The background is a complex digital visualization. It features a perspective view of a grid of glowing yellow and orange lines that recede into the distance. Overlaid on this are various patterns of binary code (0s and 1s) in different colors and orientations, some appearing to flow or be scattered. The overall color palette is dominated by warm tones like gold, orange, and red, with some cooler blue and white highlights. The text 'In the Middle of' is centered in the upper half of the image in a clean, white, sans-serif font.

In the **Middle** of

No-When: The Long and Short of **Time**

Alexander E. Kaplan

How far along is the universe in its lifespan?
Is a second a flash of time or a near-eternity?
How much mastery can we have over time?
It all depends on your perspective.

Planck time is the duration of the birth-flash of the Big Bang; it is also an elementary “grain” or “pixel” of time.

P.T. Barnum, a crooked legend of the American circus, is often quoted as having said, “There’s a sucker born every minute”—meaning, of course, that the circus may go forever. This makes counting new-born suckers as good a way as any of tracking time. A minute, however, may be too long a measure to keep pace with modern technology and science applications.

The second might be closer to our hearts—for the heartbeat is nearly as long—but its appropriateness as a measure is also relative. According to the Big Bang theory, the age of our universe is about 14 billion years, which is quite a lot of seconds— 5×10^{17} s. By contrast, a second seems long in the context of the ultimate time scale of the quantum cosmology, which is about 10^{-43} s, the so-called Planck time.

Planck time is the duration of the birth-flash of the Big Bang; it is also an elementary “grain” or “pixel” of time, within which our “regular” physics of four-dimensional space-time breaks down into a much greater number of dimensions hypothesized by the superstring theory. Some cosmological theories predict that the universe’s expansion will go on forever (the so-called “runaway” universe).

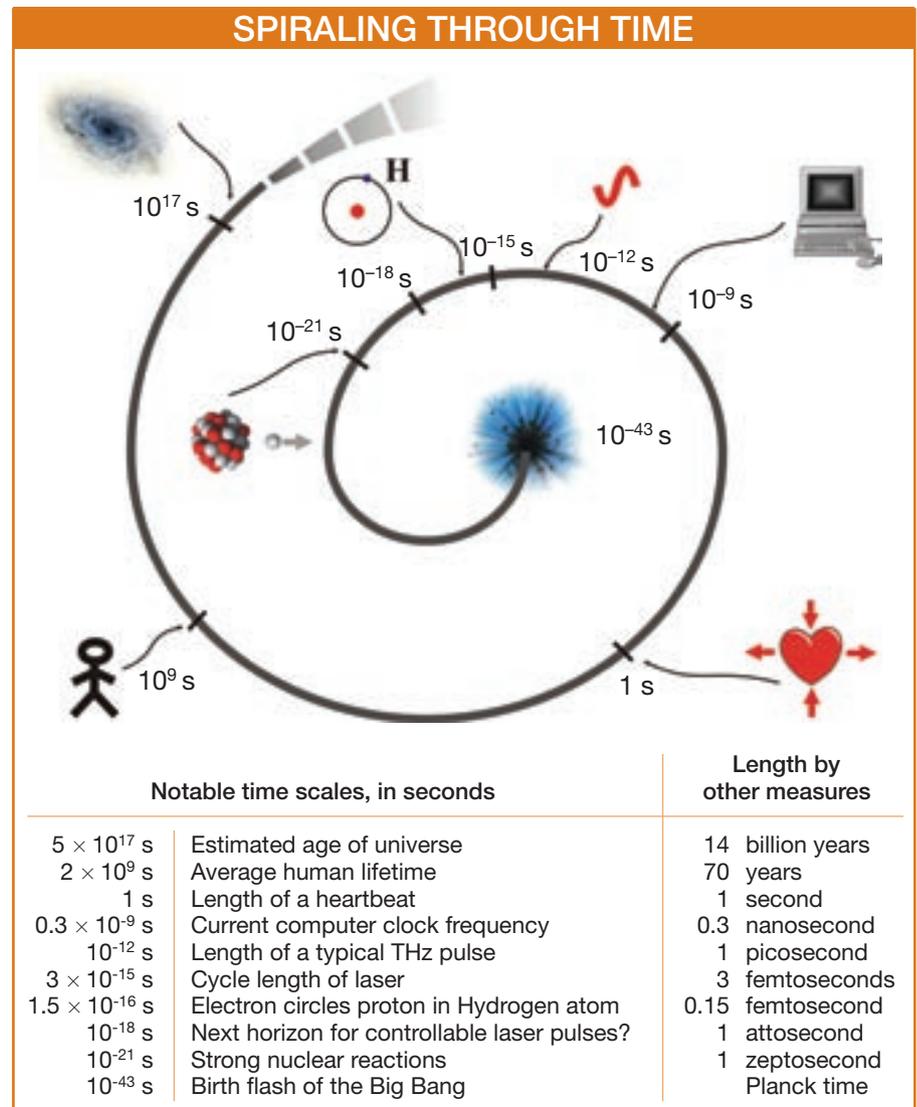
Others suggest that the universe will have a symmetrical extinction-moment, a “Big Crunch” that will occur in roughly the same amount of time as its current age. According to this school of thought, we are in the middle of time.

In any case, the span of time open for examination is enormous: About 61 orders of magnitude separate Planck time from the current age of the universe. Logarithmically speaking, the typical human lifetime of about 70 years, or 2×10^9 s,

is much closer to the age of the universe than an elementary pixel of time.

As humans acquire knowledge or engage in new activities, a common pattern is to perpetually expand our reach. In this way, we mimic the universe’s Big Bang. Such expansions are often driven by sheer scientific curiosity and characterized by continual technological or commercial developments—and sometimes the other way around.

Having learned how to keep track of time, we may regard ourselves “homo temporal.” But how much of our “time environment” can we control and use at the moment? And where will we go from there? These are questions we’re continually exploring. Yet the “long” and “short” ends of the time scale are apparently not of equal practical interest to us. Except for the builders of pyramids and interstellar probes, we do not seem much concerned



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The “short” end of the time scale is increasingly becoming a hot and bustling frontier of science and technology.

about extending our reach far beyond generation lines. At the same time, however, the “short” end of the time scale is increasingly becoming a hot and bustling frontier of science and technology.

The best known examples are from the worlds of communication and information technology. In the race to create computers with ever higher performance, one of the major parameters is the clock frequency—measured in billions of Hertz by now, or Gigahertz, or, inversely, the clock cycle.

In 1965, Intel computer guru Gordon Moore predicted that computer performance will double each 18 months. His prediction is still holding, more or less, albeit the pace has slowed recently. It is striking to realize how far we have come. Somewhere in a dark corner of my lab are the remnants of my old UNIX computer purchased in 1988, which had the clock speed of around 17 MHz; by contrast, the currently available off-the-shelf computers have a clock frequency near 3 GHz, or 0.3×10^{-9} s, and thus a 0.3 ns clock cycle. (It is worth noting, however, that performance is not solely dependent on clock speed.)

As the going gets faster, it also gets tougher—and smaller. The basic components of the computer are shrinking in size, down to the small fraction of the micrometer (μm , 10^{-4} cm). With that, the relaxation processes of electronic circuits, in particular “flip-flop” components with logic and operation memory functions (the backbone of conventional computers) impose a major physical limit on time-shortening.

Soon, as component size gets even smaller, we will run into quantum limitations. One promising idea for overcoming this problem was originated about 35 years ago; it was to go “all-optical” by developing nonlinear optical devices based on the so-called optical bistability

and/or switching to replace electronic flip-flops.

This effect has by now been observed in many systems, and advanced through innovative ideas. For example, so-called nonlinear interfaces have been used to get rid of initially used resonator-based devices to speed up switching. However, we have not yet been able to create a technologically viable device that is substantially faster than electronic circuits: No all-optical computers exist.

Regardless of potential computer applications, those who work with lasers and related technologies have always felt a great hunger to produce ever shorter pulses of light and electromagnetic pulses in general. Soon after the invention of the laser, the pulse length (duration) passed the nanosecond (10^{-9} s) and picosecond (10^{-12} s) thresholds, and the race was on to create shorter pulses.

One of the most fundamental breakthroughs—with rich potential for practical applications—was the discovery and development of chemical reaction control and femtosecond time-resolution by using powerful femtosecond laser pulses.

The sub-picosecond and femtosecond (10^{-15} s) domain became a fertile field for research, discoveries and quests for applications, ranging from the registration of super-fast processes, to time-resolved spectroscopy, to the characterization of semiconductors with sub-ps relaxation times; another application is the so-called Terahertz (THz) technology, which uses electromagnetic pulses as a diagnostic tool to “see through” opaque materials and structures. One of the most fundamental breakthroughs—with rich potential for practical applications—was the discovery and development of chemical reaction control and femtosecond time-resolution by using powerful femtosecond laser pulses.

For a long time, the record in the race to achieve the shortest pulses remained at 8 fs; recently, it has been moved to 4-5 fs. Note that the duration of a single cycle of a near-infrared laser is about 3 fs. So we set our sights on the next horizon: Can we generate controllable pulses shorter than a cycle of light? Or even shorter than 1 fs? That would put us in the sub-femtosecond and potentially attosecond (10^{-18} s) domain.

Why go shorter? One of the fundamental reasons is powerful quantum connection, which assigns shorter pulses to higher energy for basic physical processes. The highest frequency of the Fourier spectrum of a non-oscillating electromagnetic pulse is inversely proportional to its duration, τ . Recalling that the energy is proportional to the frequency, with the proportionality coefficient being the famous Planck constant, \hbar , we connect the higher energy of electromagnetic quanta, E_{max} , carried by the pulse, to the time τ as $E_{\text{max}} \approx \hbar/\tau$. While the sub-picosecond and femtosecond domains correspond to sub-eV energies—which are typical for

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molecular reactions—the domain below 0.15 fs is the territory of atomic physics.

For example, the photoionization limit of the hydrogen atom, 13.6 eV, is in the upper part of the spectrum of a 0.15-fs pulse, which is about the time it takes for an electron at the ground state of the hydrogen atom to revolve around the proton. Recently proposed avenues for generating such pulses are based on using either multiple-cascade-stimulated Raman scattering lines excited by a powerful laser in a molecule (e.g., H₂) or multiple high-order harmonics excited in atoms by a laser.

In both cases, the idea is to use many equidistant and phase-coherent spectral lines that cover a large spectral span. Essentially, this is reminiscent of a laser with many phase-locked modes capable of generating short (e.g., picosecond) pulses; however, the spectral span of these modes is blown up now by a few orders of magnitude. Most recently, the sub-fs pulses (with $\tau \sim 0.2$ fs) have been observed experimentally using high-order harmonics.

These short pulses have a new quality to them. Regular optical pulses are essentially laser oscillations modulated by a relatively slow “envelope”; picture them as a kind of a pie with the laser cycles as the filling. The new pulses have no pie-filling: They are so short that some of them are just a single burst of a rising-and-falling electrical field (the so-called “half-cycle” pulse that, upon propagation, becomes a “single-cycle” pulse).

These creatures are not too new to electromagnetic technology in general: Much longer (about 1 ps) sub-cycle pulses are now widely used for terahertz technology. In fact, those electromagnetic pulses (although on a much longer time-scale) go back 60 years, to the birth of the atomic bomb: They were first observed under the epicenter of the above-the-ground nuke explosion; the mechanism of their formation was the interaction of

a fast-expanding electron cloud with the magnetic field of Earth.

All these sub-cycle electromagnetic pulses have an extremely broad Fourier spectrum—from radio frequencies to the extreme ultraviolet for a 0.15-fs pulse. The intensity profile of such a spectrum is reminiscent of that of black-body radiation, but with a huge difference: In the case of electromagnetic pulses, all the spectral components at different frequencies ideally have the same phase, which can be described as a trans-spectral coherence across the entire super-broad spectrum, a feature hardly encountered in regular laser optics.

The other way around, the pulses of sub-femtosecond duration are plentiful in black-body radiation (e.g., sunlight). The only thing is that they arrive and behave in a very random way. In the world of pulses, it is the coherency and controllability that make all the difference.

Farther and shorter we go. What is beyond the atomic-scale horizon? The next in line are the ions of heavy elements: The larger the charge of a nucleus, and the fewer electrons left of the initially neutral

atom, the more difficult it is to further ionize the ion. Going to the “ionic extremes,” we can think of the heaviest stable atom, uranium, with all but one electron stripped away, by a high-intensity laser pulse, for example. To remove that last electron, one needs more than 110 keV—close to the K-shell transition of uranium. This would take us into respectively shorter time scales of 10^{-20} s.

Beyond that is a “quantum desert,” in which no more atomic or ionic resonances can be found. Somewhere in the middle of it lies the fuzzy border between regular (i.e., nonrelativistic) and relativistic quantum mechanics. It is determined by the rest-energy of an electron, $mc^2 \approx 0.5$ MeV (here m is the rest-mass of electron). Nonrelativistic quantum mechanics hold only for the energies significantly lower than 0.5 MeV, the spatial lengths and time intervals significantly longer than the so-called Compton wavelength, $\lambda_C \approx 2\pi \hbar/mc \approx 2.4 \times 10^{-2}$ Å, and Compton time is $\hbar/mc^2 \approx 1.3 \times 10^{-21}$ s = 1.3 zs, respectively, where zs stands for zeptosecond (10^{-21} s).

Thus, scientific interest may turn next to relativistic quantum mechanics and the so-called quantum electrodynamics (QED), such as electron-positron pair production, with the required energy about $2 \times mc^2 \sim 1$ MeV. Strong nuclear reactions may also garner more attention—for example, deuterium electro-disintegration producing a proton and neutron (with participation of an electron) near 1.2 MeV, or neutron photoproduction in beryllium or deuterium (1.7 and 2.2 MeV, respectively). These reactions are reminiscent of photoionization in atoms and ions, but on energy scales up to five orders of magnitude higher and time scales that shrink below zeptoseconds.

Recently, the scientific community has begun to discuss the feasibility of controlling time beyond attoseconds, and how one can generate electromagnetic pulses of such a duration that may illuminate,

Even if zeptosecond or shorter pulses are generated and measured in the future, we still have a long way to go before we approach the ultimate time scale, the Planck time, of 10^{-43} s.

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question "Where is everybody?" could be: "in the time pit ..."



time-resolve and ultimately possibly control nuclear reactions in the future.

One proposed idea is to drive free electrons in a tight circle with a circularly polarized laser with terawatt to petawatt power with intensity up to 10^{21} W/cm². These electrons, to be released in the shorter-than-laser-cycle massive ionization of clusters (in other words, tiny nano-corpuscules of matter), would be able to reach relativistic energies up to $E \sim 100 \times mc^2 \sim 50$ MeV due to their almost instantaneous acceleration by the laser in a device called a "lasetron."

As a result, pulses would be generated that are shorter than the laser cycle by the cube of the relativistic factor, $E/mc^2 + 1$, bringing them into QED and nuclear domain. This is about five orders of magnitude shorter than the sub-femtosecond pulses observed very recently.

Farther beyond that horizon, we enter the territory of high-energy physics, in which charged particles are brought to nearly the speed of light in huge accelerators and collide with target nuclei or similar counter-propagating particles to produce a cloud of new elementary particles. If we ever figure 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 1TeV (a million MeV), for example, could ideally be 10^{-27} s long.

Of course, even if zeptosecond or shorter pulses are generated and measured in the future, we still have a long way to go before we approach the ultimate time scale, the Planck time, of 10^{-43} s. Why bother? Here is why: One of the predictions of inflationary cosmology is that our universe is not unique, and that new universes are perpetually created within and outside it; in other words, there's a baby universe born every minute. At some point, then, any newly born sucker, in his pursuit of happiness, may want to have his or her own personal universe,

and will thus need to control events on the Planck time scale.

Even well before we reach that limit, the ability to manage time on vastly differing scales may be crucial to another human endeavor—the search for other intelligent life forms in the universe. Not surprisingly, this quest of ours has always been "homocentric": Our assumption is that our presumed "rich uncles" out there live, operate, and collect and transmit information on the same spatial and temporal scales that we do. We perceive them to be very much in our own image. We ascribe to them our favorite wavelengths (hydrogen spectral lines), our flat space (Pythagorean theorem), our discrete arithmetic (prime numbers), etc.

Could it be that we are greatly off the mark? And what is meant by intelligent life? Attempting to define it comprehensively would be a difficult (and probably not very intelligent) undertaking. Yet we can ponder the concept. Even if we assume that other intelligent life forms have a similar or greater number of information-processing elements (human beings each have 14 billion brain cells), life-span "clock" cycles (say, comparable to about 2 billion human heartbeats), and the same total time for evolution, then we might consider "advanced" beings and civilizations to be those that have much shorter generation cycles and thus more generations.

As with computers, this advanced status could be attained by faster clock-cycles due to tighter packaging of cells and/or much faster signal transmission between them. A good environment for such life forms could then be the neutron star matter; with the spacing between "brain cells"

being shorter by the factor $\sim \alpha^{-2}$, where $\alpha = 1/137$ is the fine structure constant of quantum mechanics, and the speed of signal being faster than ours by roughly the same factor, those creatures would live about a billion times faster than we do.

Of course, at the long end of the time scale, there is another, very different potential intelligent life form: the universe itself. It has an unsurpassed number of "brain cells," but its thought-processing is majestically slow. In either case, we may be faced with a communication problem: Systems with an almost infinite difference in the level of sophistication and time scales may never be able to talk to each other. The answer to Fermi's famous question "Where is everybody?" could be: "in the time pit ..."

Will we march on in our attempts to tame ever shorter time scales? Most likely, yes, we will. Are there civilizations in neutron stars? Is our universe an intelligent life form? Is the very creation of other universes a controllable process? These things we may never know, but for sure—wisely or not—we will try to. Our curiosity, that ever-turning engine of our exploration, will drive us to keep searching for answers. We are suckers for that. The circus may indeed go on ... ▲

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[Alexander E. Kaplan (Alexander.Kaplan@jhu.edu) is with the Department of Electrical and Computer Engineering, The Johns Hopkins University, Baltimore, Md.]



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