Life with the artificial Anasazi

Jared M. Diamond

How can the complex dynamics of human societies — such as population rise and fall, and movement — be explained? Combining masses of data with computer modelling is a fresh way forward.

Many complex systems exhibit properties that cannot be predicted by verbal reasoning, or even pure mathematics, from the behaviour of their components. Human society is no exception. Take, for example, the fact that "a traffic jam, which results from the behavior of and interactions between individual vehicle drivers, may be moving in the direction opposite that of the cars that cause it" (page 7280 of ref. 1). A promising approach to this general problem is 'agent-based modelling', which populates specified spatial landscapes with agents that assess the landscape and behave according to a set of decision rules[1,2]. Computer calculations reconstruct, step by step, the trajectory of the model, and compare it with real history to test the accuracy of the input information and the model's assumptions.

Two papers[3,4] have set new standards in archaeological research by applying this approach to a historical problem: the rise and fall of the Anasazi civilization of Native Americans in the southwestern United States. The authors have combined quantitative information on environmental fluctuations with rules of behaviour expected for Anasazi households, to calculate an Anasazi historical 'trajectory' in unprecedented detail. As with any good modelling program, two erroneous predictions of a first-generation model helped to identify missing factors that were then incorporated into improved models.

Until its disappearance around AD 1350, Anasazi society was marked by fluctuations in total population size, mean settlement size and preferred habitat. But why? It is generally agreed that the answers depend partly on rainfall and on groundwater levels, variations in either of which would affect Anasazi maize-based agriculture. Proxy measures of both of these variables are available for a group called the Kayenta Anasazi of Long House Valley in northeastern Arizona (Fig. 1), together with archaeological surveys of the numbers and distribution of houses for the entire span of the valley's Anasazi occupation. But how can one assess whether the proxies can explain the survey results? To give just one hint of the complexities involved: readily available groundwater can make rainfall unnecessary for maize agriculture, but the dependence of maize growth on rainfall and groundwater levels varies among

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Figure 1 **Home for the Kayenta Anasazi. This view of Long House Valley, northeastern Arizona, shows the fertile valley floor flanked by unfarmable upland zones.**

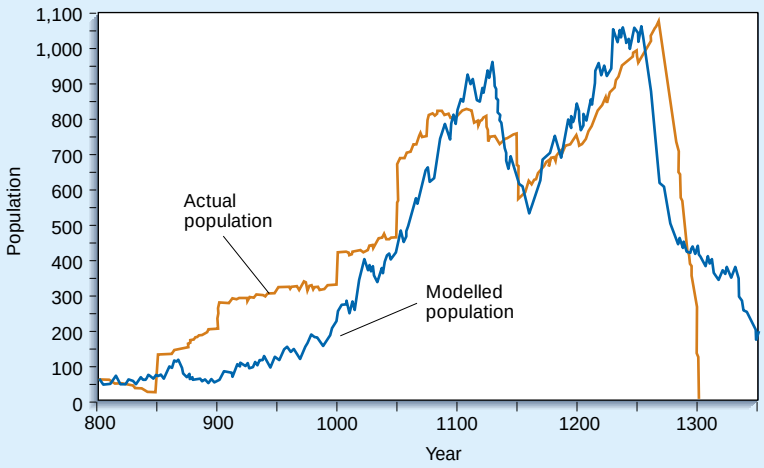

Figure 2 **Ups and downs of the Anasazi in Long House Valley. Shown here are actual (orange) and modelled (blue) numbers of the valley's population from AD 800 to AD 1350. Actual population is based on the number of house sites at a given time, assuming five people per house. The fluctuations in the modelled population reproduce those of the actual population fairly well. The main discrepancy is that the Anasazi completely abandoned the valley by 1300, at a time when the model predicts that it could still have supported a substantial population. (From Fig. 2 of ref. 4.)**

100 YEARS AGO

At the festivities held in Bologna on the occasion of Mr. Marconi's return to his native town, Prof. Augusto Righi, in congratulating his former pupil in his successes, spoke to the following effect:—Perhaps no one can appreciate better than I his exceptional inventive power and his unusual intellectual gifts. I remember with great pleasure his visits when quite a young man, for asking my advice, for explaining his experiments, made with simple apparatus ingeniously put together, and for keeping me informed of his new projects, in which his passion for applied science always stood out. Even then I predicted that he would sooner or later attain fame. The system of wireless telegraphy which he derived from Hertz's classical experiments … is the most pleasing transference to the field of practical industry of those instruments and principles which might have seemed to be relegated to the domain of natural philosophy. ... It is to the credit of Marconi that he has once more proved how much those are in error who regard with disdainful or indifferent eyes the work carried on continuously in the silence of the laboratory by the modest and disinterested scientific students, and who only appreciate science in proportion to the immediate uses that can be obtained from it.
From *Nature* 9 October 1902.

50 YEARS AGO

***Philosophic Problems of Nuclear Science*.**
One summer evening in 1925, a small and very select meeting of theoretical physicists took place in one of the Fellows' rooms in Trinity College, Cambridge. It was a special occasion. ... A brilliant young mathematical physicist, fresh from Munich, Göttingen and Copenhagen, was about to expound his work in the field of atomic physics to a handful of people capable of appreciating it. The speaker was ... Werner Heisenberg, before long to become a celebrity for his 'uncertainty principle'. Subsequent events have added not only to his distinction but also to the debt which philosophers and scholars everywhere owe him for the profundity of his thought, and for the elegance of his expression. The present book does something to bring these things home to English-speaking readers. 'Something' is probably fair comment, for here is a collection of lectures, originally in German, translated with obvious sincerity but not always with complete idiomatic success.
From *Nature* 11 October 1952.

the valley's six habitats used for agriculture.

The first-generation model (by Dean *et al.*[3]) had three steps. First, the width of annual tree rings depends on that year's climate, especially rainfall and temperature. Tree rings provide a climate record for Long House Valley extending from the present back to AD 200, with no gaps. To convert tree rings into maize yields, the authors used an empirical relation, observed over the last century, between tree-ring width and a climate measure (the Palmer Drought Severity Index, PDSI)[5] much used by agricultural scientists to calculate crop yields. The modern relation between maize production and PDSI is known for 55 different soils in southwestern Colorado, and one of the 55 closely matches the soil of one of the six Long House Valley agricultural habitats (Long House Valley General Valley floor soil). By converting tree-ring width to PDSI, and then PDSI to maize yield, Dean *et al.* calculated rainfall-dependent maize production, in kilograms per hectare, for that one soil for each year from AD 800 to AD 1350.

The next step involved the reconstruction of past rises and falls of groundwater from flood-plain stratigraphy: rising groundwater is associated with sediment deposition when the flood plain is well vegetated and stable; falling groundwater is associated with instability and erosion, which produces gulleys called arroyos. Soil stratigraphic units, and thus groundwater trends, can be dated to within a few decades by the styles of Anasazi pottery, radiocarbon-dated materials and germination dates of trees buried in each unit. It is known roughly how the combined effect of rainfall and groundwater on maize yields differs among the valley's six habitats. So Dean *et al.* took the time sequence of mean maize yields calculated in step 1 for General Valley floor soil, modified it to estimate the time sequence of yields for the other five habitats, and incorporated random spatial and temporal variations in yields around those mean values.

The last of the three steps in the first-generation model was to construct an 'artificial Anasazi' history by computer. This involved dropping a few virtual Anasazi farmers into the valley at AD 800; feeding them each year with the calculated maize crop; and letting them bear and feed children, grow old, move house sites, and send off grown children to build new houses, according to rules observed for recent maize-growing societies of Pueblo Indians descended from the Anasazi. Examples of these rules are that annual maize consumption per person is 160 kg, that surplus maize can be stored for up to two years, and that children marry and move out at age 16. The iteration was carried out for each year in turn, depending on the calculated maize crop.

The result is one estimation of the valley's total population, and the spatial distribution of its house sites. Dean *et al.* did many such simulations for each year. They turned out to differ in detail (because of the built-in stochastic variation in local maize yields) but were broadly similar. The simulations were then averaged and compared with the actual Anasazi population and its spatial distribution, as deduced from an archaeological survey of house sites (dated by their pottery styles) over the whole of the valley.

The first-generation 'artificial Anasazi' society and the actual Anasazi society compared well in several respects: population rise and fall, population shifts among the six habitats, and alternations between a few large settlements and many scattered houses. But there were two exceptions.

First, the simulated population was about six times the actual population. A likely explanation for this failure lies in previous experience with agent-based modelling, which suggested the model's deterministic demography as the flaw — for instance, that every woman became a mother at precisely age 16, and every household lasted for 30 years. When stochastic variation around those mean values was introduced, the resulting second-generation model[4] accurately reproduced the population size as well as its trajectory with time (Fig. 2). For example, the population peak around AD 1250 was 1,070 people actual, 1,040 simulated. Overall, putting Fig. 2 into words, the population first rose in an initially underused landscape, then remained flat between about AD 900 and 1000 because of groundwater limitation; it rose from 1000 to 1130 and again from 1180 to 1270 because of high groundwater and high or at least constant rainfall; and it crashed from 1130 to 1180, and again after 1275 because of a coincidence of drought with falling groundwater.

The other model failure comes after AD 1275, when the coincidental water shortages induced the actual Anasazi to abandon Long House Valley completely. Where did they go? Many people may have died of starvation. But others moved south to the Hopi pueblos and other climatically less-stressed areas, as shown by population surges and the appearance of Long-House-Valley-like ceramics and sites there. But the model suggests that valley maize yields after AD 1275 could still have fed 400 people, almost half of the peak population earlier in that century. For the first two centuries of their occupation of the valley, the Anasazi were content to live there at a population of under 400. Why did everybody leave the valley after AD 1275, when it seems that half of them could have continued to feed themselves?

When the Anasazi abandoned their settlements, the survivors were evidently motivated by something not considered in the model. One possibility[4] is that complex human societies require a certain population size to maintain institutions that its

citizens consider to be essential. How many people would choose to remain in London if half of their family and friends had just starved to death there, and if the tube, pubs and churches were no longer open? Another possibility is that although the environments of both AD 1275 and 1050 could feed 400 people according to the model, they differed in ways not taken into account by the model. For instance, perhaps the forests still growing near the valley in 1050 had been felled by 1275, leaving no nearby timber for buildings and fire, or perhaps soil fertility became exhausted.

One overall message of this project lies in the saying, "God is in the details". Without all those data on rainfall, groundwater, soil types, crop yields and household behaviour, verbal claims such as "The Anasazi abandoned their homeland because of drought" are as likely to be wrong as right. Another message (even to a computer-phobe like me) is that the trajectories of human societies are so complex that computer modelling is essential for evaluating the consequences of the data. Finally, models involving many input parameters provoke much scepticism. But here the input parameters are measured ones, and the model is really nothing more than a calculation of the consequences of those input parameters, given certain assumptions.

Experience with the 'artificial Anasazi' shows that confronting a computer model with reality yields conclusions about the questions that interest any archaeologist: why populations increased, why people moved, why their settlements varied in size, and why their society finally disappeared. This study should inspire archaeologists to gather the masses of data required to test their own verbal claims about human societies in other times and places. ■

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Superconductivity

Putting the squeeze on lithium

N. W. Ashcroft

At low temperature, some elements are superconductors under normal pressure. Others become superconducting if the pressure is raised. Lithium is the latest low-temperature, high-pressure superconductor.

The report by Shimizu *et al.*[1] (page 597 of this issue) of superconductivity in lithium, a light metal in group I of the periodic table, is noteworthy for being at odds with an old historical imperative in superconductivity. This remarkable phenomenon was discovered in 1911, and over the following 40 years a considerable database of superconductors was amassed that included both elements and compounds. Its scope was sufficient to invite a search for signs of systematics, and in 1955 Bernd Matthias[2] summarized the situation with a plot of the superconductors' transition — or superconducting — temperature as a function of the average number of valence electrons. One of its more dispiriting features was the apparently resolute exclusion of the putatively 'simple' metals of valence 1.

The half-century since then has seen a veritable avalanche of new superconductors identified, including the extraordinary but still somewhat mystifying class of high-temperature cuprate superconductors, and it became clear that attempts to find systematic effects would require far more searching assessments than that of Matthias. Nevertheless, suspicions that valence-1 elements would not be part of the unfolding story of superconductivity seem to have lingered on.

This past half-century has produced another significant development, namely the relentless drive to subject elements and compounds to ever-increasing static compression, in some cases approaching an order of magnitude above normal densities. Among other achievements, these pressures have succeeded in turning non-superconductors (and even non-conductors) into superconductors. The success of Shimizu *et al.*[1] now brings the tally of pressure-induced superconducting elements to 23 (Fig. 1). This is a very considerable achievement considering that at ordinary pressures the number is just 29.

The changes wrought by pressure are often striking. To make the point, if conditions of one million atmospheres or so were normal on Earth, some characteristic features of the periodic table would look very different from the present one-atmosphere construct. In particular, sulphur, in group VI, would be a metal, and it would also be an exceptional elemental superconductor, with a transition temperature reaching 17 K (ref. 3). Once again this is a case of historic note, for valence-6 elements were also excluded in Matthias's early one-atmosphere systematization.

So now we have the important diamond-cell experiment on compressed lithium, a group-I element, which Shimizu and colleagues[1] find to be superconducting. At pressures as high as 48 gigapascals (roughly 480,000 atmospheres), the transition temperature rises to 20 K. Notable though it is, the discovery is not entirely unheralded, because in 1986, with a quite different apparatus, Lin and Dunn[4] reported resistance changes in lithium at high pressures and low temperatures, and in interpreting their results they did not rule out the onset of a superconducting state.

Lin and Dunn apparently had no easy way

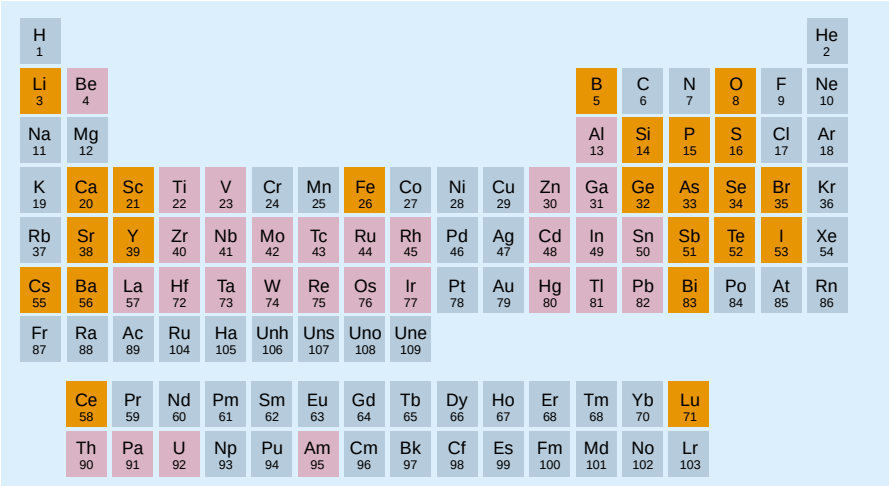

Figure 1 **Superconductors under pressure. The colour code of this periodic table (adapted from ref. 13) shows elements that superconduct under normal, atmospheric pressure conditions (purple) and those that superconduct when subjected to high pressure (orange). Shimizu *et al.*[1] confirm the superconductivity of lithium at high pressure, bringing the number of such elements to 23. Under normal pressure conditions, 29 elements are superconductors.**