John Matson is a former reporter and editor for *Scientific American* who has written extensively about astronomy and physics.

RELATIVITY

HOW TIME FLIES

Some experimental optical clocks are so precise that even a small change in elevation or velocity makes them register the passage of time differently

By John Matson

IF YOU HAVE EVER FOUND YOURSELF CURSING A NOISY UPSTAIRS NEIGHBOR, take solace in the fact that he or she is aging faster than you are.

Einstein's general theory of relativity predicts that clocks at different gravitational potentials will tick at different rates—a clock at higher elevation will tick faster than will a clock closer to Earth's center. In other words, time passes more quickly in your neighbor's upstairs apartment than it does in your apartment.

IN BRIEF

The development of ultraprecise atomic clocks has made it possible to demonstrate relativistic time effects in the laboratory.

Recent experimental atomic clocks rely on aluminum ions, which can keep time to within one second in roughly 3.7 billion years.

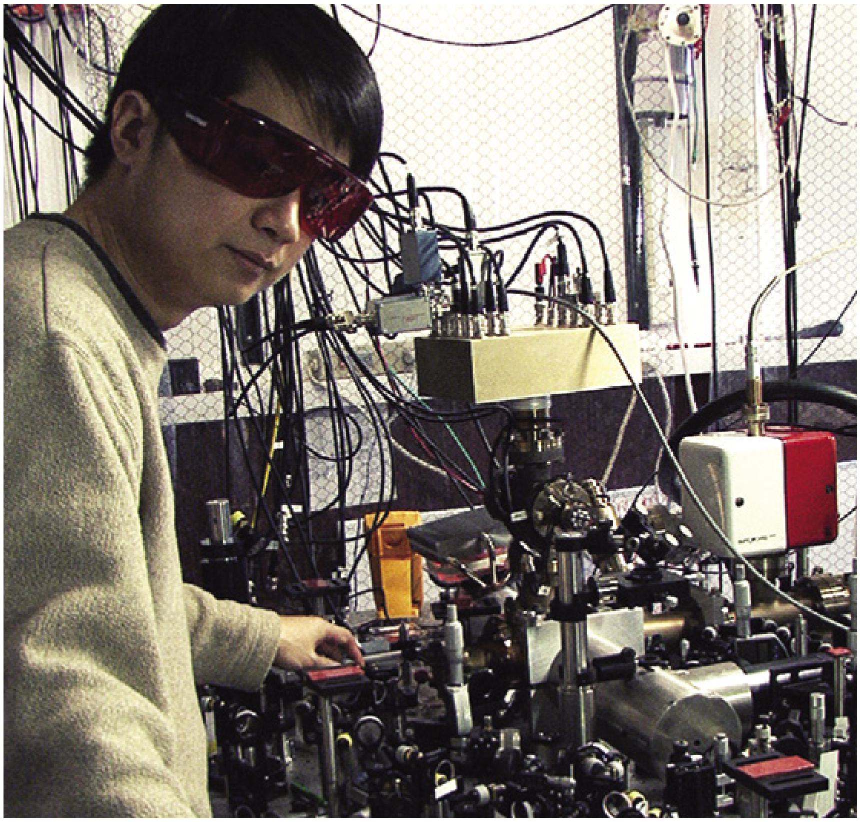
In the past relativistic effects could be detected only at massive scales of distance or velocity or by harnessing atomic oscillations too rapid to be accurately counted.

To complicate matters, Einstein's special theory of relativity, which preceded general relativity by a decade, predicts a similar effect for clocks in motion—a stationary clock will tick faster than a moving clock. This is the source of the famous twin paradox: following a round-trip journey on a spaceship traveling at some exceptionally high velocity, a traveler would return to Earth to find that her twin sibling is now older than she is, because time has passed more slowly on the moving ship than on Earth.

Both these so-called time dilation effects have been verified in a number of experiments throughout the decades, which have traditionally depended on large scales of distance or velocity. In one landmark test, in 1971, Joseph C. Hafele of Washington University in St. Louis and Richard E. Keating of the U.S. Naval Observatory flew cesium atomic clocks around the world on commercial jet flights, then compared the clocks with reference clocks on the ground to find that they had diverged, as predicted by relativity. Yet even at the speed and altitude of jet aircraft, the effects of relativistic time dilation are tiny—in the Hafele-Keating experiment, the atomic clocks differed after their journeys by just tens to hundreds of nanoseconds.

Thanks to improved timekeeping, similar demonstrations can now take place at more mundane scales in the laboratory. In a series of experiments described in the September 24, 2010, *Science,* researchers at the National Institute of Standards and Technology (NIST) registered differences in the passage of time between two high-precision optical atomic clocks when one was elevated by just a third of a meter or when one was set in motion at speeds of less than 10 meters per second.

Again, the effects are minuscule: it would take the elevated clock hundreds of millions of years to log one more second than its counterpart, and a clock moving a few meters per second would need to run about as long to lag one second behind its stationary counterpart. But the development of optical clocks based on aluminum ions, which can keep time to within one second in roughly 3.7 billion years, allows researchers to expose those diminutive relativistic effects. "People usually think of it as negligible, but for us it is not," says lead study author James Chin-wen Chou of NIST. "We can definitely see it."



It's all relative: **James Chin-wen Chou with one of the aluminum-ion optical clocks at the National Institute of Standards and Technology.**

COURTESY OF J. BURRUS *National Institute of Standards and Technology*

The NIST group's optical clocks use lasers to probe the quantum state of aluminum ions held in radio-frequency traps. When the laser's frequency is just right, it resonates with a transition between quantum states in the aluminum ion whose frequency is constant in time. By continually tuning the laser to drive that aluminum transition, an interaction that occurs only in a tiny window near 1.121 petahertz (1.121 quadrillion cycles per second), the laser's frequency can be stabilized to an exquisitely sensitive degree, allowing it to act as the clock's pendulum. "If we anchor the frequency of the oscillator—in our case, laser light—to the unchanging, stable optical transition in aluminum, the laser oscillation can serve as the tick of the clock," Chou explains.

To put the sensitivity of the optical clocks in perspective, Chou notes that the two timekeepers in the study differed after a height change of a mere step on a staircase—never mind the entire floor separating you from your noisy neighbor—or with just a few meters per second of motion. "If you push your daughter on a swing, it's about that speed," he says.

In the past such relativistic experiments have involved either massive scales of distance or velocity or else oscillations so fast that their ticks cannot be reliably counted for timing purposes, notes Holger Müller, an atomic physicist at the University of California, Berkeley. "It's an enormous achievement that you can build optical clocks so good that you can now see relativity in the lab," he says.

Müller has used atom interferometry to make precision measurements of relativistic effects—measurements that rely not on counting individual oscillations but rather on tracking the interference between quantum waves representing individual atoms. (The frequencies of such waves, which oscillate tens of billions of times faster than the petahertz laser in an aluminum clock, are simply too high to monitor and count.) It is a process akin to striking two tuning forks to listen to the pulsations of their interference without actually measuring how many times each fork vibrates. In that sense, atom interferometers are pendulums without clockwork, so although they can make physical measurements with great precision, they cannot be used to keep time.

"The new work operates on familiar scales of distance and velocity, with clocks that can be used for universal timing applications," Müller says. "They see the effects of general and special relativity, and that makes relativity something you can kind of see and touch." SA

MORE TO EXPLORE

Around-the-World Atomic Clocks: Observed Relativistic Time Gains. J. C. Hafele and Richard E. Keating in *Science,* Vol. 177, pages 168–170; July 14, 1972.

Black Holes and Time Warps: Einstein's Outrageous Legacy. Kip S. Thorne. W. W. Norton, 1994.

A Precision Measurement of the Gravitational Redshift by the Interference of Matter Waves. Holger Müller, Achim Peters and Steven Chu in *Nature,* Vol. 463, pages 926–929; February 18, 2010.

Frequency Comparison of Two High-Accuracy Al^+ Optical Clocks. C. W. Chou et al. in *Physical Review Letters,* Vol. 104, No. 7; February 19, 2010. **http://arxiv.org/abs/0911.4527**