

Stability doesn't guarantee accuracy—even a clock that keeps consistent time may not keep the *right* time, as measured against the benchmark of a perfectly isolated atom. Stability does, however, play an important role: The ability to evaluate a clock's systematic error is limited in part by the steadiness of its ticks. In the 1D lattice used by the Ye group, for example, multiple atoms often occupy the same potential well. To account for those atoms' weak, but non-negligible, interactions, the researchers must be able to detect subtle responses of the clock frequency to modulations in the number of trapped atoms.

The biggest source of systematic error in optical-lattice clocks is the blackbody radiation (BBR) shift, the energy shift due to the sensitivity of the clock atoms to thermal radiation from the surrounding apparatus. Atoms amenable to optical-lattice trapping tend to be much more susceptible to that shift than are the ions preferred for single-ion clocks.

To account for the BBR shift, one needs to determine the electric polarizability of the atoms and the radiation spectrum they see. To that end, Ye and company outfitted their clock with a retractable temperature sensor, indicated in figure 2 by the green arrow. Between frequency measurements, the sensor, coated with highly absorptive paint, can extend to measure the effective temperature of the radiation field at the position of the atoms and in the near vicinity. From the temperature, the researchers can calculate the corresponding radiation spectrum for an ideal blackbody; from its spatial gradients, they can estimate deviations from that ideal blackbody spectrum.

Combining the temperature information with a precise estimate of Sr's electric polarizability, recently obtained by researchers at Physikalisches Bundesanstalt (NIST's German counterpart),⁵ Ye and company estimated the magnitude of the BBR shift with a fractional uncertainty of 4.1×10^{-18} . Lesser sources of uncertainty—electrostatic fields due to charge heterogeneities along the viewports, interactions between atoms, and so forth—brought the total systematic uncertainty to 6.4×10^{-18} . The previous record, held by an aluminum single-ion clock, was 8.6×10^{-18} .

Ye thinks optical-lattice clocks can eventually reach a systematic uncertainty below 1 part in 10^{18} . At that level, the atomic timepieces would provide stringent tests of the variability of physical constants, such as the fine-structure

constant α that sets the strength of light-matter interactions. If α is changing over time, as some celestial observations have suggested, it should be evidenced by a drift in the ratios of different atomic transition frequencies. By comparing the ticking of Al⁺ and Hg⁺ ion clocks over the course of a year,⁶ a NIST group led by James Bergquist has already established an upper bound on α 's annual variation at 1 part in 10^{17} . A comparison between optical-lattice clocks may squeeze the upper limit further.

Ultrastable clocks might also function as quantum altimeters, capable of detecting centimeter changes in altitude based on the time-dilating effects of Earth's gravitational potential. "Imagine you have a network of these

clocks," comments Ye. "You could measure in real time how a body of water is moving along Earth. Two clocks might allow you to see a gravitational wave coming from the deep universe. They would sort of be the ultimate quantum objects for measuring the spacetime fabric."

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A nanoscale look at how soil captures carbon

Organic matter bound to mineral grains can remain there for many decades. But only a fraction of the mineral surface area ever binds any carbon.

Soil is a huge component of the global carbon cycle. As shown in figure 1, the world's soils contain more carbon than the atmosphere and all living things combined, and the flux of carbon into and out of the soil dwarfs the rate of anthropogenic carbon emission from fossil fuels.

About two-thirds of the soil's carbon is contained in organic molecules. (The rest forms inorganic minerals such as carbonates.) All organic molecules are thermodynamically unstable; left to seek their free-energy minima, they decompose into carbon dioxide, water, and other small molecules. Despite that instability, organic matter entering the soil remains there for an average of 25 years, and can even stay for centuries or millennia without decomposing.

An accurate treatment of that capacity to store and stabilize carbon is an essential ingredient in climate models. At present, soil erosion and changes in land use each release an additional gigaton or so of carbon into the atmosphere per year.¹ Better soil management could slow that trend or even reverse it, so that natural carbon sequestration in the soil might offset a portion of fossil-fuel emissions.²

The problem is that we don't really know how the stabilization happens. It's known that interactions between

organic matter and mineral grains are responsible in some way. But soils are complicated systems—composed of many different minerals, organic compounds, liquids, gases, and microbes—and their composition and dynamics vary from place to place. Models have long assumed that all mineral surfaces are equally good at stabilizing carbon, so a soil's carbon-storage capacity is determined by its total surface area—or, equivalently, its clay content. (Soil mineral particles are classified by size: micron-sized clay, larger silt, and even larger sand.) Evidence has been accumulating that the approximation is overly simplistic: Organic material doesn't cover soil mineral surfaces evenly, and clay content isn't always well correlated with stored carbon.³ But a better description has been hard to come by.

Now Ingrid Kögel-Knabner, Cordula Vogel, and colleagues at the Technical University of Munich have taken a microscopic approach.⁴ Using nanoscale secondary-ion mass spectrometry (nanoSIMS), a technique borrowed from materials science, they've shown conclusively that organic matter binds to just a fraction of total surface area. They also found that the rough surfaces of clustered mineral particles bind far more carbon than the smooth surfaces



Figure 2. The strontium optical-lattice clock shown here is now the world's most accurate timekeeper. Visible at the center is a cloud of trapped, fluorescing Sr atoms, used to determine the ticking frequency. Key to the clock's accuracy is a temperature sensor (indicated by the green arrow), which is mounted on a retractable glass tube and used to characterize systematic errors caused by blackbody radiation. (Adapted from ref. 2.)

tune the lattice light to a "magic" wavelength, at which both atomic states involved in the clock transition are shifted by precisely the same energy. At that wavelength, the clock transition mimics one in an unperturbed atom. By 2006 a handful of groups, among them Katori's and Ye's, had used the magic-wavelength strategy to build the first generation of optical-lattice clocks.

Stability

A good clock should be stable—the duration of its ticks shouldn't vary over

time. Quantum metrologists typically measure stability by running two clocks, based on the same transition, side by side. The fractional difference between the clocks' tick rates is known as the Allan deviation. With single-ion clocks, it takes several minutes of averaging to reach an Allan deviation of 1 part in 10^{16} . Optical-lattice clocks, because they measure thousands of atoms at once, can reach the same level in a matter of seconds.

Last fall a NIST group led by Andrew Ludlow ran two ytterbium opti-

cal-lattice clocks in an extended experiment to see how far the Allan deviation would fall.⁴ In such an experiment, there's no guarantee that the deviation will trend steadily downward: Frequency fluctuations of the lasers used to trap and probe the clock atoms can effectively place a ceiling on clock stability, as can subtle environmental changes such as temperature drifts. Using ultrastable lasers and carefully controlled experimental conditions, Ludlow and his team were able to keep those destabilizing factors largely in check. Their data, plotted in red in figure 1, show the Yb clocks reaching an Allan deviation of 1.6×10^{-18} —a record low for clocks of any kind—after seven hours of averaging.

Accuracy

With their new clock, based on an optical transition in strontium, Ye and company can achieve stabilities comparable to those reached in the NIST experiment. For each measurement, a few thousand ultracold atoms are loaded into a one-dimensional optical lattice generated with a titanium:sapphire laser. Figure 2 shows the clock's viewport; a cloud of trapped, fluorescing Sr atoms is seen in the center.

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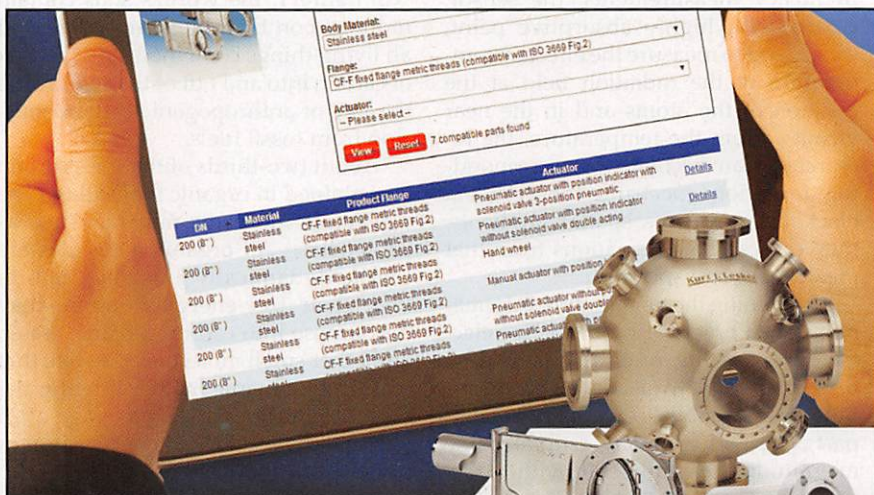
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of single grains and that new organic matter binds almost exclusively to surfaces where old organic matter is already present.

Dishing the dirt

NanoSIMS is a method for making spatially resolved maps of chemical identity. An ion beam, focused to about 100 nm, is shot at a surface. The primary ions from the beam dislodge secondary ions from the surface, which are then collected with ion optics and sorted with a mass spectrometer. Screening for the mass of a particular chemical species, such as carbon-12, gives a map of where that species is located on the surface. Available instruments allow the imaging of up to seven masses simultaneously—a useful capability, because imaging with nanoSIMS destroys the sample.

Imaging the clay-sized particles from a soil sample showed that organic carbon was confined to about 20% of the mineral surface area. Comparing nanoSIMS images with scanning electron microscope images, which allow mineral clusters to be distinguished from single clay particles by visual inspection, showed that organic matter was almost never present on single particles.

But Kögel-Knabner and colleagues wanted to go beyond that static picture to look at the process by which new organic matter—in their case, litter made from leaves of corn and potato plants—

is incorporated into the soil. They used an established soil-research technique of tracking isotopically labeled litter, made from plants grown in a closed environment and fed with CO₂ enriched in ¹³C and fertilizer enriched in nitrogen-15. That's expensive, but it works: The resulting plants have ¹³C and ¹⁵N concentrations several times higher than those found in nature. Isotopic analysis can then reveal the fate of the leaf material as it interacts with the soil.

Some isotopic tracking experiments are performed *in situ* and last for years. But the Munich researchers did theirs in a lab over just six weeks. They combined 50 g of natural soil with 0.5 g of the isotopically labeled litter and incubated the mixture under controlled temperature and moisture conditions.

Control systems, some with unlabeled litter and some with no litter, were incubated in parallel. The researchers sampled and analyzed the soil after two hours; one day; and one, three, and six weeks. They separated the clay-sized particles of interest from free organic matter and other mineral components by size and density fractionation. Then they took a drop of a dilute suspension of clay particles and let it dry on a silica wafer for nanoSIMS imaging.

Oxygen-16 images showed the outlines of the clay particles, and ¹²C and ¹³C/¹⁴N, as shown in figure 2a, revealed the overall distribution of organic matter. To see the newly incorporated organic material, the researchers looked

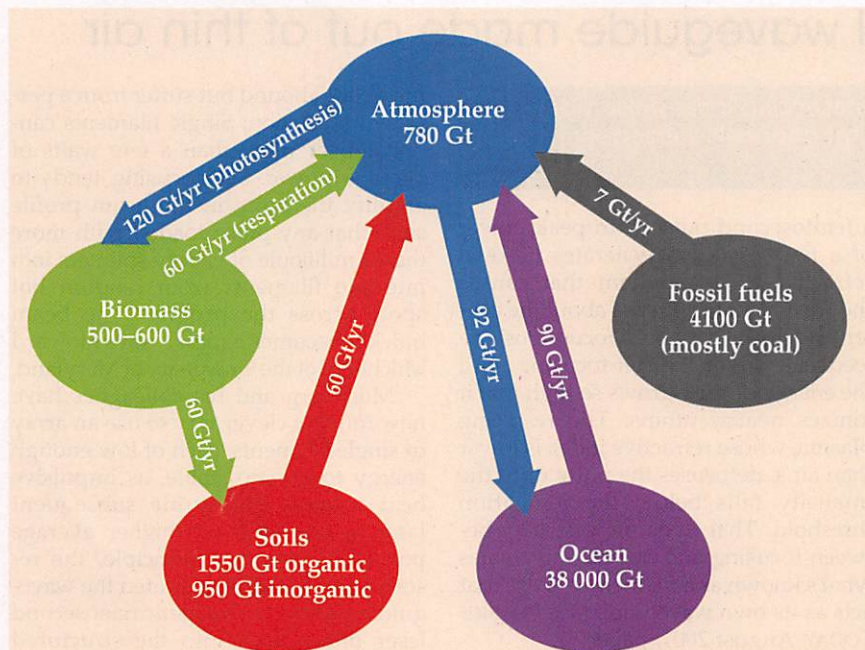


Figure 1. Global carbon pools, in gigatons, and the major fluxes between them. (Adapted from ref. 1.)

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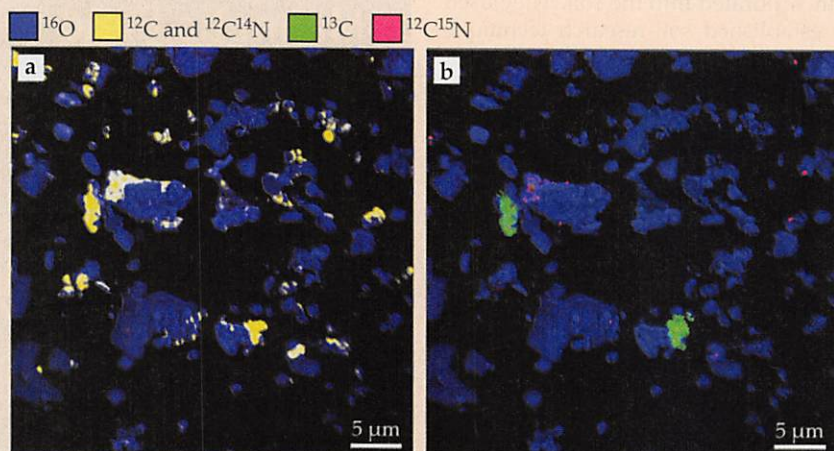


Figure 2. Nanoscale secondary-ion mass spectrometry images of clay-sized soil particles after three weeks of incubation with isotopically labeled plant litter. The oxygen-16 signal in both images shows the outlines of the mineral particles. (a) Organic matter, indicated by ^{12}C and $^{12}\text{C}^{14}\text{N}$ signals, covers about 20% of the total mineral surface. That fraction remained roughly constant over the course of the six-week experiment. (b) Newly incorporated organic matter, indicated by enrichment in ^{13}C and ^{15}N , covers a smaller but growing fraction of the area. (Adapted from ref. 4.)

for regions with unusually high fractions of ^{13}C or $^{12}\text{C}^{15}\text{N}$, as shown in figure 2b. (The mass spectrometer is sensitive enough to distinguish between $^{12}\text{C}^{15}\text{N}$ and $^{13}\text{C}^{14}\text{N}$.)

Images taken at different times necessarily showed different mineral surfaces. Even if nanoSIMS were a non-destructive technique, it would be impossible to retrieve the same clay particles from the incubator more than

once. So tracking the labeled litter's progress in binding to the clay had to be done statistically. For each nanoSIMS image, the researchers determined the fraction of the total mineral area that contained ^{12}C and the fraction of the organic area enriched in ^{13}C . The former fraction did not change over the course of the six weeks, but the latter increased: At two hours, one-third of the organic area was isotopically enriched;

at six weeks, more than half of it was. Clearly, the new organic matter was attaching to the clay, but it wasn't seeking out new mineral surfaces to bind to.

What makes rough mineral surfaces more hospitable to organic matter than smooth ones, and what makes some rough surfaces better than others? Kögel-Knabner and colleagues attribute the difference to microbial activity. The sub-micron nooks and crannies of mineral clusters make good homes for single-celled organisms, but not every suitable surface is populated by microbes.

So far, the researchers' nanoSIMS work has focused on just one type of soil—a topsoil taken from near their home in Germany and typical of soils in central Europe, the US, and parts of Australia and Asia. As a next step, they plan to extend their analysis to other types of soil and to study the effect of the soil particles' composition in addition to their size and shape. They hope that that work will paint a clearer picture of how much carbon soil can hold and how best to exploit that capacity.

Johanna Miller

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A long-lived optical waveguide made out of thin air

Sound and heat in the wake of a femtosecond laser pulse can produce a refractive-index gradient that channels subsequent higher-power pulses.

It isn't easy to deliver the concentrated power of a laser beam through air to a distant target—whether to disarm some military threat, say, or to remotely detect hazardous materials. The light diffracts, can be scattered and absorbed, and may experience phase-distorting turbulence and temperature fluctuations that blur its focus. Worse, a high-powered beam can suffer what's known as thermal blooming, in which the beam heats the air it passes through and spreads much faster than it normally would by diffraction.

If a beam is intense enough, though, it focuses itself—no lens required—thanks to the slight dependence of the index of refraction on light intensity. Brighter in the center than on its edges,

a femtosecond pulse with peak power of a few gigawatts generates its own refractive-index gradient that causes the wavefront to collapse about the center and form a tighter focus. Positive feedback drives the self-focusing until the energy density grows so high that it ionizes nearby atoms. The resulting plasma, whose refractive index is lower than air's, defocuses the pulse until the intensity falls below the ionization threshold. That dynamic interplay between focusing and defocusing creates what's known as a filament, a pulse that acts as its own waveguide (see *PHYSICS TODAY*, August 2001, page 17).

Such filaments can cover nearly a kilometer without diffracting and will propagate through clouds and fog. Ap-

plications abound but suffer from a persistent limitation: Single filaments cannot deliver more than a few watts of average power. Self-focusing tends to amplify the noise in the beam profile such that any pulse loaded with more than a millijoule of energy splinters into multiple filaments from random hot spots across the profile. "The beam quickly becomes a mess," says Howard Milchberg of the University of Maryland.

Milchberg and his colleagues have now found a clever way to use an array of single filaments, each of low enough energy to remain stable, as impulsive heat sources that guide subsequent laser beams of much higher average power. As proof of principle, the researchers have demonstrated the waveguiding effect on energetic nanosecond laser pulses shot into the structured pattern of hot air in the wake of a square filament array.¹

Theirs isn't the first filament-based