restricted to frames with relative constant velocity, but the laws of physics must be valid in any spacetime reference frame including those which are accelerating.



# Special Relativity → General Relativity

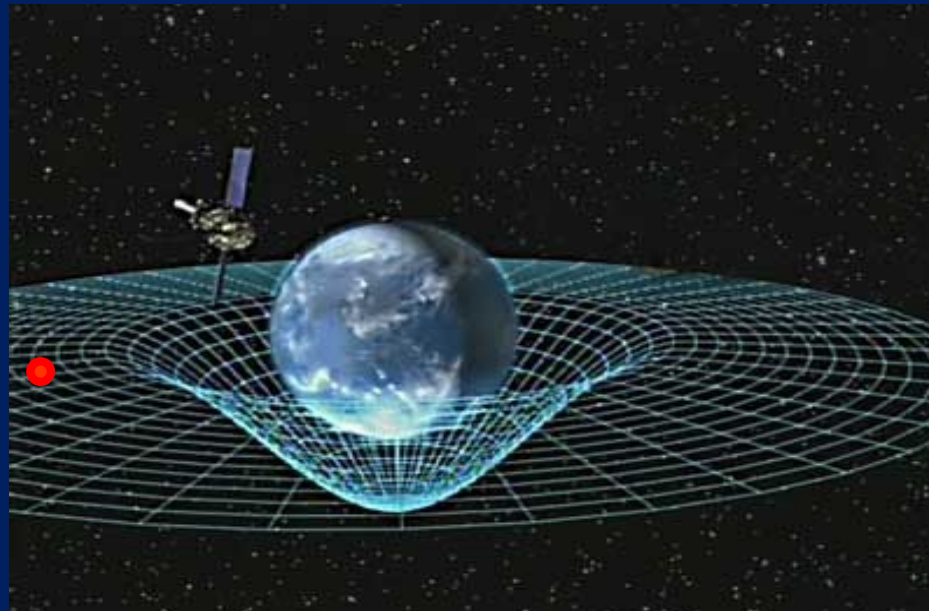
- A possible resolution occurred in 1907.
- The Principle of Equivalence: (“the happiest/luckiest thought of my life” - Einstein)  
“The effect of a constant gravitational field is equivalent to a uniformly accelerated frame”.
- In general, special relativity holds in sufficiently small regions of space-time in a non-uniform gravitational field.
- Patching up such small regions of space-time to construct the full space-time needed Riemannian geometry (curved space-time) and Marcel Grossmann (1912, Zurich).

# General Relativity-2

GR describes the changes of the geometry of space-time caused by massive objects to which other objects respond. "matter tells space-time how to curve, and curved space-time tells matter how to move"(John Wheeler)

Space-time is like an 'elastic' grid, communicative and causal...but very very stiff... $10^{20}$  times stiffer than steel!

In a curved space-time an object follows a path that maximizes the "proper time" in the frame of the object. These paths are geodesics.



# Time in General Relativity

Einstein's theory implies that time flows different for two observers in a gravitational field

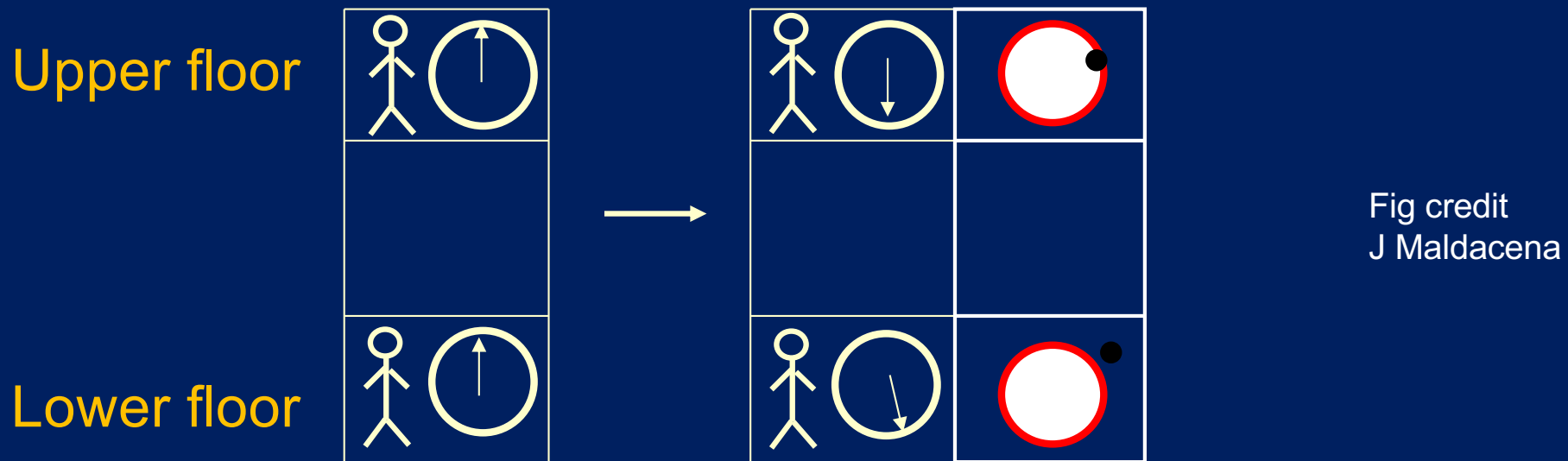


Fig credit  
J Maldacena

Time flows more slowly  
(A part in  $10^{15}$ ) for a height of 100 meters.

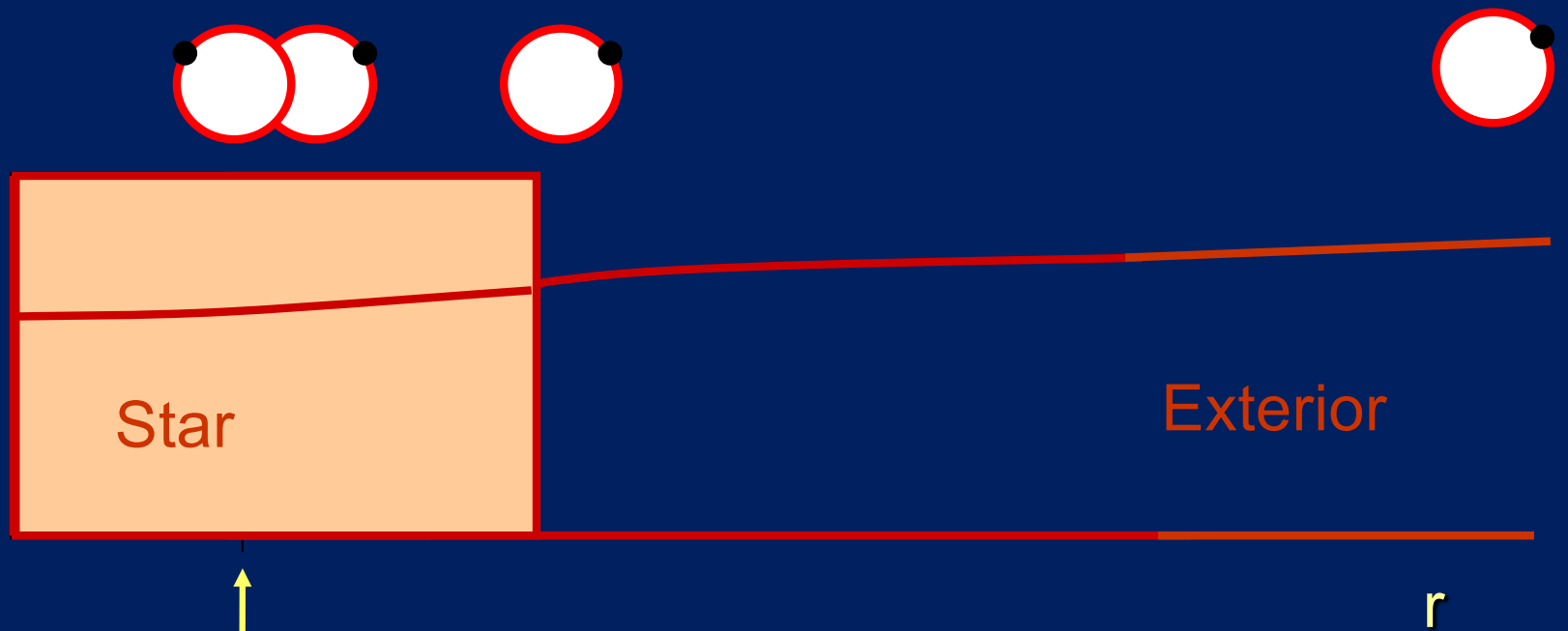
This effect is relevant for GPS!

# Flow of time in the presence of a massive Star & a Black Hole

Flow of time

$$\sqrt{1 - \frac{r_h}{r}}$$

$$r_h = 2G \frac{M}{c^2}$$



Black hole radius

Fig credits: J Maldacena

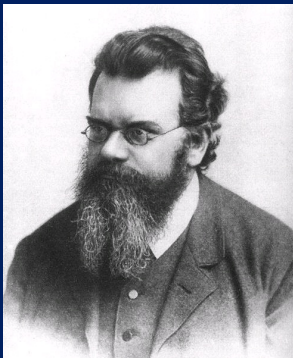
# The Second Law of Thermodynamics, Entropy and Time Irreversibility

Until now we have discussed the emergence of the concept of time and its measurement in terms of the regularities observed in nature: the motion of the earth in the solar system; the passage of constellations in the night sky; water clocks; sand glass; the mechanical clock; the quartz clock and the Cesium standard.

However, most phenomena in the real world exhibit a fundamental irreversibility. E.g., consider the burning of a piece of wood. The final state is simply ash and carbon dioxide and other gases. One never observes this final state assembling itself back to the piece of wood!

From a thermodynamic point of view, one would explain this by saying that the entropy of the final state is greater than that of the initial state of the wood and hence by the empirical 2<sup>nd</sup> law of thermodynamics the time reversed process does not happen.

To quantitatively understand this phenomenon Ludwig Boltzmann (1866) introduced a formula for the Entropy of a gas as a measure of the number of internal states that make up the system and showed under reasonable hypothesis about the randomness of collisions that the entropy always increases in time. This laid the foundations of 'Statistical Physics'. It was subsequently adopted ) in Quantum Mechanics by John Von Neumann (1932). Claude Shannon (1948) gave a discrete version of Boltzmann's formula that forms the foundation of 'Information and communications theory'.



Ludwig Boltzmann (1844-1906)

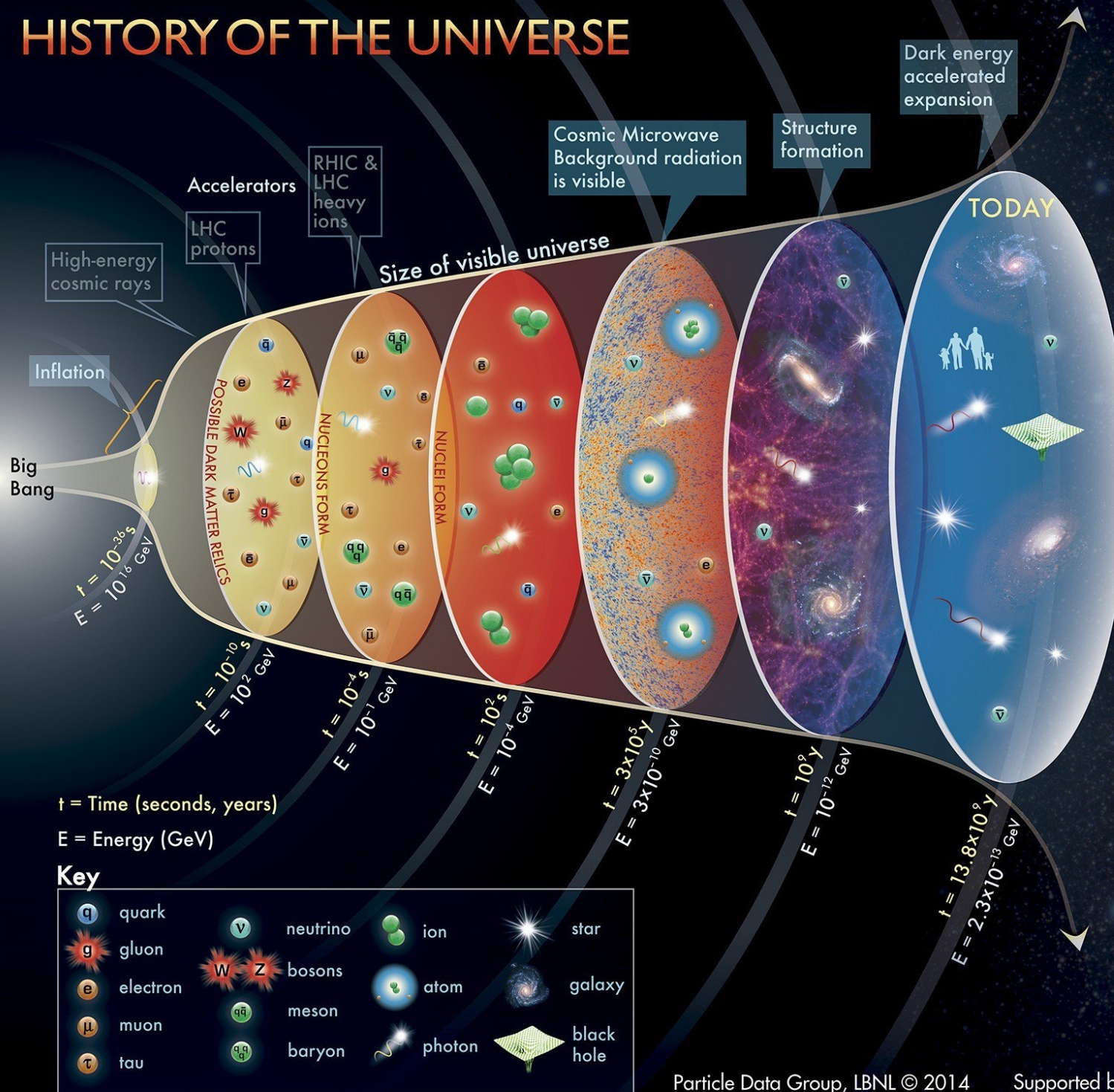


John Von Neumann (1903-1957)



Claude Shannon (1916-2001)

# HISTORY OF THE UNIVERSE



## Adapted from Brian Swimme: The Universe is a Green Dragon

“Most amazing is this realization that everything that exists in the universe came from a common origin. The material of your body and the material of my body are intrinsically related because they emerged from and are caught up in a single energetic event. Our ancestry stretches back through the life forms and into the stars, back to the beginnings of the universe. And all of this is new. None of the great figures of human history were aware of this. We are the first generation to live with an empirical view of the origin of the universe. We are the first humans to look into the night sky and see the birth of stars, the birth of galaxies, the birth of the cosmos as a whole. Our future as a species will be forged within this new story of the world.”

# Epilogue

So here we are after 13.7 billion years in this vast cooled down universe...on a small rock called Earth of age 4 billion years sailing through the universe as part of our galaxy the Milky way, with a 100 billion others...

This immensity and complexity must make us feel humble.

There is much to be said about the perturbation of the state of Earth by us, and about the preservation of our species and others that we coexist with.

One of the most important developments of the last millennium is the scientific method as a means to access the idea of truth.

Hopefully you will imbibe this and see the world in all its aspects including our history, our sociology, our environment, and our survival as a planet, through this lens.



**Thank You!**