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How long is a Second?

From atomic clocks to strontium clocks and more, time has literally come a long way in terms of its measurements.

Atomic clocks have created a revolution in our measurement and understanding of time. They hardly lose a second in a hundred thousand years! The second is defined as the time for 9,192 631 770 cycles of the hyperfine transition in Caesium-133.

So precise is this definition that it has necessitated the introduction of leap seconds. There have been twenty-three of them since 1972. We all know about leap year when an extra day is added to February. The reason for this is that astronomical accuracy implied that the year is not exactly 365 and quarter days but 365.242.... days.

This error accumulated over the centuries, so that Pope Gregory in 1582 was forced to remove 14 days from the calendar, leading to the Gregorian calendar (used currently).

Increasing seconds

Further refinement implied that only century years divisible by 400 are leap years. Now with the advent of atomic clocks, the gradual lengthening of the day due to the slowing down in the earth's rotation caused by the Moon's tidal drag can be easily measured.

The day is increasing by sixteen milliseconds per century, that is, it would be longer by sixteen seconds a million years hence. Due to conservation of angular momentum in the Earth-moon system, this implies that the Earth-Moon distance is increasing by 3.5 centimetres per year and this has been verified by bouncing laser beams off laser reflectors left behind on the Moon by the Apollo astronauts! So all laws are working fine! This gradual lengthening of the day due to tidal friction was the reason for introducing leap seconds.

The time scale that standard laboratories disseminate is called co-ordinated universal time, or UTC, which is based on the above atomic frequency standard. The decision as to when to add a leap second is made by the International Earth Rotation and Reference Systems Service.

Most discordant discrepancies between atomic and astronomical time arise from unpredictable fluctuations in the Earth's rotation rate due to uplift of tectonic plates, glacial melting etc. The accuracy of atomic clocks over the years has become so high that corrections for Einstein's general relativity are so large that ignoring them in comparing rates of atomic clocks in different labs or in the timing systems of the GPS satellites can cause huge errors!

Again introduction of leap seconds can cause havoc in systems requiring precise synchronisation including power grids (leading to blackouts!). The caesium atomic frequency hitherto used as the time standard involves transition frequency in the microwave range.

We are now entering a new era of optical atomic clocks and optical frequency metrology leading to clocks reaching an accuracy of one part in 1017 or even 1018 (loss of a second in a few billion years!).

Changing times

The very recently introduced Mercury Ion Clock is one such atomic clock (optical frequency range), which is precise to one part in a hundred quadrillion!

Last year the strontium atomic clock was introduced at 429 Tera Hertz with a somewhat lower accuracy. The duration of a second is measured using signals from latest state of the art atomic frequency standards maintained in some primary laboratories and supplemented by signals from hundreds of commercial frequency standards in about sixty international labs.

The clocks are simultaneously synchronised by observing signals from GPS satellites. These comparisons are now precise to one part in a quadrillion. At such accuracies, the effects of gravity on time become crucial.

As atomic clocks become even more accurate, to compare them to one part in a pentillion (one followed by eighteen zeros!), we would have to know the altitudes of clocks to within a centimetre! It must be borne in mind that the effects of gravitational potential (due to altitude) on atomic clocks are very different from a host of mundane factors like temperature, magnetic fields or light intensity etc. The fundamental effect of gravity is not to affect the operation of the clock (unlike the other effects) but to alter time itself. To correct local time for the effect of gravity one uses the distance to the geoid, a hypothetical surface of constant gravitational potential. The geoid is not something static but constantly in turmoil owing to many effects. Solid earth tides cause amplitude of about thirty centimetres causing frequencies to vary by a few parts in ten to the power of seventeen!

Many other sources of fluctuations exist such as motion and uplift of tectonic plates, atmosphere pressure variations, climate change, glacial melting etc. They give rise to uncontrollable frequency changes of several parts in a pentillion or more! So as gravity of the earth is inextricably ingrained with time, there is an upper limit to the accuracies, which we can achieve in comparing or synchronising time standards. Beyond some accuracy there can be no "true timekeeper"!

As it is we can now manipulate time to an accuracy of one part in a pentillion. This is manifested for example, in attosecond laser pulses. We have all heard of nanoseconds and nanotechnology. That will be outdated soon. It would be attoseconds and attotechnology in the future! One attosecond is one billionth of a nanosecond. Compared to an attosecond, a second would be longer than the age of the universe! There are thirty-six orders of magnitude between an attosecond and the age of the universe. As far as physical processes are concerned, a second is long enough to record several billion high-energy scattering events and millions of subtle chemical reactions. There is much more to a second than the blink of the eye!

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