songs worked like a charm. So it seems that the male forms of *fru* fine-tune these neurons in the male to perfect his song.

Even if it is not well tuned, a song circuit is present in females. So what makes them hide their singing talent? The selective activation of thoracic song circuits in males but not females is likely to be controlled by some subset of the *fru* neurons in the brain. Indeed, classic studies of gynandromorph flies (which have a mixture of male and female nervous tissues) indicated[4] that certain brain regions must be 'male' to trigger the song. In this context, it is interesting to note that several pairs of neurons descending from the brain to the thorax are *fru*-positive[1]. These neurons are prime candidates to convey sex-specific commands to the thoracic song circuits.

The picture that emerges from these studies is that the circuitry for song generation, like that for pheromone processing[9,10], is largely shared between the sexes. The crucial sex differences seem to lie somewhere in between these bisexual input and output circuits, in dimorphic 'decision-making' centres in the brain. A similar design has recently been proposed[11] for the circuits that regulate sexual behaviour in mice: in females unable to perceive certain olfactory cues, male-like sexual behaviour results, presumably reflecting the activation of otherwise dormant circuits for these male behaviours in females. This modular and bisexual design affords considerable flexibility, which may even be exploited within the animal's own lifetime. Some species of fish, for example, change their sexual behaviour in response to social cues[12]. They may do this by simply resetting a few critical switches in the decision-making centres of an otherwise bisexual nervous system.

There is great excitement in neuroscience these days, as genetic tools are used to anatomically and functionally dissect the neural circuits that mediate complex animal behaviours[13]. Clyne and Miesenböck's work[1] beautifully illustrates the essential role photoactivation methods will have in this endeavour. As biochemists and biophysicists have long appreciated, surprising insights come when one can address questions of causality as well as correlation, reducing a system to its essentials and pushing it beyond its normal operating range. The mating behaviours of the humble fruitfly seem to be particularly amenable to this type of reductionist approach. ■

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ELECTRONICS

The fourth element

James M. Tour and Tao He

Almost four decades since its existence was first proposed, a fourth basic circuit element joins the canonical three. The 'memristor' might herald a step-change in the march towards ever more powerful circuitry.
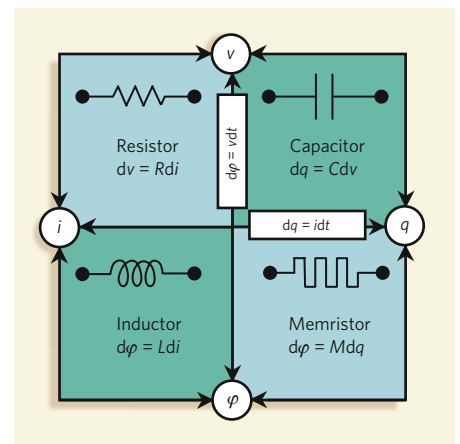
We learn at school that there are three fundamental two-terminal elements used for circuit building: resistors, capacitors and inductors. These are 'passive' elements, capable of dissipating or storing energy — but not, as active elements are, of generating it. The behaviour of each of these elements is described by a simple linear relationship between two of the four basic variables describing a circuit: current, voltage, charge and magnetic flux.

As the electrical engineer Leon Chua pointed out[1] in 1971, for the sake of the logical completeness of circuit theory, a fourth passive element should in fact be added to the list. He named this hypothetical element, linking flux and charge, the 'memristor' (Fig. 1). Almost 40 years later, Strukov *et al.*[2] (page 80 of this issue) present both a simple model system in which memristance should arise and a first, approximate physical example.

So what? Beyond its fundamental interest, the excitement lies in the possibility that the memristor could markedly extend how we can make electronic circuits work. In doing so, it might provide us with a way to keep on exponentially increasing computing power over time — thus maintaining something approximating to Moore's law, the rule-of-thumb to that effect that has been valid over the past few decades.

But before we get ahead of ourselves, some basics. According to the theory, a memristor is essentially a device that works under alternating current (a.c.) conditions[1] in which the applied voltage varies sinusoidally with time. As the polarity of this voltage changes, the memristor can switch reversibly between a less conductive OFF state and a more conductive ON state. Crucially, the value of the current flow through the memristor (the measure of its resistance) does not in the second half of the cycle retrace the exact path it took in the first. Because of this 'hysteresis' effect, the memristor acts as a nonlinear resistor the resistance of which depends on the history of the voltage across it — its name, a contraction of 'memory resistor', reflects just that property.

The memristor is a special case of a more general class of nonlinear dynamical devices called memristive systems[3]. Whether physically realized or not, since memristance was first proposed the memristor has been successfully used as a conceptual tool for analysing signal processing and for modelling the workings of, for instance, electrochemical and nonlinear semiconductor devices.

Even so, the concept has not been widely adopted, possibly because in normal microscale chips the memristance is minute. But everything changes on the nanoscale, because

Figure 1 | Complete quartet. There are six independent permutations of two objects from a bank of four. Thus, six mathematical relations might be construed to connect pairs of the four fundamental circuit variables (current, i; voltage, v; charge, q; magnetic flux, φ)[1]. Of these, five are well known. Two arise from the definitions of two of the variables concerned: charge and magnetic flux are the time integrals of current and voltage ($dq = i\,dt$ and $d\varphi = v\,dt$), respectively. The other three lead to the axiomatic properties of three classic circuit elements: resistance, R, is the rate of change of voltage with current; capacitance, C, that of charge with voltage; and inductance, L, that of flux with current. The sixth relation leads to a fourth basic circuit element, which had been missing. Strukov *et al.*[2] have now found it: the memristor, with memristance, M, defined as the rate of change of flux with charge. (Figure adapted from refs 1 and 2.)

the size of memristance effects increases as the inverse square of device size. Strukov *et al.*[2] use a simple model to show how memristance arises naturally in a nanoscale system when electronic and atomic transport are coupled under an external voltage. The authors realize this memristive system by fabricating a layered platinum–titanium-oxide–platinum nanocell device. Here, the hysteretic current–voltage characteristics relate to the drift back and forth of oxygen vacancies in the titanium oxide layer driven by an applied voltage[4].

This observation provides a wonderfully simple explanation for several puzzling phenomena in nanoscale electronics: current–voltage anomalies in switching; hysteretic conductance; multiple-state conductances (as opposed to the normal instance of just two conductance states, ON and OFF); the often mischaracterized 'negative differential resistance', in which current decreases as voltage increases in certain nanoscale two-terminal devices; and metal–oxide–semiconductor memory structures, in which switching is caused by the formation and breakdown of metal filaments owing to the movement of metal atoms under applied bias.

But what of Moore's Law? Established by Intel co-founder Gordon Moore in 1965, this empirical rule states that the density of transistors on a silicon-based integrated circuit, and so the attainable computing power, doubles about every 18 months. It has held for more than 40 years, but there is a sobering consensus in the industry that the miniaturization process can continue for only another decade or so.

The memristor might provide a new path onwards and downwards to ever-greater processor density. By fabricating a cross-bar latch, consisting of one signal line crossed by two control lines[5], using (two-terminal) memristors, the function of a (three-terminal) transistor can be achieved with different physics. The two-terminal device is likely to be smaller and more easily addressable than the three-terminal one, and more amenable to three-dimensional circuit architectures. That could make memristors useful for ultra-dense, non-volatile memory devices.

For memristor memory devices to become reality, and to be readily scaled downwards, the efficient and reliable design and fabrication of electrode contacts, interconnects and the active region of the memristor must be assured. In addition, because (unlike with transistors) signal gain is not possible with a memristor, work needs to be put into obtaining high resistance ratios between the ON and OFF states. In all these instances, a deeper understanding of the memristor's dynamic nature is necessary.

It is often the simple ideas that stand the test of time. But even to consider an alternative to the transistor is anathema to many device engineers, and the memristor concept will have a steep slope to climb towards acceptance. Some

will undoubtedly trivialize the realization of this ubiquitous nanoscale concept, whereas others will embrace it only after the demonstration of a well-functioning, large-scale array of these densely packed devices. When that happens, the race towards smaller devices will proceed at full steam. ■

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CLIMATE CHANGE
Natural ups and downs

Richard Wood

The effects of global warming over the coming decades will be modified by shorter-term climate variability. Finding ways to incorporate these variations will give us a better grip on what kind of climate change to expect.

Climate change is often viewed as a phenomenon that will develop in the coming century. But its effects are already being seen, and the Intergovernmental Panel on Climate Change recently projected that, even in the next 20 years, the global climate will warm by around 0.2 °C per decade for a range of plausible greenhouse-gas emission levels[1]. Many organizations charged with delivering water and energy resources or coastal management are starting to build that kind of warming into their planning for the coming decades. A confounding factor is that, on these timescales, and especially on the regional scales on which most planning decisions are made, warming will not be smooth; instead, it will be modulated by natural climate variations. In this issue, Keenlyside *et al.* (page 84)[2] take a step towards reliably quantifying what those ups and downs are likely to be.

Their starting point is the ocean. On a timescale of decades, this is where most of the 'memory' of the climate system for previous states resides. Anomalously warm or cool patches of ocean can be quite persistent, sometimes exchanging heat with the atmosphere only over several years. In addition, large ocean-current systems can move phenomenal amounts of heat around the world, and are believed to vary from decade to decade[3,4].

To know and predict the state of the ocean requires an approach similar to

weather forecasting: one sets up (initializes) a mathematical model of the climate system using observations of the current state, and runs it forwards in time for the desired forecast period. With a given climate model, enough observations to set the ball rolling and a large-enough computer to move it onwards, the exercise is conceptually straightforward.

But does it actually produce anything useful? We don't expect to be able to predict the details of the weather at a particular time several years in the future: that kind of predictability runs out after a week or two. But even predicting, say, that summers are likely to be unusually wet during the coming decade would be useful to many decision-makers. Only recently, with the study from Keenlyside *et al.*[2] and another
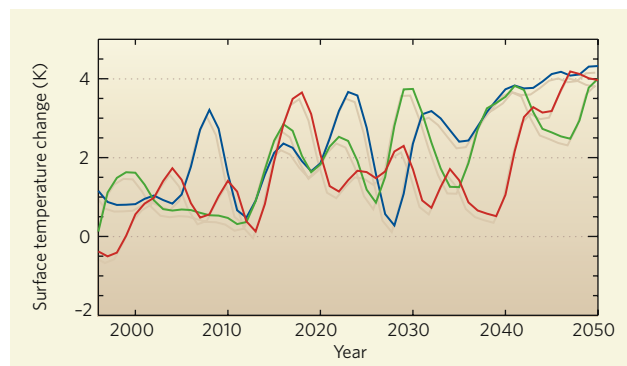
Figure 1 | Heat up? These three possible trends of winter temperature in northern Europe from 1996 to 2050 were simulated by a climate model using three different (but plausible) initial states[6]. The choice of initial state crucially affects how natural climate variations evolve on a timescale of decades. But as we zoom out to longer timescales, the warming trend from greenhouse gases begins to dominate, and the initial state becomes less important. Keenlyside and colleagues[2] use observations of the sea surface temperature to set the initial state of their model. Their results indicate that, over the coming decade, natural climate variability may counteract the underlying warming trend in some regions around the North Atlantic. (Figure courtesy of A. Pardaens, Met Office Hadley Centre).