The long and the short of it...

Time: how much of the cosmological timescale do we control and use?

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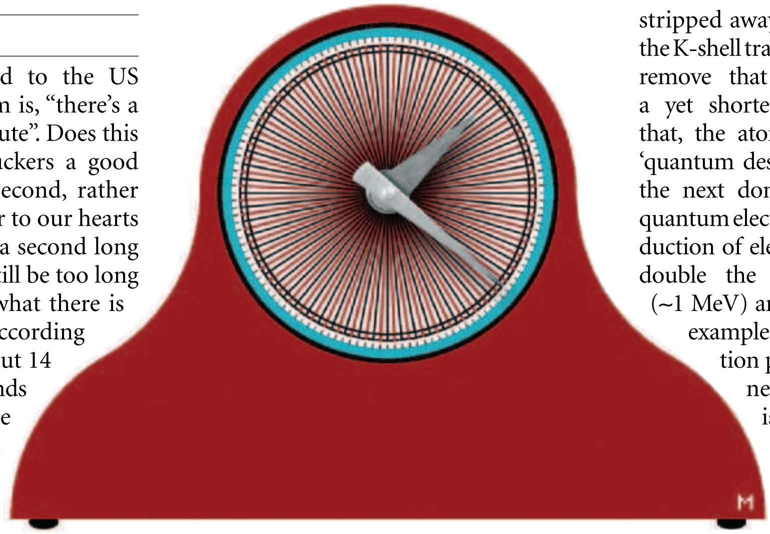

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A quote often attributed to the US showman P. T. Barnum is, “there’s a sucker born every minute”. Does this make counting new-born suckers a good way of measuring time? A second, rather than a minute, might be closer to our hearts — as our heartbeat is nearly a second long — but even this scale might still be too long or too short, depending on what there is to measure. Our Universe, according to the ‘big bang’ theory, is about 14 billion years, or 5×10^{17} seconds (s) old. The ultimate timescale (‘Planck time’) of quantum cosmology — approximately 10^{-43} s, the big bang’s birth-flash — is an elementary grain or pixel of time, within which our normal physics of four-dimensional space and time breaks down into much greater number of dimensions as hypothesized by the ‘superstring’ theory.

In logarithmic terms, we, with a lifetime of around 70 years (roughly 2×10^9 s), exist on a scale that has more in common with the age of the Universe than with Planck time. We have learned how to keep track of time — we could even regard ourselves as ‘*Homo temporal*’ — but how much of it is controlled and used by us? Although the ‘long’ end of this scale is still only of academic interest, the ‘short’ end is becoming a hot and bustling frontier of science and technology. The most familiar examples would be communication and computers. In the quest of higher computer performance, one of the major parameters is the clock frequency or, inversely, the clock cycle. Somewhere in a dark corner of my lab, there are remnants of my old 1989 UNIX computer, which had a clock frequency around 17 MHz. Today’s off-the-shelf computers have a clock cycle of almost 3 GHz, or 0.3 nanosecond (ns, 10^{-9} s).

Lasers have been moving even faster into shorter time domains. Soon after the invention of laser in 1959, the length (duration) of a pulse of light passed the ns and then picosecond (ps, 10^{-12} s) thresholds, and the race was on to get to even shorter pulses. The sub-ps and femtosecond (fs, 10^{-15} s) domain became a field of rich research, with topics such as the registration of super-fast processes, time-resolved spectroscopy, characterization of semiconductors with sub-ps relaxation times, and the control of chemical reactions and fs time-resolution by powerful laser pulses. This domain also hosts the so-called Terahertz technology, which uses these pulses as, for example, a diagnostic tool to ‘see-through’ opaque materials and structures.

The record for the shortest laser pulses now stands at 4–5 fs, which is close to the length (~3 fs) of a cycle of a near-infrared laser. The challenge is to generate controllable pulses even shorter than 1 fs. Why go shorter? The highest spectral frequency of a sub-cycle pulse is inversely proportional to its length, τ. The photon energy is the frequency times the Planck constant, $\hbar$, so we have the pulse’s highest photon energy as $E_{max} \approx \hbar/\tau$. Although the sub-ps and fs domains correspond to E~0.1–0.01 eV (which is typical for molecular reactions) the domain below 0.15 fs (150 attoseconds, 150×10^{-18} s) is in atomic physics territory — this is the time it takes an electron at the ground state of a hydrogen atom to revolve around the proton. A few methods to generate such pulses have been proposed. Recently, the sub-fs pulses have been observed experimentally using high-order harmonics. Although these sub-cycle or single-cycle pulses have an extremely broad Fourier spectrum (from radio to extreme ultraviolet domains), they differ dramatically from those generated by regular super-broadband sources (for example, black-body radiation) because ideally all their spectral components have the same phase. Such large-scale trans-spectral coherence has never been encountered in regular optics. Indeed, although super-short pulses are plentiful in the black-body radiation (for example, sunlight), they arrive and behave completely at random. Coherency and controllability make all the difference in the world of pulses.

Beyond the atomic-scale horizon, there are ions of heavy elements. In the ‘ionic extreme’, we can think of the heaviest stable atom, uranium, with all but one electron stripped away. More than 110 KeV (close to the K-shell transition of uranium) is needed to remove that last electron, which makes a yet shorter timescale, $\sim 10^{-20}$ s. Beyond that, the atomic/ionic physics runs into a ‘quantum desert’. Going shorter still, we hit the next domain of fundamental interest: quantum electrodynamic (QED), such as production of electron–positron pairs requiring double the rest energy of an electron (~1 MeV) and strong nuclear reactions, for example, deuterium electro-disintegration producing proton and neutron near 1.2 MeV. These are reminiscent of photoionization in atoms, but on an energy scale up to five orders of magnitude higher. The timescale respectively shrinks to zepto-seconds (zs, 10^{-21} s). The feasibility of generating and controlling sub-as to zs pulses that may illuminate, time-resolve, and even ultimately control nuclear reactions, have been discussed recently. The idea is to drive free electrons in a tight circle by a laser with the currently available intensity up to 10^{21} W/cm^2 in the so-called ‘lasetron’ configuration. These electrons, which will be almost instantaneously released and accelerated to the energy E~50 MeV in the massive ionization of nanoparticles of matter, should be able to generate photons in QED and nuclear domains.

Past that horizon, we enter the territory of high-energy physics, when charged particles brought to almost the speed of light in huge accelerators collide with target nuclei (or similar counter-propagating particles) to produce a cloud of new elementary particles. If we ever work out how to coherently control the production of the same particles in these collisions, the radiation may be made much faster. A pulse with the highest photon energy of, for example, 1 TeV (millions of MeV) could ideally be $\sim 10^{-27}$ s short. This is still long way from the ultimate time scale, 10^{-43} s...but why bother? Oh, but our curiosity, that ever revving engine of our inquisitive exploration, will most likely make us do it. We are suckers for that... ■

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FURTHER READING

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