SCIENTIFIC AMERICAN.COM

What is the fastest event (shortest time duration) that can be measured with today's technology and how is this done?

R. Mitchell
Melbourne, Australia

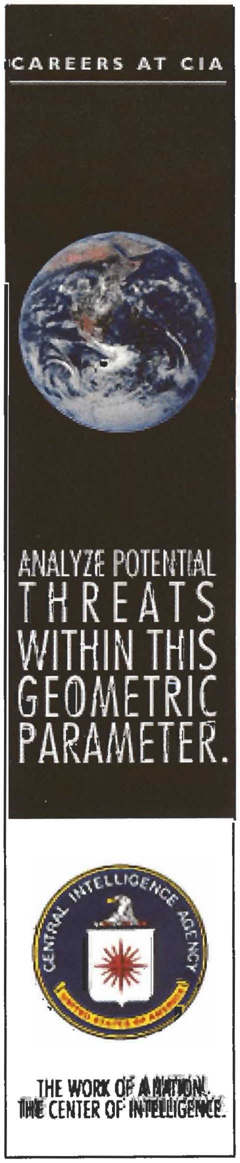
Scott Diddams and Tom O'Brian of the Time and Frequency Division of the National Institute of Standards and Technology, explain.

Just how fast an event is depends somewhat on your point of view. In nature around us there are various physical events that occur on time scales from the yoctosecond (10^{-24} second) to the exasecond (10^{18} second). In the time it just took your heart to beat once, the computer on the desk next to you completed about one billion clock cycles, whereas the electron of a hydrogen atom could have circled its proton about 1 quadrillion (10^{15}) times. On the other hand, that very slow heart beat is actually quite fast and fleeting if one considers it relative to the 500 quadrillion (500×10^{15}) second lifetime of our universe. Within this tremendous range of time scales, science and technology, which are constantly improving, determine how accurately different events can be measured or inferred.

For example, in the late 19th century, the best scientists and technologists struggled to measure time intervals on the order of a hundredth or thousandth of a second. In a well known (and often mythologized) story, photography pioneer Eadweard Muybridge, on commission from Leland Stanford, took several years to develop a system of rapid-sequence photography to conclusively prove that a galloping or trotting horse briefly has all four feet aloft simultaneously--an event too fast for the human eye to follow. Muybridge was able to perfect his system to record events on the scale of about 0.001 second in 1877.

But this story also points out a challenge in answering the original question: The answer depends on how one interprets the word "measured." This might sound like a pedantic dodge, but at the National Institute of Standards and Technology (NIST) we spend a lot of time trying to understand and apply the subtleties of measurement. Muybridge's photography was a record of short duration events--possibly the best such record of its time--but was not a measurement of time interval in the strict sense. Both the recording or inference of short duration events and accurate measurements of such events are of interest, so we suggest rephrasing the original question into two new questions: "What are the shortest time durations that can be measured with a particular accuracy?" and "What are the shortest duration events that can be recorded or inferred in experiments?"

To best answer the former question about measurement with a particular accuracy, let us agree to define measurement as a comparison to a generally accepted standard. By international treaty the standard for the second, the unit of time, is defined as exactly 9,192,631,770 cycles of a particular electron transition in cesium-133 atoms. So a time measurement is a direct or indirect comparison to this defined standard.



Currently, the best technical approach to measuring time against this standard is to use laser-cooled cesium atomic fountain frequency standards, known as cesium atomic fountain clocks. The handful of these cesium atomic fountain devices operating around the world are actually frequency standards rather than clocks (timekeeping devices), and they are used to realize the defined cesium standard frequency with exceptional accuracy of about 1 part in 10^{15}. The best reported uncertainty at the time of this writing is about 6×10^{-16} for the NIST-F1 fountain standard. Because 86,400 seconds make up one day, this relative uncertainty means the standard is accurate to about 50 picoseconds (50×10^{-12} second) per day. Put another way, if the frequency standard could be operated indefinitely as a clock it would neither gain nor lose more than a second in 50 million years compared to a perfect clock.

Cesium atomic fountain standards are the world's most accurate primary standards of any kind. No other standard--including ones used for length, mass and electrical current--has an accuracy within even a factor of 1,000 of the cesium atomic fountain clock. The atomic fountain standard uncertainty of about 1×10^{-15} might seem to imply that these "clocks" could be used to measure events on the order of femtoseconds (10^{-15} second), but in fact fountain standards are not generally useful for directly measuring short-duration events.

Arguably the shortest events that can be directly created, controlled and measured are quick bursts of laser light and their interaction with matter. These pulses occur on time scales of femtoseconds (10^{-15} second), and more recently, attoseconds (10^{-18} second). Femtosecond pulses can function in a manner similar to the flash on a camera used to "freeze" events that are too fast for the eye to register, which can be a valuable tool in analyzing events in the microscopic world. For example, many chemical reactions, including those related to vision and photosynthesis, occur on the femtosecond time scale.

A common source of femtosecond-order light pulses is a so-called mode-locked laser. In such a laser many optical waves cooperate (in other words, are mode-locked) to produce a short pulse periodically in time. Although laser light is often thought of as being a single color or frequency, in fact a large spread of colors or frequencies in the laser is required to generate a short pulse. The spread of frequencies is inversely related to the temporal length of the pulse. For example, a visible pulse that is approximately five femtoseconds in duration requires a range of optical frequencies on the order of 200×10^{12} hertz--or equivalently a small rainbow of light spanning from 500 nanometers to 750 nanometers. (For comparison, green light has a wavelength of about 550 nanometers and red light about 630 nanometers.)

Although such short bursts of light can now be produced rather routinely, it is yet another problem to accurately measure the pulse duration. There are no photodetectors or electronics fast enough to directly measure events on the femtosecond timescale. The fastest electronics available today have a time resolution of about 10^{-11} seconds (10 picoseconds). As a result, one must use the femtosecond pulse to measure itself in what is commonly called an optical autocorrelator. This technique involves using a replica of the pulse itself to act as a “gate" in a nonlinear medium that effectively multiplies the two pulses together. If the original pulse and the gate pulse meet in the medium, a signal is produced that is proportional to their product. If one pulse arrives and the gate pulse is not present, then no signal is produced. The two pulses can be delayed relative to each other using a variable path length delay, and the speed of light can be used to transform the difference in path length to a time interval. Such correlation techniques are the basis of virtually all measurements on the femtosecond time scale, and adaptations of this same idea can be used to measure the properties of atoms and molecules as they evolve and change. Most recently, the techniques of pulse generation and measurement have been extended to the ultraviolet and soft x-ray region of the spectrum where pulses on the order of 250 attoseconds have been created and used to study the motion of electrons around the nucleus of a neon atom.

Now let us consider the second formulation of the question: "What are the shortest duration events that can be recorded or inferred in experiments?" Events as short as about 10^{-25} second have been indirectly inferred in extremely energetic collisions in the largest particle accelerators. For example, the mean lifetime of the top quark, the most massive elementary particle so far observed, has been inferred to be about 0.4 yoctoseconds. (There are a few other elementary particles that have mean lifetimes of a fraction of a yoctosecond as well).

It is difficult to compare such a short interval to our usual experiences and ideas about time. Many people casually use nanosecond (one billionth of a second) to indicate unimaginably short times. A nanosecond is roughly the time it takes for light to travel one foot (about 30 cm). But on a logarithmic scale, a nanosecond is roughly the midpoint between the 0.4 yoctosecond top quark lifetime and a period of 80 million years. That is, there are about as many top quark lifetimes in one nanosecond as there are nanoseconds in 80 million years--(about 2.5×10^{15} in either case).

The top quark lifetime determination is actually an indirect measurement of the energy spread or uncertainty (ΔE) of the top quark and then a determination of the limits on the lifetime (Δt) by using the Heisenberg uncertainty principle. In the determination of the top quark lifetime, protons and antiprotons collide at extremely high energies in enormous accelerators, resulting in the formation of showers of exotic particles, very occasionally including a top quark. The Einstein energy-mass relationship $E = mc^2$ indicates that the energy of a particle such as the top quark is directly related to its mass, and vice versa. The top quark has the greatest mass of any known fundamental particle with energy of about 175 billion electron volts (GeV), which is comparable to the mass (or energy) of a gold atom. The top quark exists so fleetingly that it has never been directly observed, but its longer-lived decay by-products can be directly or indirectly detected with great effort, with the total energy of these by-products adding up to the original energy of the top quark. These energy measurements yield a spread or uncertainty in the inferred top quark energy, which is partly due to experimental uncertainties, but also reflects the fundamental energy uncertainty of the top quark due to its very short lifetime through the Heisenberg relationship ($\Delta E \; \Delta t >= h / 4 \pi$). Thus, indirect inference of the energy uncertainty of the top quark determines its 0.4 yoctosecond lifetime.

The question of whether there is a limit to how short a time interval could conceivably be measured gets to the heart of complex and currently untestable theories about space, time and energy. A short and incomplete answer is "no one knows for sure if there is a limit to how finely time can divided and measured. But accepted current theories suggest that there are limits to how finely time could be measured." There is of course no limit to how small a time interval we could conceive, but if present understandings of the nature of time, space and energy are correct, there would be insurmountable limits to measuring time intervals.

Most current theories of the universe hold that time, space, and energy all become intertwined at very short time intervals and over very short distances, for which energy becomes very large. This apparent limit on time interval is about 10^{-43} second and is called the Planck time. The Planck distance--how far light travels in one unit of Planck time--is about 10^{-35} meters, or about 10^{20} times smaller than the size of the nucleus of an atom. As discussed above for the inference of the top quark lifetime, it generally takes more and more energy to probe physical events on shorter and shorter time scales. Inferring the top quark lifetime requires the most powerful particle accelerators in the world, and these extremely high energy events are still about 10^{20} times weaker than the energies that would be required to observe events on the scale of Planck time.

Answer posted on December 27, 2004