influences on climate. For instance, some studies[5,6] suggest that changes in solar irradiance may have been a factor in the warming in the early part of the century. Aerosols injected into the upper atmosphere by volcanic eruptions, and changes in ozone, are also components that need to be included to reproduce some aspects of variability in the climate system[7].

This approach of adding in additional factors to reproduce the twentieth-century record has been criticized as being merely a curve-fitting exercise. However, Allen and colleagues' projected temperature change for the middle of the twenty-first century appears to be insensitive to whether or not a forcing or process is missing (such as the effect of sulphate aerosols on clouds, or of variations in solar or volcanic influences). At the least, they argue, this should be the case provided that the climate feedbacks of the missing process or forcing are close to linear for small departures from the present climate. Of course, all these conclusions fall apart if a sudden, yet highly improbable, nonlinear transition between climatic regimes occurs. Such a transition might occur, for instance, if the North Atlantic 'conveyor' were to shut down. The conveyer transports warm surface water northwards and cold deep water southwards, and has a large influence on climate.

In 1996, the United Nations Intergovernmental Panel on Climate Change (IPCC) published a report[8] in which the controversial statement "The balance of evidence suggests a discernible human influence on global climate" appeared. Many studies (for instance refs 5 and 6) have since provided strong support for this view. But policy-makers care little about the intricacies of scientific modelling and data analysis. Rather, they require future climate projections to come with quantitative uncertainty estimates. Allen *et al.* have provided a way forward to that end.

Climate-model projections, of course, are only as good as the 'scenarios' used to infer future levels of anthropogenic greenhouse gases and aerosols. The study by Allen *et al.* relies on the so-called 'business-as-usual' scenario set forth in 1992 by the IPCC[9], in which greenhouse gas concentrations grow at about 1% compounded annually, and aerosol concentrations in industrialized areas increase substantially until the middle of this century. Earlier this year, however, a series of 40 different emission scenarios were published[10], based on a variety of forecasts of socioeconomic change, energy use, population growth and technological advance. It will be impossible for modellers to undertake the necessary ensemble of integrations for the full range of scenarios, so we can expect to see only a few illustrative examples emerging in the years to come. But we can now hope to have quantitative uncertainty estimates attached to them. ■

Andrew J. Weaver is at the School of Earth and Ocean Sciences, University of Victoria, PO Box 3055, Victoria, British Columbia, V8W 3P6, Canada.
e-mail: weaver@uvic.ca
Francis W. Zwiers is at the Canadian Centre for Climate Modelling and Analysis, Meteorological Service of Canada, c/o University of Victoria, PO Box 1700, Victoria, British Columbia, V8W 2Y2, Canada.

1. Allen, M. R., Stott, P. A., Mitchell, J. F. B., Schnur, R. & Delworth, T. L. *Nature* **407,** 617–620 (2000).
2. Haywood, J. M., Stouffer, R. J., Wetherald, R. T., Manabe, S. & Ramaswamy, V. *Geophys. Res. Lett.* **24,** 1335–1338 (1997).
3. Mitchell, J. F. B., Johns, T. J., Gregory J. M. & Tett, S. B. F. *Nature* **376,** 501–504 (1995).
4. Hasselmann, K. *et al.* in *Proceedings of "Modern Dynamical Meteorology", Symposium in Honor of Aksel Wiin-Nielsen, 1995* (ed. Ditlevsen, P.) 201–221 (European Centre for Medium-range Weather Forecasts, Reading, UK, 1995).
5. Tett, S. F. B., Stott, P. A., Allen, M. R., Ingram, W. J. & Mitchell, J. F. B. *Nature* **399,** 569–572 (1999).
6. Hegerl, G. C. *et al. Clim. Dyn.* **13,** 613–634 (1997).
7. Hansen, J., Sato, M., Lacis, A. & Rueby, R. *Phil. Trans. R. Soc. Lond. B* **352,** 231–240 (1997).
8. Intergovernmental Panel on Climate Change *Climate Change 1995: The Science of Climate Change* (Cambridge Univ. Press, 1996).
9. Intergovernmental Panel on Climate Change *The Supplementary Report to the IPCC Scientific Assessment* (Cambridge Univ. Press, 1992).
10. Intergovernmental Panel on Climate Change *Special Report on Emission Scenarios* (Cambridge Univ. Press, 2000).

Cognitive science

The logic of human learning

Nick Chater

We view the world not as a continuous flux, but in terms of discrete, labelled categories, such as tables, trees and teapots. These categories are by no means arbitrary — a 'pseudo'-category consisting of an arbitrary assortment of objects starting with the letter 't' would not only be extremely difficult to learn, it would be hard to remember and to interpret in new situations. But what makes some categories 'better' than others? Why are we disposed to divide the world into teapots and not 't-words'? On page 630 of this issue, Jacob Feldman[1] takes an important step towards answering this question. He suggests that there is a formal measure of complexity that determines how natural a category is and how difficult it is to learn.

Feldman is specifically concerned with the important, although limited, class of 'boolean concepts' — that is, categories that can be defined in terms of logical operations such as AND, OR and NOT. In the experiment, subjects were presented with images of 'amoebas', which differed in binary features, such as shape of the nuclei, number of the nuclei and so on (Fig. 1). Boolean categories were then defined in terms of these features. So, with features a, b and c we might define the boolean concept (a AND b) OR (NOT c). This concept applies to items that either have properties a and b, or do not have property c, or both. This concept can, of course, be logically expressed in (infinitely) many ways — for example, as NOT(c AND ((NOT a) OR (NOT b))).

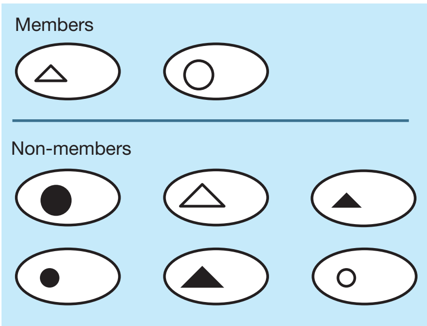

Figure 1 **Learning complex rules. In Feldman's experiments[1], subjects were presented with images of 'amoebas', which were defined by simple binary features (such as the shape and size of nuclei). Subjects had to learn to distinguish members of a particular 'species' of amoeba from non-members. Each species corresponded to a 'boolean category' of varying logical complexity. Feldman shows that the difficulty of learning a particular concept is related to its logical complexity.**

Feldman pursues the intuitively attractive idea that simple boolean concepts are the easiest to learn. But how can complexity be measured? First, the complexity of a logical formula is defined as the number of non-logical terms (the primitive features a, b and c) that occur in that formula — this measure is boolean complexity. So, for example, the formula (a AND b) OR (a AND (NOT b)) would have a boolean complexity of 4. Second, we can define the complexity of a boolean concept as the minimal complexity of any logical formula that expresses that concept. The boolean concept associated with (a AND b) OR (a AND (NOT b)) can most simply be expressed by a very simple formula: a. Hence it has a boolean complexity of 1. Feldman presents impressive experimental data showing that the greater the boolean complexity of a concept, the harder it is to learn. So it seems that boolean complexity provides a measure of the 'naturalness' of a concept.

Feldman has established an important result in the restricted domain of boolean concepts. How far might this result general-

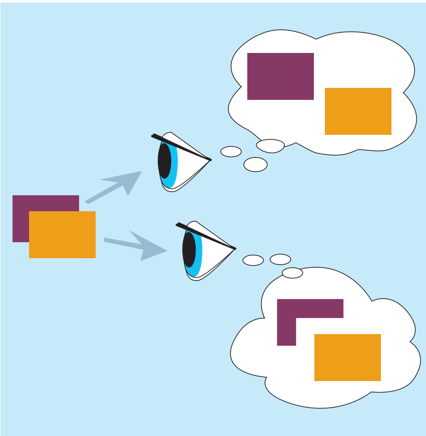

Figure 2 **Simplicity in perception. The visual stimulus on the left can be interpreted as one square tile 'on top' of another or as an 'r' shape abutting a tile. The preference for the 'two tile' interpretation may be due to its simplicity — two squares are simpler to specify than an 'r' and a square. Feldman[1] suggests that this kind of simplicity principle, already widely applied in perception, may also explain how people learn to divide the world into discrete categories.**

ize to learning other kinds of concepts, or to learning across the board? Some considerations suggest caution. First, boolean concepts are very rare among natural language concepts. We simply cannot define, say, a face as a boolean combination of mouth, nose or other features, despite vast efforts to provide such definitions in philosophical analysis and artificial intelligence[2]. Second, real-world concept learning may draw on innate content-specific knowledge, such as the knowledge that biological categories can be usefully organized into nested hierarchies (for example, from dachshund to dog to animal to living thing)[3].

More persuasive, though, are indications that Feldman's result may form part of a very general theory of cognition. Feldman notes that boolean complexity is closely related to the more general idea of Kolmogorov (or K) complexity[4]. The K-complexity of an object is the shortest computer program that can generate that object. So, Hamlet would have high K-complexity, as there is no short program that can generate it; on the other hand, a sequence of a billion zeroes has low K-complexity, because it can be produced by a very short computer program.

If the 'programming language' is elementary logic, and we assume that the objects to be encoded are boolean concepts and that the code length is dominated by the non-logical terms, then K-complexity approximates to boolean complexity. But K-complexity is a more general notion that applies not just to boolean concepts, but to representations of any kind: logical, linguistic, probabilistic or pictorial. As a purely abstract theory, K-complexity has led to methods for inductive inference, based on the search for the simplest interpretation of the current data, which are theoretically well justified and effective in machine learning and statistics[5,6].

Feldman's results may therefore be a special case of a general principle: that human cognition favours simple interpretations of the world, or interpretations involving low K-complexity[7]. This view has been widely advocated in the psychology of perception[8,9]. For example, simplicity may determine the preferred interpretation of ambiguous figures (Fig. 2). In language acquisition, it has been proposed that children search for patterns or regularities that 'compress' their linguistic input[10]. And in physiology it has been argued that finding short codes for sensory input may be a fundamental goal of the brain[11]. Feldman's work may therefore relate not only to categorization, but also to fundamental principles of human learning. ■

Nick Chater is in the Department of Psychology, University of Warwick, Coventry CV4 7AL, UK.
e-mail: nick.chater@warwick.ac.uk

1. Feldman, J. *Nature* **407,** 630–633 (2000).
2. Fodor, J. A. *Concepts* (Oxford Univ. Press, 1998).
3. Atran, S. *Behav. Brain. Sci.* **21,** 547–609 (1998).
4. Li, M. & Vitanyi, P. *Introduction to Kolmogorov Complexity and its Applications* (Springer, Berlin, 1997).
5. Quinlan, J. & Rivest, R. *Inform. Comput.* **80,** 227–248 (1989).
6. Rissanen, J. *IEEE Trans. Inform. Theory* **42,** 40–47 (1996).
7. Chater, N. *Q. J. Exp. Psychol.* **52A,** 273–302 (1999).
8. Leeuwenberg, E. & Boselie, F. *Psychol. Rev.* **95,** 485–491 (1988).
9. Chater, N. *Psychol. Rev.* **103,** 566–581 (1996).
10. Brent, M. R. & Cartwright, T. A. *Cognition* **61,** 93–126 (1996).
11. Barlow, H. B., Kaushal, T. P. & Mitchison, G. J. *Neural Computat.* **1,** 412–423 (1989).

Meteorites

The long trip to Earth

Clark R. Chapman

In the 1790s, European scientists accepted the once preposterous notion that meteorites — rocks that fall from the skies — were of cosmic origin and not lightning bolts, volcanic ejecta, or the eighteenth-century equivalents of ghosts or UFOs. By coincidence, the first asteroid was discovered in space in 1801. As more asteroids were found, the idea naturally developed that meteorites were fragments of asteroids. Early theories that a planet had exploded to create the asteroid belt between Mars and Jupiter gave way to the modern understanding that asteroids are the left-over building blocks of a planet that never formed. Although meteoriticists continued to assume that these exotic rocks were asteroidal, physicists increasingly doubted that rocks could be moved intact from the asteroid belt to Earth. After 200 years of disparate astronomical observations of asteroids and laboratory studies of meteorites, a quantitative model, reported by David Vokrouhlický and Paolo Farinella on page 606 of this issue[1], now shows how a suite of processes bring small asteroid fragments to Earth.

From a physics perspective, the simple billiard-ball analogy of collisions between rocks knocking each other around the inner Solar System does not stand up to elementary scrutiny. It is no easier to 'bump' icy, rocky or even metallic objects, with finite material strengths, from the asteroid belt into Earth-crossing orbits than it is to hit eggs around the fairways with a golf club. Much gentler accelerations are required, such as those exerted on comets at the edge of the Solar System by the gravity of passing stars and giant molecular clouds.

By the 1970s physicists had realized that periodic gravitational forces produced by Jupiter and Saturn could gently move an asteroid fragment located in one of two specific narrow zones (known as 'orbital resonances') into an elongated orbit that might intersect with that of the Earth. At the very least, the fragment might pass near Mars, which in turn could gravitationally deflect it into an Earth-crossing orbit. In 1985 Jack Wisdom[2] used chaos theory to show how such transfers might work. Indeed, nowadays, asteroids are missing from these resonant 'escape hatches', providing evidence that asteroids were cleared out this way in the past.

The picture that emerged showed how collisions involving asteroids such as 6 Hebe, located at the edge of a resonance, would eject fragments at tens to hundreds of metres per second (consistent with the degree of shock seen in meteorites) into the resonance gap for quick delivery to Earth. If true, then meteorites must represent just a few, favourably located asteroids, not the vast majority, which are far from the resonances. But the Earth encounters a surprisingly large amount of meteoritic material, perhaps 1,000 tons per year. For this to come from just a few asteroids requires an unnaturally high transfer efficiency and model parameters had to be tweaked uncomfortably to make the numbers work. The selectivity of the resonance process at least helped to explain why astronomers could not find main-belt asteroids with the same spectral attributes as the most common meteorites in our museums, the ordinary chondrites. But it undercut meteoriticists, whose theories assumed that ordinary chondrites were common asteroidal materials.

Ten years ago, the advent of fast computers gave new impetus to this research, but a problem soon emerged. Farinella and