ICTS | INTERNATIONAL CENTRE for THEORETICAL SCIENCES

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

A History of Time

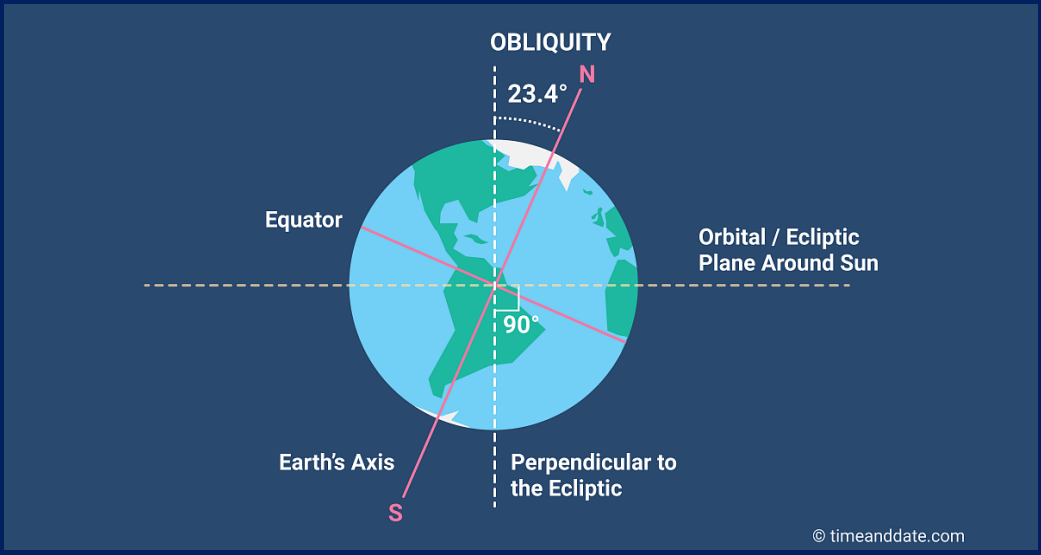
Spenta R. Wadia
ICTS-TIFR Bengaluru

Kaapi with Kuriosity
Nehru Planetarium
Bengaluru
23 Feb 2025

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.

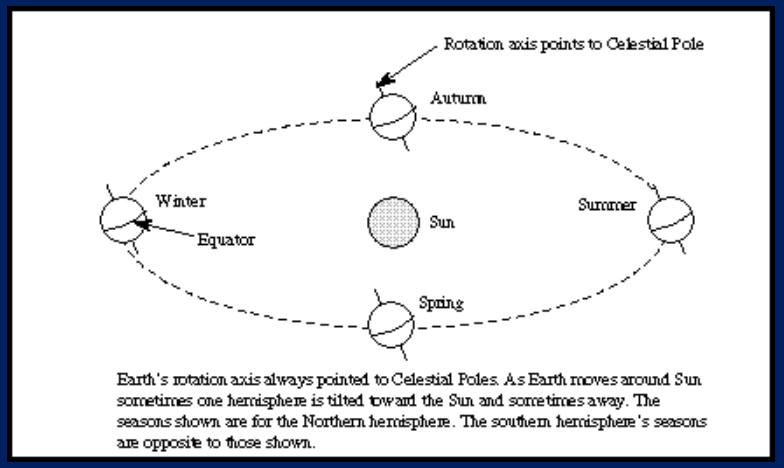


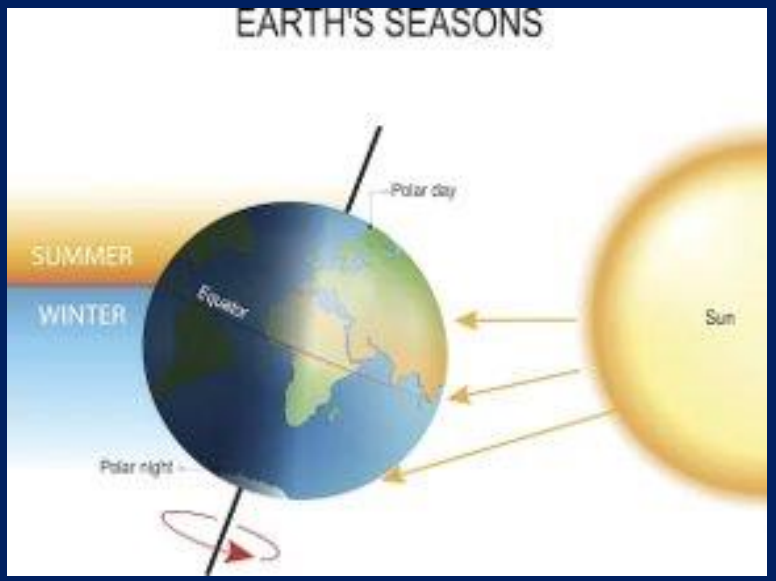
Time and celestial phenomena-2

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.





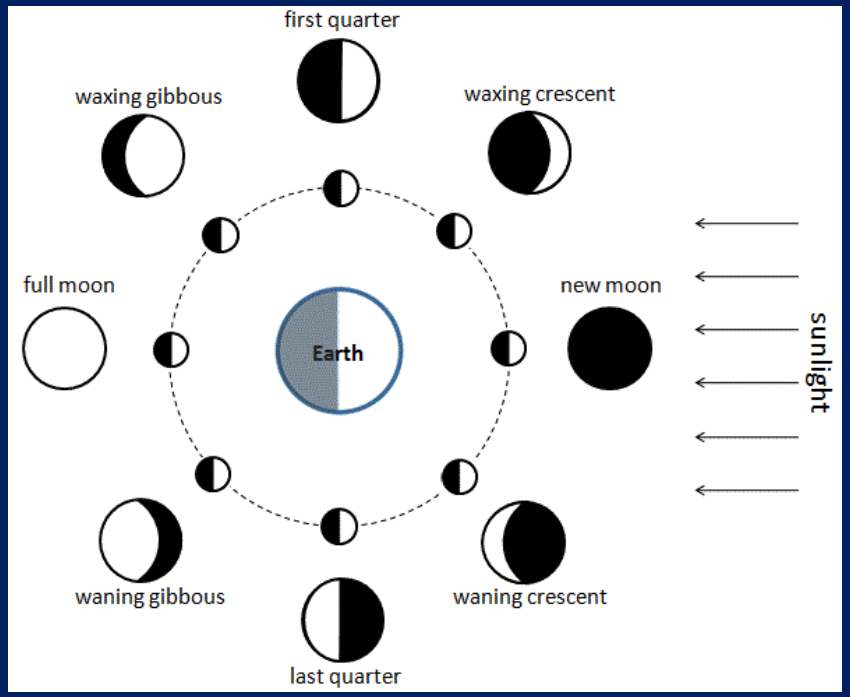
Time and celestial phenomena-3

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 that implied a passage of time.

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 0.2422x500=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 since the 3rd millennium developed various terrestrial time keeping devices e.g., the water clock, the sundial, sandglass, incense and the candle clock…

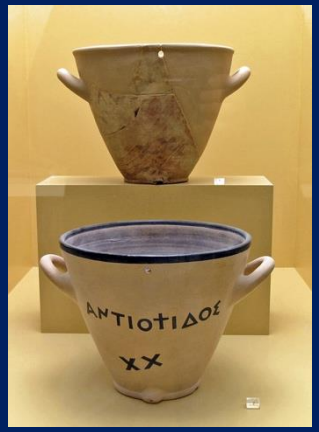
These devices are not very accurate timekeepers. E.g., the water clock's measure of time depends on the temperature of water. The sundial does not work at night or on a cloudy day…

A sandglass

An Ancient Egyptian sundial

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

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



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

Sundial at Jantar Mantar In Jaipur, 1727

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.

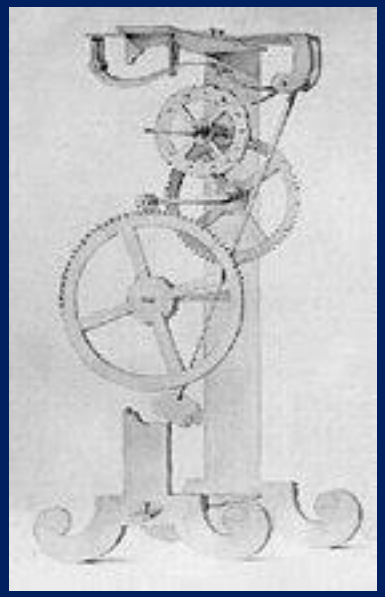
Towards the end of the 13th century European craftsmen refined this mechanism to create the first mechanical escapement mechanism that led to the mechanical clock.

The Gros-Horloge, Rouen France (1389-)

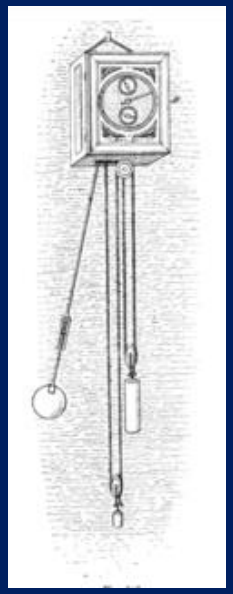
The mechanical clock tower at Crawford Market, Mumbai (1869-1990)…

The Mechanical Clock-2

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 continued to become more accurate with new innovations and reached its pinnacle in the 18th century.

The Marine Chronometer of John Harrison

- In 1770 after many trials and versions since 1735 John Harrison, an English carpenter, made one of the most accurate and robust mechanical time keeping device that enabled accurate navigation on the high seas.
- The clock was resistant to variations of temperature, humidity and rocky motion on high seas and kept time to within 0.33 seconds a day! More accurate than today's quartz watch.
- Since the Earth rotates 15 degrees per hour, longitude is determined accurately by comparing local time (from the sun) with time at a fixed reference point (e.g. Greenwich Mean Time). This accuracy led to safer navigation and ultimately transformed maritime travel.
- Harrison's clock remains one of the greatest achievements in horology and set the foundation for modern chronometers used in precision time keeping.
- History: "Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time" by Dava Sobel.

The Marine Chronometer H5 of John Harrison

The Mechanical Clock's Social Impact

- "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 & 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.

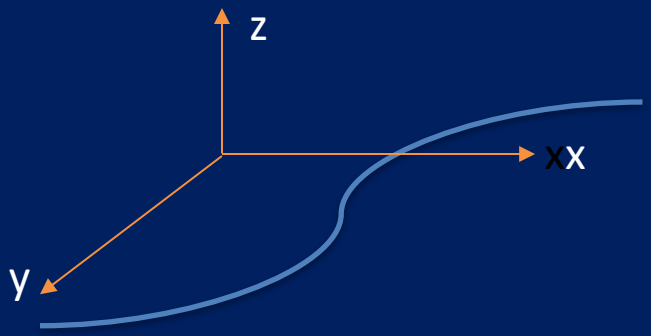
- He died in 1642 the year his successor Isaac Newton was born.

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 a 3-dim. geometry.



(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.

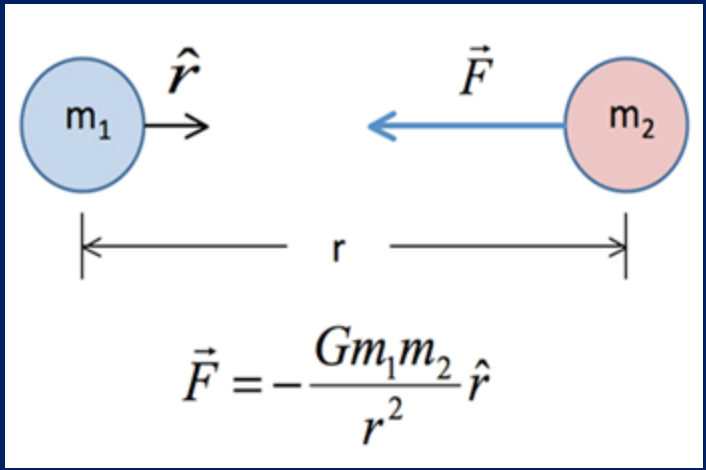
Time is absolute and the same for all observers. Coordinates may be rotated or moved with constant velocity.

Newton's law of motion:

$F = m_i a$

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) = $m_{1i}\, a_1$
- Inertial mass $m_{1\,i}$ = 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; Kepler found symmetry in big `data'... 20+ years of work.

Newton on the Law of Universal Gravitation

Newton's law does not explain gravity but says that it works!

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."

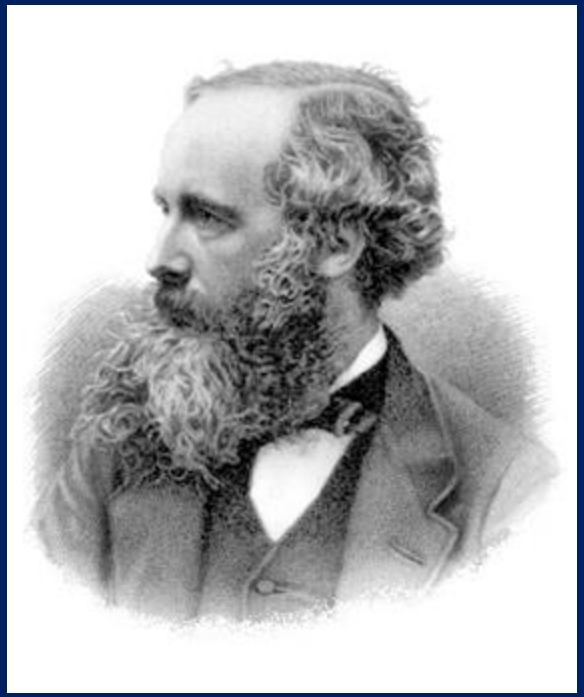
Newton (1713):

"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."

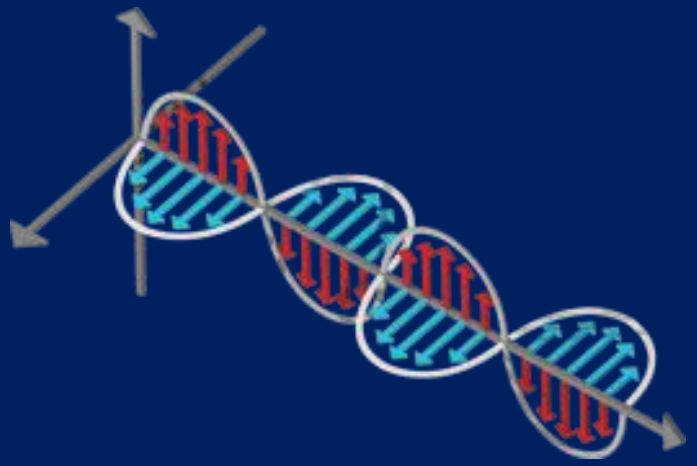
Electricity and Magnetism
and
Electromagnetic Waves
and
the Constancy of the Speed of Light for Inertial Observers

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).

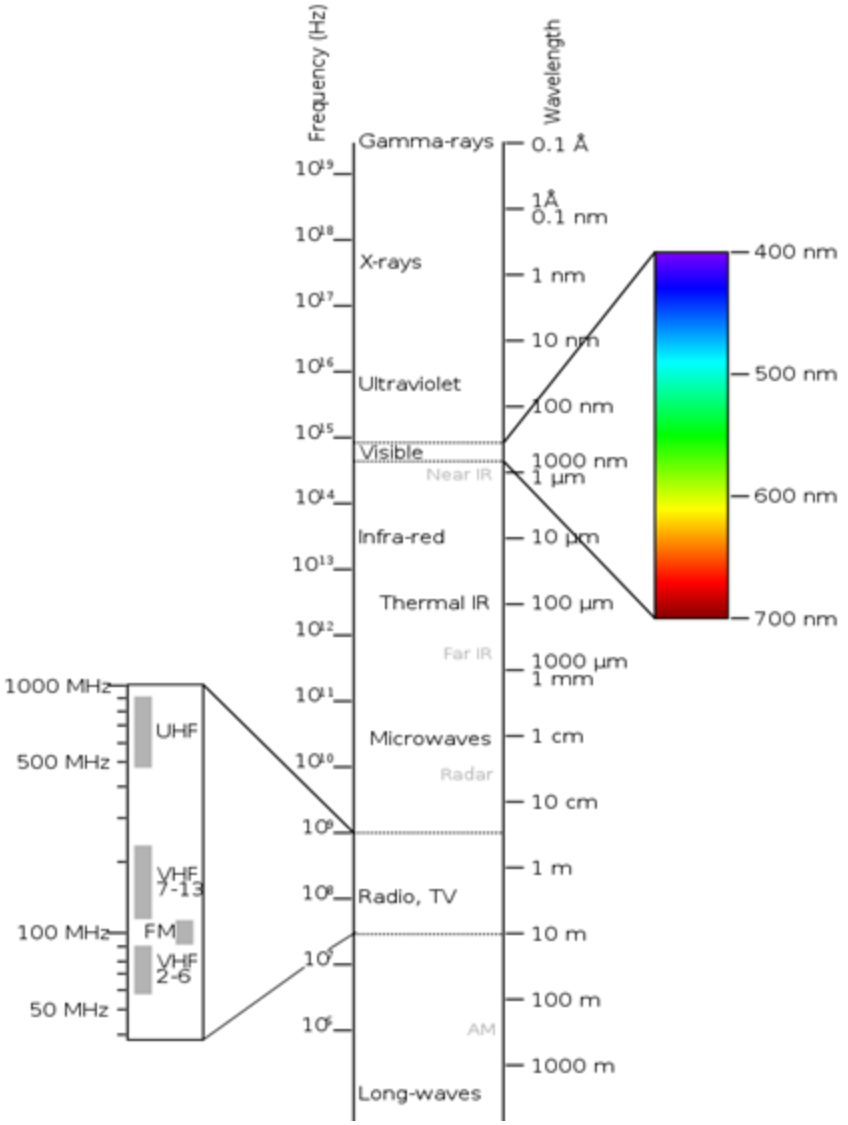


Force between charged particles is not instantaneous. It is transmitted by the electromagnetic field at the speed of light which is finite.

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.



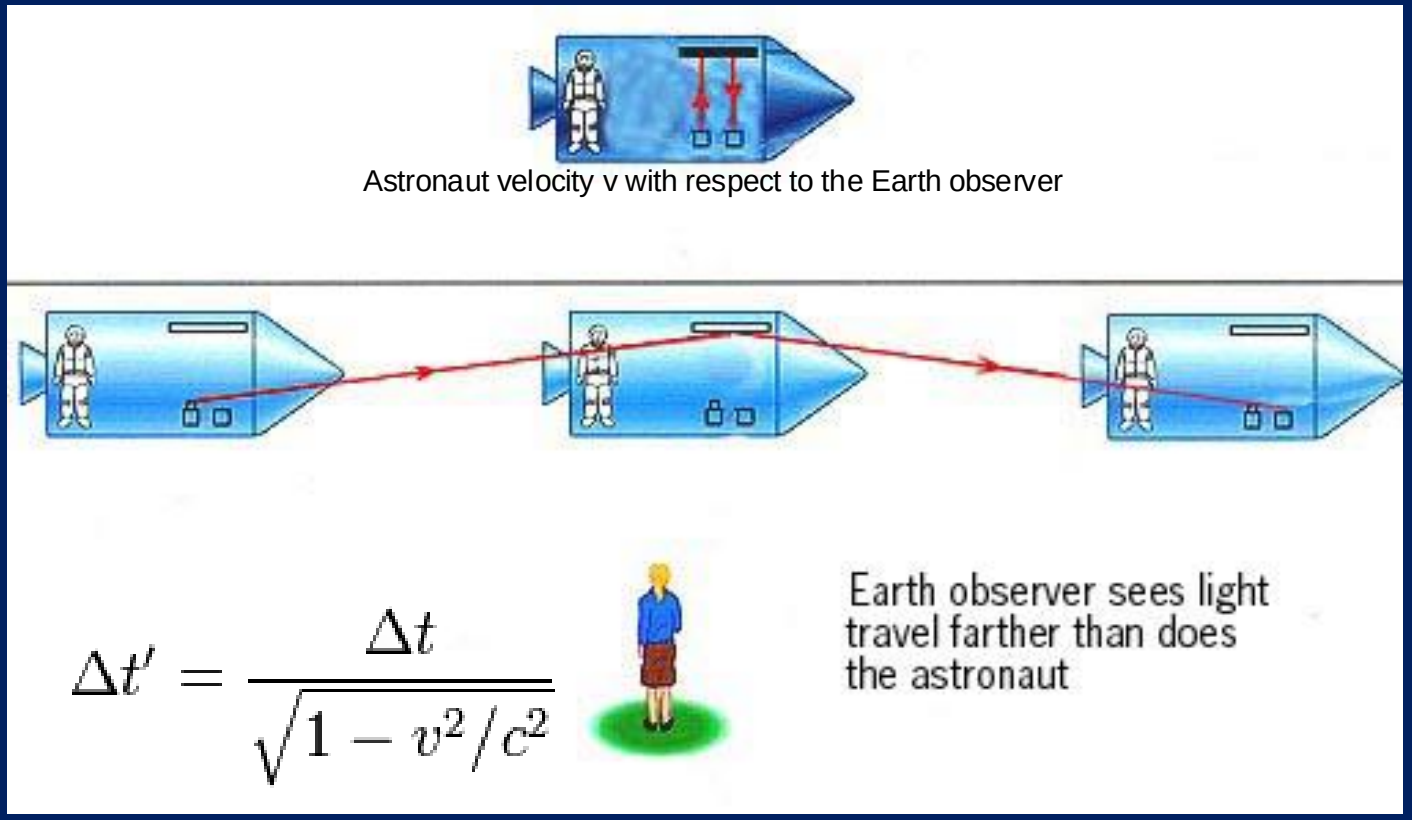
Lorentz, Poincare, Einstein: Special Relativity (1905)

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 for the Earth based observer are stretched and longer compared to the observations of the astronaut.



4-dimensional Space-Time Geometry

Hermann Minkowski (1864-1909)

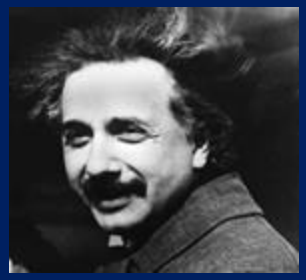
"Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality."

Introduced Geometry in Special Relativity

- Time is a 4th 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 rotationally invariant distance.

General Theory of Relativity and Time

General Relativity-1



Einstein

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. 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.

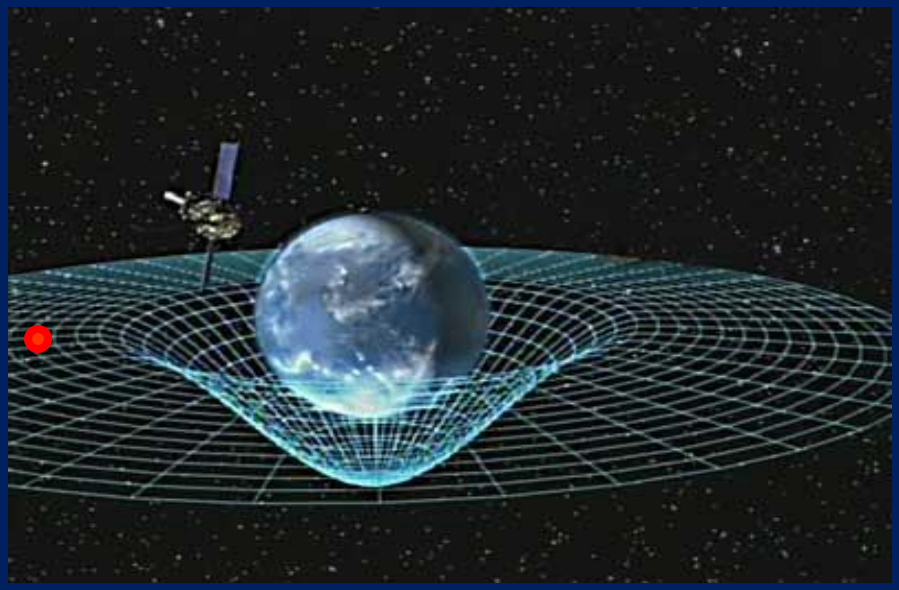
Here the role of the `electromagnetic field' is played by the waves of the `metric' of spacetime.

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

Upper floor

Lower floor

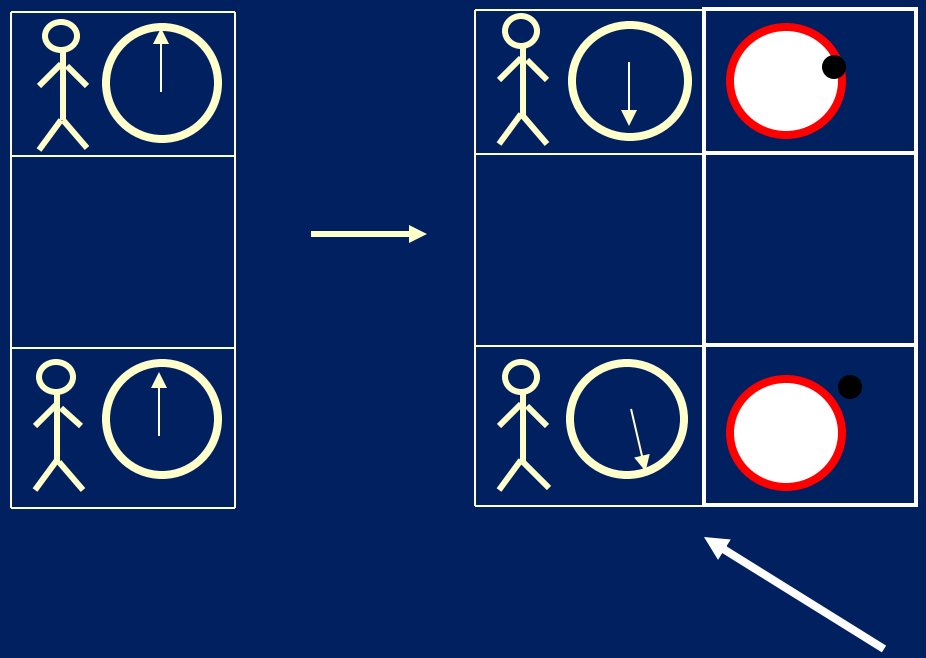


Fig credit
J Maldacena

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

This effect and special relativity is relevant for accuracy of GPS!

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

Flow of time $\sqrt{1-\frac{r_h}{r}}$

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

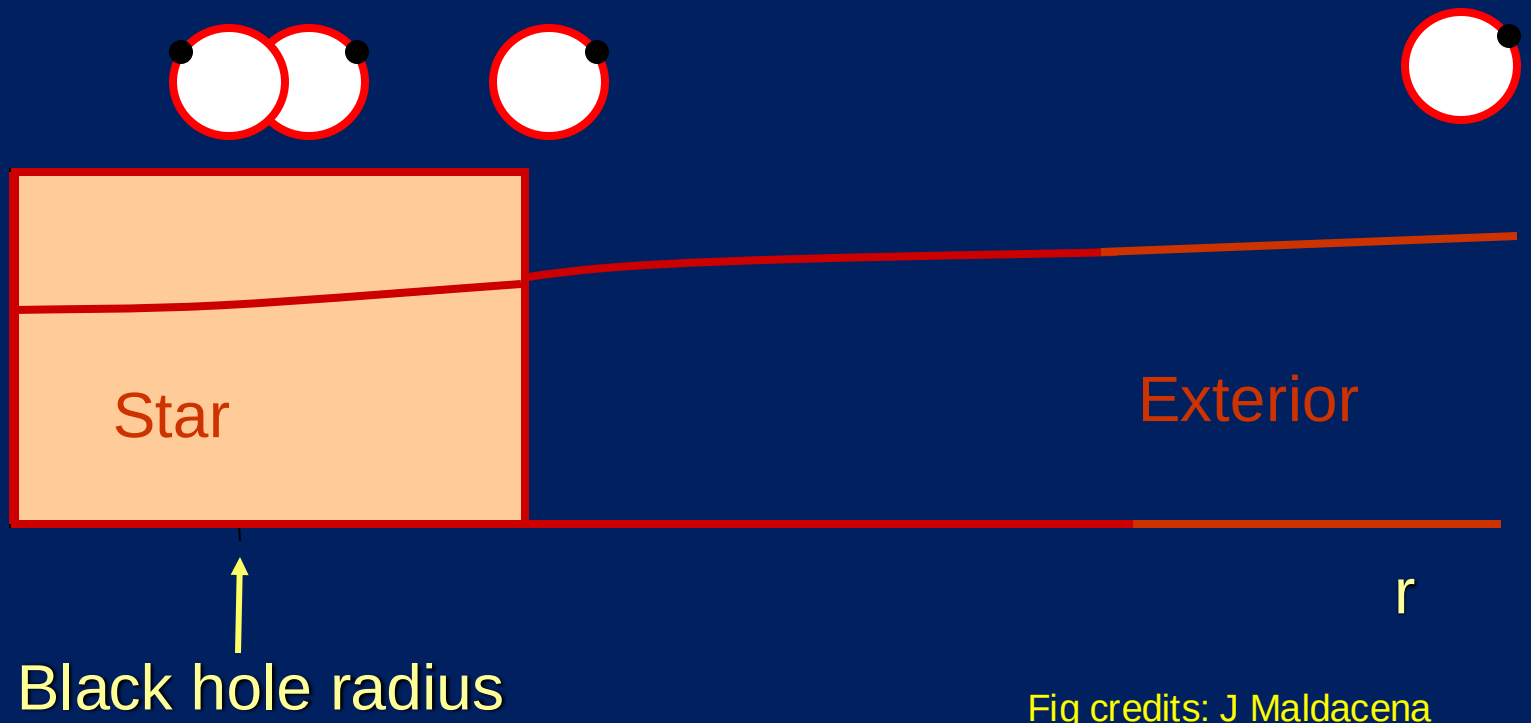


Fig credits: J Maldacena

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. Not influenced by temperature or gravity…hence used in satellites.
- "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." This is the world's official timekeeper.
- The Strontium based atomic timekeeper gains or losses only one second in 40 billion years!
- A nuclear clock based on Thorium-229 promises to be 100,000 times more accurate and more robust to thermal noise than the previous best effort. It would also be sensitive to interactions with dark matter. All time measuring devices obey the laws of physics and hence their deviations can be inferred by sensitive time keeping devices.

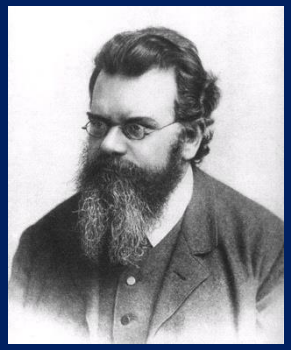
The Second Law of Thermodynamics, Entropy and Time Irreversibility

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 2nd law of thermodynamics the time reversed process does not happen.

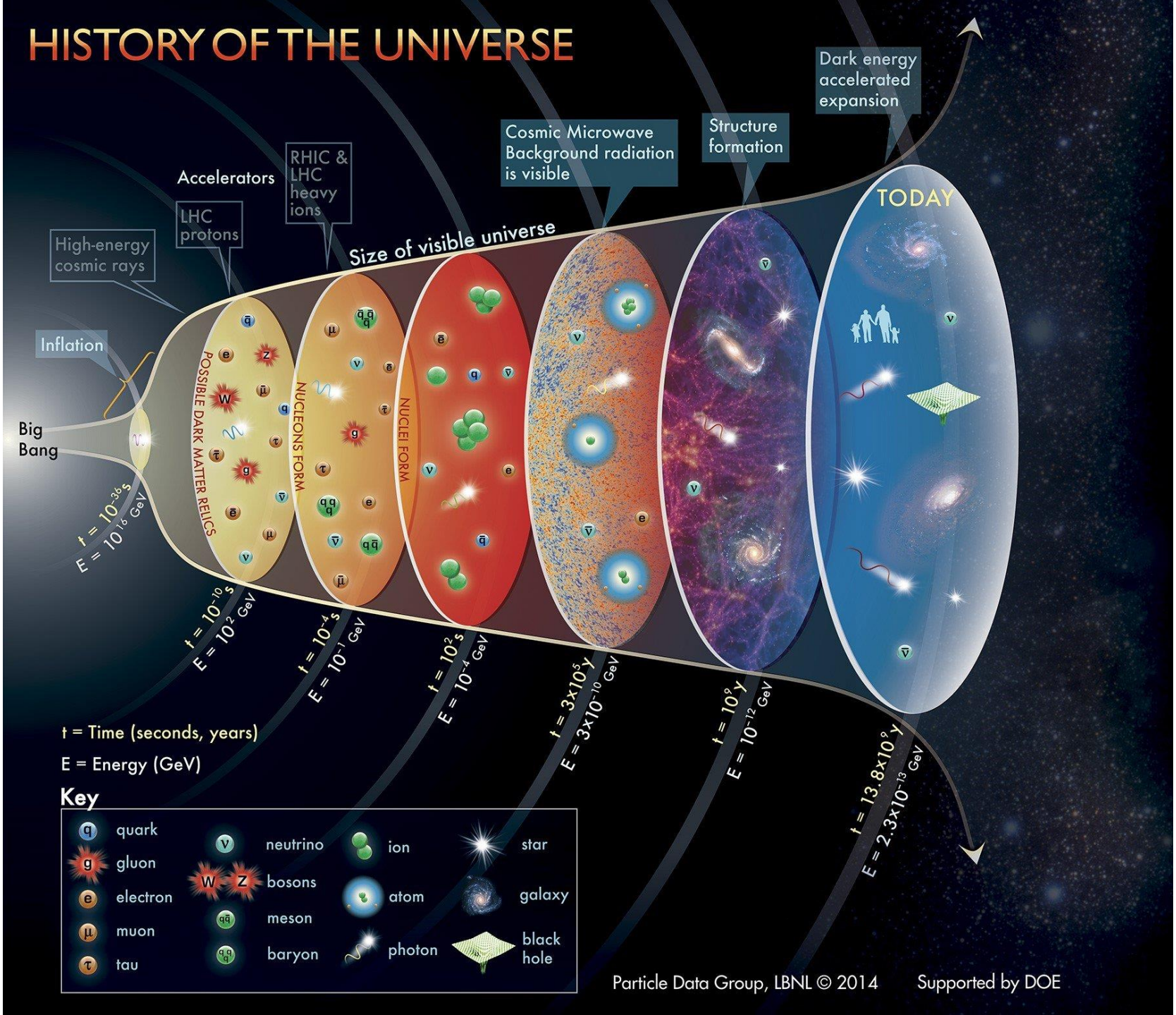
To quantitatively understand this phenomenon Ludwig Boltzmann (1866) introduced a formula for the Entropy of a gas as a measure of the number of internal states that make up the system and showed under reasonable hypothesis about the randomness of collisions that the entropy always increases in time. 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
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
TODAY
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE

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 13.8 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

Thank You!

To

- All of you for coming on a Sunday afternoon
- The Nehru Planetarium for hosting Kaapi with Kuriosity
- The ICTS Outreach Team
- The web resources for images
- Juan Maldacena for use of his images
- R. Loganayagam and G.Mandal for pointing to two amazing books that helped in preparing this talk