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Stopping Time

What can you do in a billionth of a billionth of a second?

by Alan Burdick, Photography by Sian Kennedy

Time just got shorter. Granted, it was pretty short already: Four years ago, physicists managed to create a pulse of laser light lasting only five femtoseconds, or five quadrillionths (5×10^{-15}) of a second. In everyday photography, a camera flashbulb can "stop time" at about 1/1,000 of a second—fast enough to freeze the swing of a baseball batter, if not a speeding fastball. Likewise, the femtosecond "flashbulb" enabled scientists to observe phenomena never before seen in freeze-frame: vibrating molecules, the binding of atoms during chemical reactions, and other ultrasnall, ultrafleeting events.

But ultrafast is not good enough. All kinds of important things can happen between one quadrillionth of a second and the next, and if your flashbulb is too slow, you'll miss out. So scientists have been pressing on, punching the clock, hurrying to create even tinier windows of time through which to study the physical world. Recently, an international team of physicists finally succeeded in breaking the so-called femtosecond barrier. With a complex, high-energy laser, they generated a pulse of light little more than half a femtosecond long—650 attoseconds, to be precise. The attosecond (10^{-18} second) has long existed as a theoretical entity, but this is the first time anyone has actually seen it. It's a newfound slice of time—a tiny one but with gargantuan potential.

"This is the real timescale of matter," says Paul Corkum, a physicist with the Steacie Institute for Molecular Sciences in Ottawa and one of the principal investigators in the study. "We're gaining the ability to look at the microworld of atoms and molecules on its own terms."

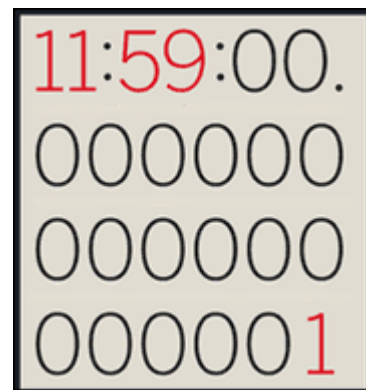
Although the fact is rarely appreciated, humans function in—and rely upon—several different timescales simultaneously. The average human heart beats once per second. Lightning strikes in a hundredth of a second. A home computer executes a single software instruction in nanoseconds, or billionths of a second. Circuits have switching times in picoseconds, or trillionths of a second. The shorter time gets, the harder it is to keep up with.

The invention of the laser in the 1960s offered a boost to scientists struggling to keep pace. The most common type of laser works by exciting the atoms of a noble gas like neon. (Other lasers work with solids, such as rubies, or even with organic dyes.) As the atoms "relax" and their electrons fall back into place, the gas glows at a characteristic wavelength of light—visible, microwave, red, or blue; it all depends on the atom involved. A laser forces the light waves to travel in unison and focuses the glow into an intense beam of light.

Creating a laser pulse is trickier. Physicists first use tiny mirrors to make a light beam run back and forth across itself inside a laser. Where the waves of light interfere—where their peaks and valleys coincide—spots of darkness and spots of light result. Tiny, ultrafast shutters can then be used to eliminate all but a single wavelength. Voilà, a pulse of light.

By the late 1980s, the laser pulse had reached a record brevity of six femtoseconds. (For a rough sense of scale, one femtosecond is to 90 seconds what 90 seconds is to the age of the universe.) No longer were researchers relegated to watching before-and-after pictures of chemical reactions; now they could watch slow-motion movies of the intermediate states. In the years since, a new science, femtochemistry, has come to focus on the mechanics of photosynthesis and other molecular reactions. In 1999 Ahmed Zewail, at Caltech, won the Nobel Prize in chemistry for a series of elegant experiments that revealed how chemical bonds break and re-form over a timescale of 100 to 200 femtoseconds.

The femtosecond pulse isn't just a camera shutter or a flashbulb; it has evolved into a powerful tool. It is superb for drilling tiny holes: Its energy is deposited so quickly, there's no time for the surrounding material to heat up, so there's less mess and inefficiency. Also, femtosecond pulses are only about a thousandth of a millimeter long. (In contrast, a pulse of light one second long would stretch from Earth to the moon.) Think of them as tiny bombs. They can be focused to strike just below the surface of a transparent material without actually piercing it. Femtosecond pulses are being used to etch optical waveguides inside panes of glass—a development that could



Using high-energy laser pulses, physicists have recently broken time down to attoseconds—fractions of a second so small the digits on a clock would seem to go on forever. We're used to seeing Olympic skiers win events by hundredths of a second. A skier who won by a single attosecond would be ahead by less than the width of an atom—less even than a proton. Insignificant as they sound, such time frames are opening new windows onto chemical reactions and other impossibly speedy events.

revolutionize data storage and telecommunications. Femtosecond researchers are developing a new method of laser eye surgery that operates directly on the cornea without damaging the tissue above it.

"It's a way of putting your hand inside biological materials, and doing so with very little energy," Corkum says.

In short, the femtosecond is great for handling whole atoms and molecules. But for the physicist interested in electrons, which are far smaller, lighter, and faster than the atomic nuclei they swarm around, that timescale is just too slow. "We're interested in taking this a step further," says Ferenc Krausz, a principal investigator of the study and a physicist at the Photonics Institute at the Vienna University of Technology.

Enter the attosecond. Theorists long suspected that a femtosecond-size pulse of visible light is in fact composed of—and can be subdivided into—several attosecond-length light pulses, much as a musical note contains many harmonic tones. The problem is measuring them. Electromagnetic harmonics are very weak, with wavelengths in the ultraviolet and X-ray range—too short to be detected.

With a modified interferometer—a special light filter for lasers—Krausz and his coworkers set off to hunt for attoseconds. They fired ultrabrief (seven-femtosecond) laser bursts of red light into a stream of neon atoms, thereby stripping the electrons free of their neon nuclei. The electrons were then carried along by the laser pulse and almost instantly smashed back into the neon nuclei. The effect was a bit like that of shooting a bell. The collision, as predicted, produced high-frequency harmonic tones of X rays and extreme ultraviolet rays. The physicists then filtered the harmonic light, allowing only select bursts of

X rays—including one only 650 attoseconds long—to pass.

No sooner had the physicists caught an attosecond pulse than they demonstrated its usefulness. They aimed an attosecond pulse and a longer pulse of red light into a gas of krypton atoms. The attosecond pulse excited the krypton atoms, kicking electrons free; then the red-light pulse hit the electrons and took a reading of their energy. By adjusting the time delay between the two pulses, the scientists gained a very precise measurement—within a matter of attoseconds—of how long it takes the electron to decay. Never before had electron dynamics been studied on so short a timescale.

The experiment set the physics world buzzing. "Attoseconds will give us a new way to think about electrons," says Louis Dimauro, a physicist at Brookhaven National Laboratory. "They become a new probe of matter that will then be applied across the sciences. The age of attophysics has begun."

Eventually, physicists hope to do more than just watch electrons gain and lose energy. "We can think of using attosecond pulses not only to trace these processes but also to control the relaxation of an atom following its excitation," Krausz says. "It's very exciting." For example, by controlling the means by which atoms, at attosecond timescales, release X rays, one might build an efficient X-ray laser, long a dream among physicists. The semiconductor industry, which has a thirst for speeding up computer chips, transistors, and other electronic devices, likewise wouldn't mind getting a taste of some attoseconds. "We know that every other advance that's led to shorter pulses has led to major advances," Corkum says. "This is the next step."

Of course, one day, perhaps not so very far in the future, even the speedy attosecond will fail to satisfy. Electrons will look downright poky. "As you go into smaller structures of matter, inside the atomic nucleus, processes become even faster," Krausz says. "In nuclear physics, the natural timescale is several orders of magnitude faster—in the realm of zeptoseconds," or sextillionths of a second.

In the meantime, physicists will have to manage with the little free time they've gained already. One can imagine them getting carried away: filling up their hard drives with electron home videos, clogging the airwaves with attosecond flicks that seem to yawn for seconds—for eternity, basically. Corkum assures that won't happen: "In practice, we're only looking at a reasonable period of time." In small time, he says, just like in the big time, viewer boredom still sets the limits. "My brother-in-law recently sent some movies of their baby," Corkum says. "It was fun at first, but after 15 minutes—wow, that's a lot of time."

How far is a second?

Time has been chopped so fine by modern physicists that its subdivisions are getting harder and harder to grasp. One way to keep them in perspective is to imagine a road trip from Los Angeles to New York City—2,787 miles—that takes only one nanosecond to complete. In one picosecond, the car would make one thousandth of the trip—about 2.8 miles, or all the way to East Los Angeles. In one femtosecond, it would have gone a millionth of the way, or less than two car lengths. An attosecond—the shortest time interval now measurable—would account for only a billionth of the trip: about a fifth of an inch.

Were the car to keep on going for the relative eternity of a full second, it could make half a billion trips to New York and back. At that pace, it would be traveling at 16 million times the speed of light. Of course, the driver could just as well choose to ignore New York entirely and head into orbit. Were he to spend the entire second leisurely circling Earth, he would make it around the planet about 112 million times. Were he to circle the solar system instead, he'd manage about 120 tours of the sun on Pluto's orbital path.



Sky photograph by Bill Frymire/Masterfile.

Web Resources:

The Vienna University of Technology's attophysics page has a number of links to relevant papers: info.tuwien.ac.at/photonik.

A rather technical description of attosecond pulse generation, from the Max Planck Institute for Quantum Optics: www.mpg.de/lpg/research/attoseconds/attosecond.html.

An accessible explanation of Ahmed Zewail's work in femtochemistry can be found at www.nobel.se/chemistry/laureates/1999/press.html.

Read more about Ahmed Zewail's work with femtosecond pulses in "Welcome to Femtoland," by Gary Taubes, *Discover*, February 1994, page 82. This article is available at www.discover.com.

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