the expense of its orbital energy. And since the bulge is larger and the gravitational attraction is stronger at the perijove, its influence wins out: Io's tidal bulge causes Io to spiral inward toward Jupiter. Much of the energy that goes into growing, shrinking, and shifting the bulge is dissipated through friction; the resulting heat is thought to be responsible for Io's volcanic activity, the most dramatic in the solar system.

Which tidal effect is stronger, and whether Io's total energy is actually increasing or decreasing, depends on how severely Io and Jupiter are distorted by tidal forces. Those things can't easily be observed from Earth. To infer the tide-induced accelerations from observations of the moons' orbits, one must track the Jovian moons for a long time. The earliest usable measurements of the moons' positions are photographic plates that date back to 1891. But the positions must be determined with much greater precision than any individual hundred-year-old measurement—or even many modern measurements—can provide. Averaging many measurements helps, but the positions must also be constrained through use of a model.

Tides over time

Several groups in the past have attempted to derive the orbital accelerations of Jupiter's Galilean moons from the records of their positions.[2] But they've always done it by treating the tidal effects as secular accelerations—that is, by modeling the system in the absence of the tidal effects and deriving the tide-induced accelerations from the differences between the actual trajectories and the modeled ones. The dynamical models they used have systematic uncertainties similar in magnitude to the accelerations themselves. And the method of secular accelerations doesn't allow any conclusions to be drawn about the tidal magnitudes: Since tides in Jupiter and tides in Io have similar but opposite consequences for the moons' orbits, the two effects can't be decorrelated by looking at the orbital accelerations alone.

Lainey and colleagues were the first to include the tidal effects directly in a model. They numerically integrated the orbits, in two-hour time steps, from 1891 to 2007. Then they iterated the integration to fit the 26 parameters of their model: the initial position and velocity vectors of each of the four moons (they included Callisto even though it's not in the Laplace resonance and doesn't interact strongly with the others) and Jupiter's and Io's susceptibility to tides. They were able to separate the two tidal mechanisms because Io's tides had a substantial effect on the eccentricity of Io's orbit, whereas Jupiter's tides had a much smaller effect.

The calculation revealed that Io is speeding up and thus spiraling inward and losing energy, whereas Europa and Ganymede are slowing down, spiraling outward, and gaining energy: At the end of the 116-year period, Io is 55 km farther ahead in its orbit than it would have been without any acceleration, Europa is 125 km behind, and Ganymede is 365 km behind. From Io's tidal parameter, Lainey's collaborators Özgür Karatekin and Tim Van Hoolst, geophysicists at the Royal Observatory of Belgium, determined how much heat is generated by Io's shifting tidal bulge. They concluded that if heat were lost from Io at the same rate as it was generated, the average heat flux at Io's surface would be 2.24 ± 0.45 W/m^2. Io's actual heat flux has been measured several times from IR spectral data,[3] with most estimates being between 2 and 2.5 W/m^2. It appears, therefore, that Io is close to a thermal steady state—that its volcanic activity is driven by the heat generated by tidal friction now, rather than by heat retained from a past period when tides might have been even higher.

Longer-term trends?

Lainey and colleagues reconstructed what happened to Io, Europa, and Ganymede over a period of 116 years. But on the time scale of orbital evolution, 116 years is just the blink of an eye. What's next for the Jovian moons? It's hard to tell, because the evolution the researchers found is not sustainable. Since Io's orbital period is shortening while Europa's and Ganymede's are lengthening, the moons are evolving out of their Laplace resonance. Once the resonance is broken, Io's orbit will lose its eccentricity, so the tidal bulge in Io will no longer grow and shrink and will no longer be susceptible to torque from Jupiter. That means no more spiraling inward and, most likely, no more volcanism. The present results don't offer any predictions, though, about how soon the resonance will be effectively broken, how much Io's orbital energy will ultimately decrease, or what will happen once it starts increasing again.

"Moving out of resonance and Io's inward spiraling are both expressions of an evolution that cannot persist," says David Stevenson of Caltech. "That's the story of greatest interest, I think. It's also the part we understand least well."

Johanna Miller

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2. Ref. 1, table 1.
3. Ref. 1, figure 2.

Chaotic semiconductor lasers generate random numbers at high speed

Two groups have harnessed subnanosecond intensity fluctuations to produce unpredictable binary sequences.

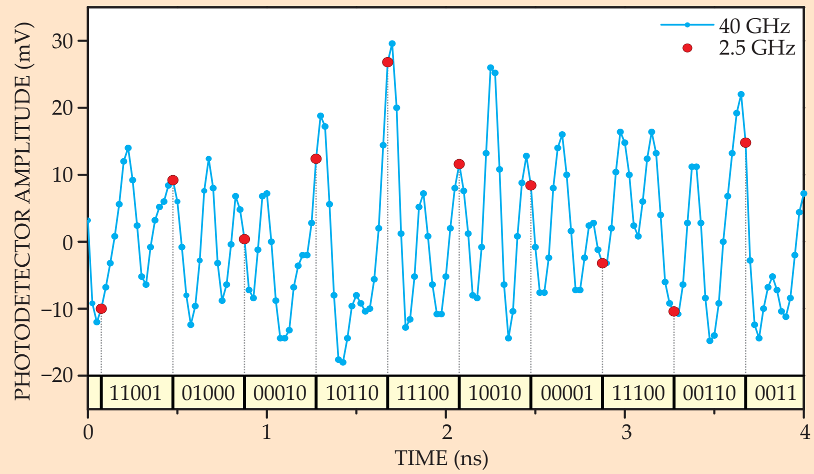
The familiar "random number generators" used in computers and calculators are actually based on the outputs of deterministic algorithms. So although the sequences they generate may pass established statistical tests of randomness, they're not entirely unpredictable, because an attacker could guess the algorithm itself. That's not a problem for some applications, such as Monte Carlo simulations or randomized music playlists. But others, such as online gaming or secure communications, benefit from sequences that are truly unguessable, such as can be generated from measurements of a stochastic physical process. A simple example of such a process is the roll of a die. More sophisticated possibilities, and ones that can generate sequences more quickly and be automated more easily, involve quantum or thermal noise.

As computing and communications speeds increase, there is a growing need for faster methods of generating random sequences. Last year Atsushi Uchida, now of Saitama University in Japan, and his colleagues developed a method,[1] based on the digitized outputs of two chaotic semiconductor lasers, for producing random binary sequences at a rate of 1.7 billion bits per second—much faster than any previously developed method based on a physical process. Now, Ido Kanter, Michael Rosenbluh, and their students Igor

Reidler and Yaara Aviad at Bar-Ilan University in Ramat-Gan, Israel, have found a way, using only one laser, to produce up to 12.5 billion random bits per second.[2]

Laser chaos

Semiconductor diode lasers—indeed, all lasers—exhibit small intensity fluctuations that are thought to be quantum in origin. When a certain fraction of a semiconductor laser's output is fed back into the laser, those fluctuations are amplified, and the laser's intensity exhibits large, irregular oscillations at subnanosecond time scales, as shown in the figure. Measuring and digitizing that intensity could provide a source of random numbers, but for the fact that the laser oscillations very nearly repeat themselves with a period equal to the feedback time. If the laser light traverses a delay line a few meters long before being reinjected into the laser, as is typical, the feedback time is a few tens of nanoseconds. Choosing the period between measurements to be incommensurate with (that is, not a rational fraction of) the feedback time is not enough to solve the problem: After only a few multiples of the feedback time, the measurements come close enough to sampling the same part of the oscillation cycle that they strongly correlate with the measurements made during the first cycle.



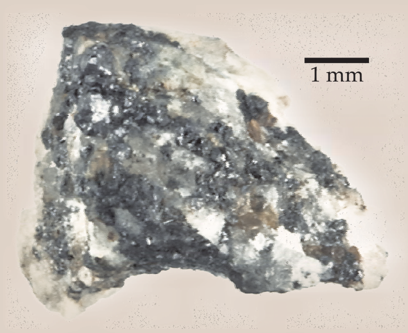
The chaotic output of a semiconductor laser sampled at 40 GHz (blue dots). Researchers from Bar-Ilan University in Israel use the output of one such laser to generate a random binary sequence by digitizing measurements taken at 2.5 GHz (red dots) into eight-bit numbers, taking the differences between consecutive measurements, and retaining from each difference the five least significant bits, shown at the bottom of the figure. (Adapted from ref. 2.)

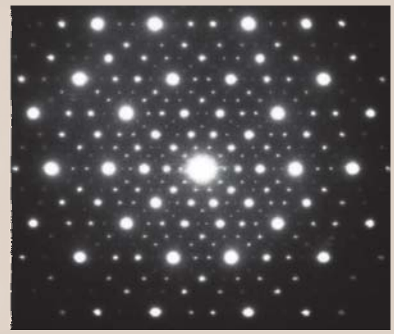
Uchida and colleagues solved that problem by using two single-mode distributed-feedback semiconductor lasers with feedback times incommensurate with each other and with the sampling time. To generate one bit in their sequence, they measured the intensity of both lasers, digitized each using one-bit analog-to-digital converters (so an intensity above a threshold value becomes a "1" bit, and a lower intensity becomes a "0"), and then performed an XOR operation on those two bits.

Natural quasicrystal found in a museum specimen

The hallmark of a conventional crystal such as table salt is translational symmetry; a single unit cell repeats at regular intervals. That defining symmetry imposes long-range correlations, but it also greatly restricts the rotational symmetry that crystals can exhibit. Celebrated theorems nearly 200 years old permit only two-, three-, four-, and sixfold symmetry axes.

Quasicrystals do not have the translational symmetry of crystals, but they do have a subtle long-range order. Along any symmetry axis of a quasicrystal, the placement of atoms can be expressed as a sum of two or more periodic functions. But the wavelength ratio for any two of those functions is irrational, and as a result, no single periodic function can represent the atomic positions. The atoms' quasiperiodicity—indeed, "quasicrystal" is short for quasiperiodic crystal—implies long-range correlations and, as with conventional crystals, allows quasicrystals to display sharp, structure-revealing diffraction patterns. The freedom from translational invariance enables quasicrystals to have a wealth of rotational structures not allowed in crystals; the first quasicrystal to be discovered, for example, displayed fivefold symmetry axes (see reference 1 and PHYSICS TODAY, February 1985, page 17).





To date, more than 100 quasicrystal specimens have been synthesized in the laboratory. Now Luca Bindi of the Natural History Museum of Florence in Italy, Princeton University's Paul Steinhardt, and colleagues from Princeton and Harvard universities have reported the first observation of a natural version of one of those quasicrystals[2]—icosahedral $Al_{63}Cu_{24}Fe_{13}$. The material, a 100-μm grain, is from a mineral assemblage (left figure) now housed in the Florence museum, where it is listed as coming from the Koryak region of far-eastern Russia. The main component in the assemblage is khatyrkite ($CuAl_2$), but the sample also includes cupalite (CuAl) and other minerals.

The search that led to the natural quasicrystal began about 10 years ago. By that time the International Centre for Diffraction Data (ICDD) had published a catalog of 80 000 x-ray powder diffraction patterns obtained from both synthetic materials and minerals. Because the smashed-up crystals of a powder have random orientations, the sharp diffraction spots that one would obtain with a pure crystal or quasicrystal are smeared into circles. Nonetheless, one might hope that the spacing of the circles would reveal the underlying symmetry of the powdered material. Could the ICDD database be systematically explored and possible quasicrystal candidates identified?

That was the challenge Steinhardt posed a decade ago to Peter J. Lu, then his undergraduate thesis student. Lu rose to the task, and in 2001 he, Steinhardt, and two other Princeton colleagues announced the results of their systematic search through the ICDD catalog, including a list of quasicrystal candidates that merited further study.[3] At the end of the paper, Lu and Steinhardt invited anyone with a plausible quasicrystal candidate to get in touch with them for possible collaboration. Two years ago Bindi took them up on their offer: After a painstaking search through numerous minerals and consultations with his US-based colleagues, he identified the Florence museum's khatyrkite sample as possibly hosting a quasicrystal. The US team then probed a small piece of it with transmission electron microscopy. Diffraction patterns such as the 10-fold symmetric pattern shown in the right figure identified quasicrystal regions. Subsequent x-ray fluorescence analysis of pure quasicrystal grains determined the material's chemical formula.

Geologists and physicists have much to learn about the conditions under which quasicrystals form. The study of natural materials can help address that question and may turn up new, never previously contemplated structures. **Steven K. Blau**

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The rate at which they could generate random bits was limited not by any aspect of their procedure but by the characteristic time scale of the chaotic laser intensity oscillations. They found that at sampling rates up to 1.7 GHz, their method generated sequences in real time that passed statistical tests for randomness. Small drifts in the lasers' average intensities, however, could throw off the sequence's balance of ones and zeroes, so the lasers needed to be kept carefully tuned.

Significant discard

The Bar-Ilan researchers sample the intensity of a single, inexpensive, edge-emitting diode laser—again, with a sampling time incommensurate with the laser feedback time—digitize the measurements using an eight-bit analog-to-digital converter, and compute the differences between pairs of successive measurements. For each difference, an eight-bit binary number, they discard the three most significant bits and keep only the five least significant.

Their method avoids the problem of sensitivity to intensity drifts: Even if the distribution of intensity measurements is skewed to one side or the other, the differences between measurements must be symmetrically distributed—what goes up must come down. Using only the least significant bits of each difference measurement allows them to avoid any measurable correlation between measurements made during different repetitions of the oscillation cycle. It also allows them to make measurements slightly more frequently, up to 2.5 GHz. Since each new measurement adds five bits to their sequence, they can generate up to 12.5 billion random bits per second.

Johanna Miller

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