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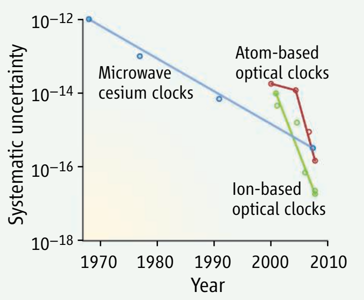
PHYSICS

A Milestone in Time Keeping

Daniel Kleppner

Researchers have made atomic clocks so precise that effects of general relativity are on the verge of complicating the concept of keeping time.

A clockmaker who aspires to hold the record for creating the best clock in the world faces a dilemma: The claim would be unprovable because there would be no absolute reference clock with which to compare it. The only solution would be to build a second clock as good as the first. Two groups have done just that: Rosenband *et al.* report their results on page 1808 of this issue (*1*), and Ludlow *et al.* on page 1805 (*2*). Each group compared two clocks and demonstrated a precision that significantly exceeds that of today's best time standards (see the first figure).



Clocking progress. The systematic uncertainty is the uncertainty due to all known perturbations. Cesium (blue) remains the legal time standard. The ion-based optical clocks (green) operated with Hg$^+$, Yb$^+$, Sr$^+$, or Al$^+$. The atom-based optical clocks (red) include the pioneering measurement of the hydrogen 1S-2S transition by Hänsch and his colleagues (*7*) (first red point). Other optical clocks operated with Ca and Sr. The final points are for the clocks reported by Rosenband *et al.* and Ludlow *et al.*

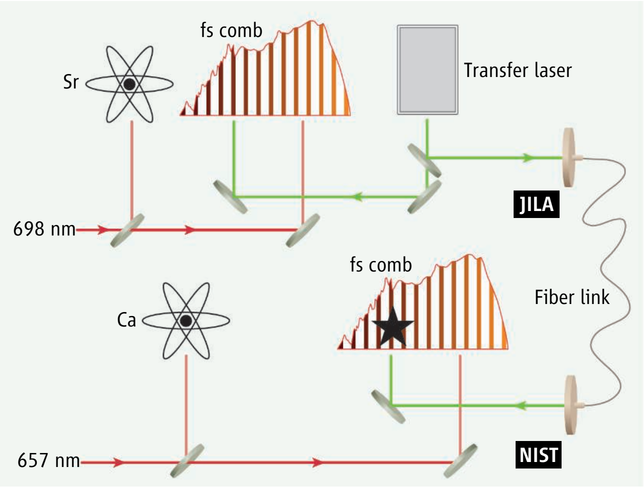
Atomic clocks became a reality in the mid-1950s with the development of the cesium clock. The time-keeping element in this clock is a microwave transition in the cesium atom. The first clocks achieved an uncertainty of about 10^{-10}. By steady research and refinement, the clocks were improved until their uncertainty reached the level of about 5×10^{-16}. However, it is generally agreed that major improvements in cesium clocks are no longer likely. Fortunately, a new type of clock is now being realized.

The timing element in an atomic clock is the frequency of a transition between energy levels in an atom or ion. The measured precision of the clock is proportional to the size of the transition frequency, assuming that the ability to measure the frequency is kept the same. Because optical frequencies are larger than microwave frequencies by a factor of $\sim 10^5$, optical clocks hold the potential of being enormously more precise than the cesium clock.

Rosenband *et al.* report the comparison of two atomic clocks based on the frequencies of optical transitions in single ions. One clock uses the Al$^+$ ion; the other uses the Hg$^+$ ion. They measured the ratio of the frequencies of the two clocks to an uncertainty of 5.2×10^{-17}. This result is among the most precise measurements ever made in physics.

The clocks used by Rosenband *et al.* employ a single ion that is confined in a trap by electric fields. The experimental challenge is to approach as closely as possible the ideal of a single particle at rest in space, free from all perturbations and measured as well as quantum mechanics permits. They use a series of imaginative techniques that have been developed by themselves and others. As with every high-precision measurement, the principal challenge was to evaluate the effects of perturbations and sources of uncertainty. Although the sources are quite different for the two clocks, their final uncertainties are approximately the same, yielding an overall uncertainty of 5.2×10^{-17}.

When precision is pushed to new levels, ever more subtle effects must be taken into account. For instance, the error budget includes a small contribution, 1×10^{-18}, due to an uncertainty in the gravitational potential of the two clocks. This corresponds to a difference in their altitudes of 1 cm. This heralds one of the most interesting aspects of time keeping with optical clocks: The effects



Comparing clocks. Lasers (red) are frequency-locked to atomic transitions in each laboratory, forming independent atomic clocks. Another laser (green) is used to communicate between the clocks over an optical fiber. The frequencies of the red and green beams are controlled and compared by using a femtosecond frequency comb in each laboratory.

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of general relativity that mix time with gravity are starting to approach a point that will require rethinking the basic concept of "keeping time."

Clockmakers face a second dilemma: The more accurate clocks are, the more difficult it is to compare them. The clocks used by Rosenband *et al.* were located in the same building, at the National Institute of Standards and Technology (NIST) in Boulder, Colorado, and compared with fiber links of a few hundred meters. Comparing clocks that are very far apart presents a separate challenge. Precision timing signals between distant laboratories are currently transmitted over microwave networks or by satellites, but these fail at the levels of precision now being achieved with optical clocks.

Ludlow *et al*. describe the comparison of clocks that employ optical transitions in neutral atoms, in contrast to ions. Furthermore, the clocks are separated by kilometer-scale urban distances (see the second figure). One clock was located at JILA on the campus of the University of Colorado in Boulder, and the other at NIST just outside the campus. The JILA clock employed strontium atoms held by light waves; the NIST clock used calcium atoms that were unconfined but so cold that their velocities were relatively low. These clocks also outperformed cesium clocks, and their rates were compared with a fractional uncertainty at the level of 10^{-16}. Most notably, by comparing clocks in different laboratories with optical signals transmitted by fiber in contrast to microwave communications, this work represents an important advance in time transfer at the frontiers of precision.

Ion-based atomic clocks currently achieve the highest accuracy because of their relative freedom from perturbations. However, neutral atom-based atomic clocks offer the advantage of much stronger signals, because the ion clocks use only a single particle whereas atom clocks typically use tens of thousands of atoms. There are numerous candidates for the new generation of optical atomic clocks, and eventually the second will be redefined based on one of them. However, that is unlikely to happen soon, because currently there is no obvious best choice for an ion or atom optical clock.

The advances in optical clocks described by Rosenband *et al.* and Ludlow *et al.* represent a milestone in time keeping because both groups achieved uncertainties that are significantly below those of primary cesium time standards. These realizations of optical atomic clocks rest on developments that stretch back more than 20 years. Enabling technologies include methods for trapping and cooling single ions developed by Wineland and his collaborators in the 1980s (*3*); laser cooling atoms for which Chu, Cohen-Tannoudji, and Phillips received the Nobel Prize in 1997 (*4*–*6*); the development of methods for ultrahigh optical and ultraviolet spectroscopy of ions by Bergquist and his collaborators in the 1990s (*3*); and the invention of the femtosecond frequency comb and optical frequency metrology for which Hänsch and Hall received the Nobel Prize in 2005 (*7*, *8*).

It will take some time to engineer an optical clock so that it can operate with the reliability and simplicity needed for practical applications, but once the goal is clearly in sight, this sort of engineering can move speedily. The question inevitably arises as to what the next generation of clocks will be useful for. One can point to basic tests such as the constancy of the fundamental constants, and possible applications such as geodesy. However, the best response to that question is simply to note that when atomic clocks were invented 50 years ago, nobody was dreaming of the Global Positioning System (GPS). The development of the GPS illustrates the truth of the adage that revolutionary technologies are likely to generate revolutionary applications.

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ECONOMICS

When a Commodity Is Not Exactly a Commodity

Nancy Folbre

Economic transactions for services such as health and elder care are complicated by personal interactions and emotional connections.

The metabolism of our global economy relies on trillions of daily transactions, many of which involve goods and services termed commodities. In the idealized competitive markets of conventional economic theory, specific commodities are homogeneous and their quality is easily assessed. Because all pork bellies are alike, your choices among them can be based on price alone. But market transactions are not always so straightforward. Researchers have recently begun to explore the ways in which the process of exchange itself may modify the exchangers—altering product quality in unanticipated ways.

Labor, for example, is not a perfect commodity because its quality can be profoundly affected by the motivation of the laborer. The difficulty of controlling motivation makes labor contracts incomplete—the services being purchased cannot be perfectly specified in advance and are subject to change.

John Maynard Keynes noted that employers whose demand for labor falls often prefer layoffs to nominal wage reductions, which can elicit retaliation in the form of reduced effort (*1*). Mathematical models of the strategic relationship between individuals (principals) trying to control the behavior of others (agents) show that employers may pay a wage premium or offer gifts to workers in order to elicit greater effort (*2*–*4*). And a growing empirical literature based on laboratory experiments shows that workers' perceptions of fairness may also affect effort (*5*). In other words, wage-cutting can backfire.

These complexities of employer-worker interaction can be compounded by interactions between workers and consumers. Such interactions are relatively uncommon in the purchase of agricultural products or manufactured goods, where sales are typically distant from the point of production. The purchase of services, however, often entails high levels of personal interaction. The emotional dimension of work is particularly salient in services that entail provision of care for dependents—children, the elderly, and the sick or disabled.

Health, education, child care, and elder care account for a growing percentage of paid employment in countries like the United

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