A game of chance

Mark Buchanan

When someone makes a 'prediction', he or she usually contends that a specific event will take place at some point in the future: it will rain tomorrow morning; an earthquake will shake the San Francisco area next Thursday. This is 'prediction' as we usually define it. But in modern science, the idea of prediction has evolved subtler interpretations, and the concept continues to develop today, as scientists grapple with phenomena of ever-greater complexity.

By 700 BC, the Babylonians had developed skill in predicting lunar eclipses; they understood their world better and feared it less, presumably, than earlier peoples did. Over the ensuing 2,500 years, science honed its ability to make accurate predictions, with Galileo, Kepler and finally Newton bringing the world's mechanistic predictability to centre stage. In the newtonian Universe, as Pierre-Simon Laplace pointed out, a being of sufficient intelligence could predict the future in detail by knowing the positions and velocities of all particles at any moment.

Today, we casually use the term 'prediction' in a slightly more general sense. One might predict that a new material will be superconducting below 40 K, or that a mouse that lacks a certain gene will show a particular trait. Such predictions always precede their experimental test, yet aim less to foretell the future than to explore scientific understanding. Prediction in this sense is the engine of science: we design the present (the experiment) and observe the future (the result) so as to compare our theories to empirical reality.

A more interesting twist to the idea arises when forecasting in the newtonian sense is impossible. No one can solve the equations of motion for the 10^{24} particles in a bucket of water, nor would such a solution be useful. For this reason, Boltzmann, Maxwell and other physicists of the nineteenth century executed a strategic retreat to 'prediction' in a weaker sense. One can predict the statistical distribution of molecular velocities in the bucket. Foregoing exact knowledge, statistical mechanics also predicts the likelihood of the 10^{24} molecules being in any particular microscopic state. Strikingly, acquiescence to probabilities at this level yields definite predictions at the higher collective level — we can predict that the water will be solid below 0 °C, for example.

More recently, quantum physics has taken statistical prediction as a fundamental concept, and the idea has also entered the study of chaotic systems, for which detailed prediction is impossible over long periods. Climate scientists refrain from making precise predictions, instead exploring 'scenarios', which effectively project a probable increase in global mean temperature of 1.4–5.8 °C by the year 2100. Earth scientists similarly find it useful to communicate their knowledge to the public by predicting the probability of an earthquake in a given window of space, time and magnitude. Today we are so used to statistical predictions that it is difficult to appreciate the profundity of this retreat into probabilities.

Yet a retreat into statistics does not imply an abandonment of the search for meaningful regularities. Indeed, this search lies at the heart of recent studies of 'complex systems'. Such systems frequently involve many interacting parts that achieved their current organization through a process of evolution. We might think, for example, of a food web, or the intricate tree-like network of streams and tributaries that make up the drainage basin of a great river. In each case, accidental events — such as the chance extinction of a species — have lasting consequences for the system. As with biological evolution, one might replay the 'tape of history' many times and never twice obtain the same result, as the outcome depends on innumerable fine details that lie beyond scientific scrutiny.

Prediction

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For such systems, one might sensibly wonder whether there is anything to predict. Yet for river drainage basins, studies have identified a well-defined fractal structure — in a statistical sense, river networks exhibit a degree of self-similarity, with small portions of the network being rough copies of larger portions. All drainage basins appear to be alike in this respect, regardless of differences in geography and the many accidents of history that determined their precise structure. Moreover, this 'law-like' feature seems to emerge as the inevitable result of a dynamic process that minimizes the dissipation of energy.

Given this theoretical understanding, it is possible to predict the expected fractal character of any newly discovered basin. An erosion basin recently identified on the surface of Mars appears to validate this prediction. For complex systems, many macroscopic details may indeed be unpredictable; yet predictable statistical regularities may lie hidden behind these details. Recent work on complex networks underlines this point, illuminating deep similarities between the structure of systems as diverse as social networks, the Internet and the biochemistry of the cell.

The idea of prediction may have still further implications for the study of evolution. As the physicist Giorgio Parisi has argued, it may be that for some systems of biological interest — cells, or even large proteins — it will never be possible to predict the properties of individual systems. Science may instead retreat further, making predictions that can be confirmed only by studying the statistics of many cells or proteins, for example. Such an approach may seem to undermine the search for detailed understanding, yet freedom in interpreting the concept of 'prediction' will continue to broaden the scope and power of science. ■

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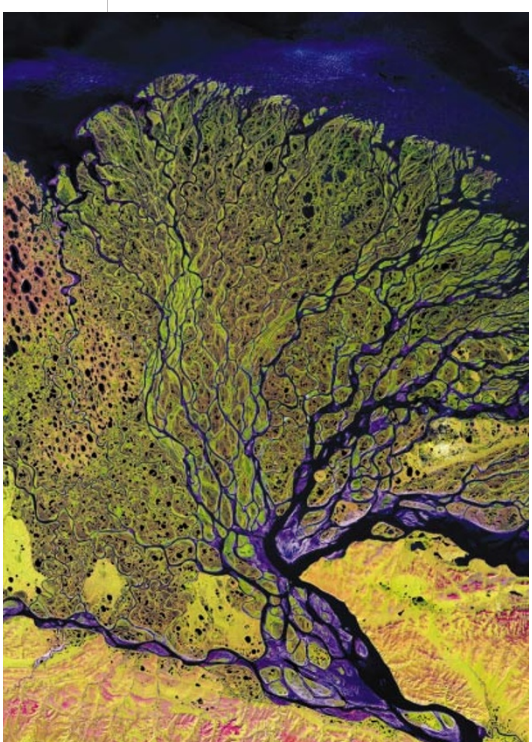

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Twisting tail: the delta of the Lena River in Russia reveals its intricate and convoluted structure.

FURTHER READING

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