it may seem, cryptographers crave such problems because hard problems can be used to create difficult-to-break encryption.

In some cases, Alice may need to recover, say, the 217th bit of the message Bob intended without having to read all of the message she received. For this we turn to "locally decodable" codes and, specifically, to a remarkable recent result of Yekhanin (*6*): Bob's message can be encoded so that, should a small enough fraction of its symbols die in transit, Alice would still be able, with high probability, to recover the original bit anywhere in the message she chooses. The surprise: She can do it by picking at random a mere three bits of the received message and combining them the right way.

The randomness of the three single-bit lookups makes locally decodable codes ideally suited for private information retrieval. The concept was introduced by Chor *et al.* (*7*) to allow users of a database to make queries without divulging what they are. Yekhanin's scheme would keep the anonymity of a query by breaking it down into three subqueries and passing on each one to a separate copy of the database. Individually, each subquery would look random and therefore unrelated to the parent query.

Computing theorists have been borrowing from coding theory for decades. Recently they have begun to return the favor. This symbiotic relationship, it is safe to predict, is far from having run its course. The quest for a practical solution to private information retrieval is still wide open. How to turn the beautiful mathematics of local decoding into working privacy tools is one of the main challenges ahead.

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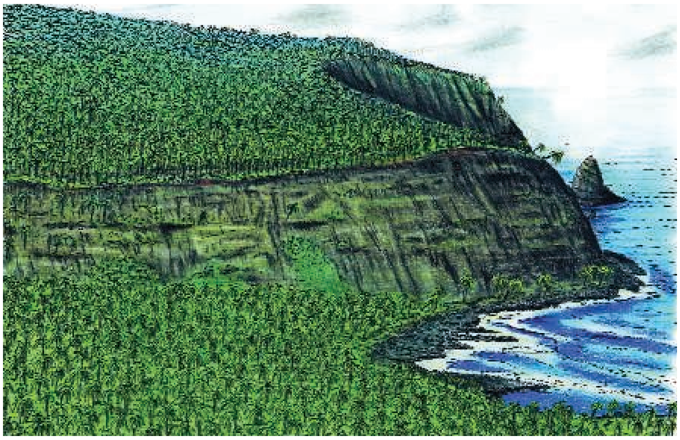
ARCHAEOLOGY

Easter Island Revisited

Jared Diamond

New information about Easter Island is helping to identify the cause of the massive deforestation that occurred prior to European arrival, but unanswered questions remain.



Before human arrival. In this artist's view, the Poike Peninsula is covered with a forest dominated by a giant palm tree, now extinct.

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Easter Island is famous for many reasons: its remoteness, its total deforestation, its hundreds of giant stone statues, their destruction by the carvers' own descendants, the violent transformation of its Polynesian society, and as a metaphor for our world today (*1*). New information about these themes has recently been flooding in from on-going projects.

When first seen by Europeans in the 1700s, Easter was almost unique among tropical Pacific islands in lacking trees over 3 m tall. But pollen in swamp cores revealed the former existence of a giant palm similar to the world's largest living palm, the Chilean wine palm (see the first figure). By identifying 78,000 bits of burned wood from raidocarbon-dated ovens and middens, Orliac and Orliac (*2*) recognized more than 20 other tree and woody plant species exterminated during human settlement. The palm was mostly gone by A.D. 1450, and the other large trees by A.D. 1650, after which the islanders had to burn grasses and sedges instead of wood for fuel.

The end of the forest brought other huge losses for islanders. The palm had yielded food (more than 400 liters of sap per tree per year, plus nuts and palm hearts) and material for baskets, sails, thatching, and mats (*3*). Other vanished tree species had yielded edible fruits, fiber for rope, bark cloth, and wood for canoes, levers, and carvings (*2*).

Deforestation also forced changes in horticultural practices (*3–6*). Easter's early farmers planted crops between the palms, which provided fertilizer, shade, and protection for the soil. In that first phase, erosion was negligible, and horticulture was sustainable (*3*). Around A.D. 1280, the islanders began felling the palms, removing the trunks (presumably for timber), and burning the debris, as shown by a radiocarbon-dated charcoal layer, burned roots and palm nuts, and burned palm stumps chopped off near the ground, but no large pieces of trunk wood at these sites (*3*). The loss of the palm canopy exposed soil to heating, drying, wind, and rain. The resulting sheet erosion proceeded uphill at 3 m/year, removing fertile topsoil and burying down-slope settlements and gardens (*3*). Palm burning and sheet erosion have been studied especially at Poike but also appear elsewhere until A.D. 1520.

Faced with lower crop yields as a result of deforestation, the islanders responded around A.D. 1400 by occupying the formerly little-used uplands, and by introducing the remarkable labor-intensive gardening method of "stone mulching" on a vast scale (*3–6*). That meant covering half of the island with more than a billion stones averaging 2 kg in weight (*6*). In experiments, stone mulching decreases soil water evaporation, protects against wind and rain erosion, and reduces daily temperature fluctuations (*7*). Pulverized stones may also raise soil fertility by slowly releasing nutrients (*8*). That function would have been valuable, because nutrient levels (especially phosphorus) often limit tropical

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plant growth. Phosphorus levels in most Easter soils are low today, and the islanders' extermination of former seabird colonies eliminated phosphorus input in guano (*9*).

Van Tilburg and Arévalo have inventoried the more than 900 statues on Easter Island (*10*). They have also mapped the interior of Rano Raraku crater, from whose stone most statues were carved. The carving areas define 19 distinct quarries, grouped into a western and an eastern set of quarries. The crater's western half produced statues resembling those on platforms (ahu) in the island's western part, whose clans had higher social status, and where ahu occur earlier. The crater's less accessible eastern half produced bigger statues resembling those on the late eastern Ahu Tongariki, with 15 huge statues of up to 90 tons. This contrast suggests that easterners challenged westerners for status and supremacy by erecting larger statues (see the second figure) (*11*).

See podcast online at www.sciencemag.org/multimedia/podcast/#20070921

Vargas *et al.* (*12*) recognized archaeological style changes toward the 1600s as wood became scarce. There was a proliferation of more than 1000 stone buildings 2 m in height, described in oral tradition as chicken houses; Vargas *et al.* indeed found chicken bones, feathers, eggshells, and guano in many of them. Human houses became smaller and were built with less wood. Earth ovens became stone-lined for efficiency when firewood was scarce. Oral traditions describe caves as refuges during the late period of chronic fighting; that tradition was confirmed by features indicating prolonged occupation of a defensible site. The caves were closed by massive stone walls, accessible through a narrow entrance, and provided with food and utensils.

Thus, major changes unfolded on Easter Island before European arrival. Those changes included deforestation; the loss of palm sap as a food and water source; switching from wood to grasses and sedges as fuel; establishing stone mulching; ceasing to carve statues, because deforestation meant no more big logs and fiber rope for transport; abandoning upland plantations, probably used to feed workers transporting statues; and (as described in oral traditions) increases in warfare, statue destruction by rival clans, and use of refuge caves. However, alternative views have been proposed.

One view is a version of Rousseau's noble savage myth: the claim that bad things began happening on Easter only after European arrival (*13*–*15*). Undoubtedly, Europeans on Easter, as elsewhere in the Pacific, did serious harm through slave raids, worsened erosion, and introduced diseases, grazing animals, and plants. But this view ignores or dismisses the abundant evidence, summarized above, for pre-European impacts.

Another view recognizes pre-European deforestation but blames it on hypothesized droughts (*2*). However, there is no direct information about climate change on Easter between A.D. 1000 and 1700. Easter's forests had already survived tens of thousands of years of climate fluctuations (*1*), and it seems unlikely that a drought in the 1600s (if there was one) destroyed the forests just coincidently soon after human arrival.

According to a third view, deforestation was caused by introduced rats, as suggested by rat gnaw marks on many nuts of the extinct palm (*15*). This hypothesis does not account for all those palm stumps cut off at the ground and burned, nor for the larger number of palm nuts burned rather than gnawed, nor for the disappearance of the long-lived palm trees themselves (with an estimated life span of up to 2000 years) (*16*). If rats were responsible, they were unusual ones, equipped with fire and hatchets. Thousands of other Pacific islands overrun by introduced rats were not deforested, and many other tree species that survived on other rat-infested islands disappeared on Easter (*16*).

Instead, Easter's deforestation can be understood in terms of its environmental fragility. Throughout the Pacific, islanders brought rats and felled and burned trees. The resulting pre-European deforestation ranged from negligible on some islands to complete on Easter. Among 81 islands analyzed, this variation in deforestation parallels measured variation in nine environmental parameters that determine tree growth rates: The more slowly trees grow back, the more extensive was deforestation (*17*). All parameters were stacked against Easter: It is relatively cold, dry, low, small, and isolated, with negligible nutrient inputs from atmospheric dust and volcanic ash, relatively old leached soils, and no uplifted-reef terrain. Thus, Easter became deforested not because its inhabitants were uniquely improvident, nor because its European visitors were uniquely evil, but because Easter Islanders had the misfortune to inhabit one of the Pacific's most fragile environments.

Much remains to understand about Easter. Here are my six favorite unsolved questions.

First, was Easter's mysterious rongorongo writing invented after or before the arrival of Europeans? If the latter were true, Easter would have been by far the world's smallest society to invent writing independently. Orliac's recent ^{14}C-dating of one surviving rongorongo object is a tantalizing first step toward an answer (*18*).

Second, did Easter Islanders live in isolation from other humans from the time of colonization until European arrival, or did further Polynesian settlers arrive? For instance, was the sweet potato brought by the first settlers, or only later (*19*)?

No mean feat. Van Tilburg and Ralston (*11*) enlisted modern islanders to drag a 9-ton statue over a distance of 10 km, using methods described in oral traditions. The task required 70 adults pulling in unison, supported and fed by their families numbering about 400 people. By extrapolation, Ahu Tongariki's big statues required a population of thousands in the eastern chiefdoms alone.

CREDIT: EASTER ISLAND STATUE PROJECT

Third, when, within the period from A.D. 800 to 1200, did the first settlers arrive (*12*, *16*, *20*)? This question is unlikely to be solved by finding and dating the first settlement site itself, which would be like seeking a needle in a haystack. Instead, the answer will come from dating widespread impacts left by the first settlers, such as burned charcoal (*16*) and annual sediment layers (*21*) in swamp cores, appearance of rat bones, and declines in numbers of bones of native birds killed by settlers (*9*).

Fourth, along what time course did Easter's human population rise and fall, and what was the peak population? Vargas *et al.* have reported an initial analysis based on hundreds of dated archaeological sites (*12*).

Fifth, was each of Rano Raraku's 19 quarries owned by a different one of the dozen or more territorial clans described in Easter oral traditions (*10*)?

Finally, stone itself cannot be radiocarbon-dated. By what other method can we date the statues and ahu, recognize stylistic changes with time, and specify (independently of the oral tradition suggesting around A.D. 1680) when the last statue was carved?

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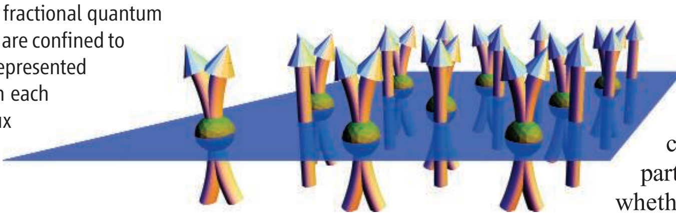
PHYSICS

Electrons Acquire a Split Personality in Bismuth

Unusual collective quantum states seen only in two-dimensional layers of electrons may have now been observed in a three-dimensional metal.

Andrew Huxley and Andrew G. Green

When many identical particles such as electrons interact with each other, new and unusual quantum states can emerge. Given that a single cubic centimeter of condensed matter may contain as many as 10^{23} electrons, however, one cannot hope to identify from theory all the states that may form. Guidance from experiment is crucial. For example, fractional quantum Hall states, which occur when electrons interact and regroup to create new "quantum particles" with noninteger electrical charge, were identified only after the experimental observation of strange features in the electrical conductance of a two-dimensional (2D) sample. On page 1729 of this issue, Behnia *et al.* report measurements revealing signatures similar to those associated with fractional quantum Hall states, but in 3D crystals of bismuth (*1*). Because 2D confinement of the electrons is fundamental to the accepted understanding of fractional quantum Hall states, this presents a new challenge: to understand how the observed behavior can occur in a 3D host.



Fractional states. In this schematic picture of a fractional quantum Hall state, the electrons (represented by spheres) are confined to move on a 2D surface traversed by flux tubes (represented by arrows). A pair of flux tubes is associated with each electron to form a composite object. A third flux tube per electron remains unbound. This causes the composite objects to move in quantum orbits, completely filling one orbit level.

Magnetic fields are the key. An applied magnetic field causes electrons to move in quantum orbits that are organized in levels somewhat similar to the energy levels in an atom. In this case, the number of orbits in each level is proportional to the strength of the magnetic field, and in 2D materials the levels have distinct energies. Physical properties such as electrical conductance show oscillations as the magnetic field increases, reflecting successive changes in the number of levels needed to accommodate the electrons. Impurities can provide a reservoir of electrons, preserving the complete filling of a level over a range of fields. This changes the oscillations into steps, and such steps are seen in the so-called integer quantum Hall effect. Above a certain field, the quantum limit is reached where the lowest-energy level can accommodate all of the electrons. Gathering all the electrons together in this way provides perfect conditions for the formation of new collective states.

Tsui *et al.* (*2*) observed plateaus in the Hall resistance corresponding to fractional electron filling of the lowest-energy orbits, evidence that new states form when the field is increased above the quantum limit in 2D electron gases. In other words, these states behave as though they are composed of particles possessing fractions of the charge of an electron. Laughlin (*3*) subsequently proposed a wave function that could account for the plateaus.

One way to visualize Laughlin's wave function is to consider the magnetic field to be composed of flux tubes with each electron attached to a specific number of flux tubes to form a composite object (see the figure). The objects behave as fermions or bosons (the two categories into which all quantum particles must fall), depending upon whether they are made with even or odd numbers of flux tubes (*4*). In the standard fractional quantum Hall state, an even number of flux tubes are bound to each electron so that the composite objects behave like fermions. The composite fermions orbit around remaining unattached flux tubes, giving rise to plateaus of the Hall resistance as with the integer quantum Hall effect. The plateaus occur for fractional fillings of the lowest electron orbit type because the unbound flux tubes correspond to only a fraction of the total magnetic flux.

In 3D materials, such as bismuth, each orbit spans a range of electron energies owing to the motion of the electrons along the third direction. This means that the quantum Hall effect does not occur, but as the magnetic field is increased, physical properties still undergo small oscillations known as quantum oscilla-

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