differentiation in the chick limb but also in positional signalling and programmed cell death[11].

The connection between NF-κB and *Twist* provides the satisfying link to Saethre–Chotzen syndrome. This human condition is characterized by craniofacial and limb anomalies, and the same developmental pathway probably operates in both regions of vertebrate embryos. At present, it is difficult to see just how alterations in *Twist* could lead to the specific anomalies in the limb (short digits and soft tissue webbing between digits). For although genes bring different worlds together, the challenge remains to understand how gene expression is translated into anatomy. □

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Computing

Parallel thinking

C. S. Calude and J. L. Casti

The computer seems to be the only commodity ever to become exponentially better as it gets cheaper. Its information handling capacity has grown at a rate ten million times faster than that of our nervous systems during the four billion years since life began on Earth. Yet the theory and technology of computing has rested for more than 50 years on the Turing-machine model of computation, which leads to many intractable or undecidable problems. Are there alternatives? This was the question addressed at a conference in January*, where three new models of computation were discussed: the DNA model, the quantum model and the reversible model.

DNA has a potentially gigantic memory capacity (in reasonable concentrations, a litre of DNA solution can store up to 10^{22} bits of information), and biochemical operations are massively parallel. So DNA has a built-in computational power. The familiar double helix of DNA arises by the bonding of two separate polymer chains, composed of the four DNA bases A, G, C and T. These obey the Watson–Crick complementarity rule: A bonds with T and C bonds with G. This restriction means that one DNA chain can pair with another chain only when their sequences of bases are complementary. Thus, fundamental information is available for free: knowing one member of a bond means automatically knowing the other.

The startling thing is that complementarity yields universality, in the Turing sense (A. Salomaa, Turku Univ.). Consider the set of all possible words (sequences) that can be obtained from two given words by shuffling them without changing the order of letters. For instance, shuffling AG and TC we get AGTC, ATCG, TCAG and TAGC. Then collect all shufflings of all pairs of complementary words into the so-called twin-shuffle language. There is a simple way to go from a DNA double strand to a word in the twin-shuffle language and back. Universality follows from the fact that any Turing computation can be performed by using an appropriate finite automaton to filter the (fixed) twin-shuffle language. So DNA computers could in theory perform any operation that digital computers can.

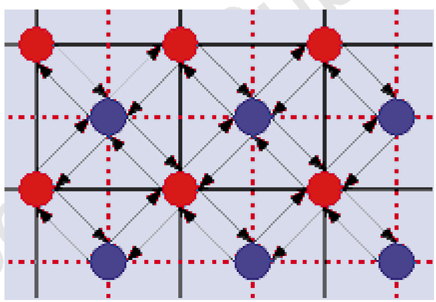

Figure 1 **The layout of a single cell of 'Flattop', an adiabatic (and therefore reversible) processor. It is based on the billiard-ball cellular automaton, in which logic values are modelled by the presence or absence of 'billiard balls' moving along paths in a grid. This scheme has now been realized, using a split-level charge-recovery logic circuit.**

It is a long way from theory to implementation, however. Biochemical operations are slow and prone to errors. The extraction of DNA strands containing a particular sequence is far from certain. Physical constraints, such as volume (performing the computation within a practical volume of DNA), time (some operations can take up to 100 minutes, at present) and energy (operations such as denaturing and annealing require heating or cooling) are difficult to control. But a new cloning readout procedure that overcomes some of these problems was described at the meeting. Using bacteriophage DNA rather than synthesized DNA to carry encoded solutions, operations such as removal, restriction and sorting can be performed by gel electrophoresis, and the result can be obtained in an error-resistant way by picking individual clones and sequencing their DNA (M. Amos, Liverpool Univ.).

Computers, in contrast to Turing machines, are physical devices: whatever they can or cannot do is determined by the laws of physics. Quantum effects, such as interference and entanglement, are especially important, because in the race for miniaturization, computers will inevitably use circuits approaching the level of atoms and photons. There are also certain algorithms that, in principle, can be solved by a quantum computer much more quickly than by a conventional one.

Not all quantum effects may be needed. Nonlinearity (to support quantum logic and ensure universality) and coherence (for the manipulation of coherent quantum superpositions) are necessary and, in principle, sufficient conditions for computation. Conventional devices under investigation for carrying out these operations include ion traps, high-finesse cavities for manipulating light and atoms using quantum electrodynamics, and molecular systems designed to compute using nuclear magnetic resonance. These last store quantum information in the states of quantum systems such as photons, atoms or nuclei, and realize quantum logic by semiclassical potentials such as microwave or laser fields. Unconventional ideas for quantum computation include fermionic quantum computers, bosonic computers (which use a Bose–Einstein condensate of photons, phonons or atoms), and architectures relying on anyons (whose nonlocal topological nature makes them intrinsically error-correcting and virtually immune to noise and interference).

The third strand of the meeting was reversibility. An operation is reversible if it can be undone; it is simply determinism looking backwards in time. Conventional computers are irreversible, and constantly discard information about their states. This limits their efficiency, as it increases the energy required to perform computations and involves the dissipation of heat. But since the laws of physics are reversible at a microscopic level (a given microstate can only be reached by a single path), it follows that irreversible operations and the accompanying production of entropy are in principle not necessary. In practice, reversible computations are likely to dissipate far less energy — but avoiding all entropy production may hurt other measures of performance, such as speed.

The world's first fully reversible universal computer was presented at the meeting (T. Knight, MIT). Working with a parallel architecture (Fig. 1), the machine can perform any computation using arbitrarily little energy per operation (ignoring leakage and power-

** Unconventional Models of Computation,* Univ. Auckland, New Zealand, 5–9 January 1998.

supply issues). Even with actual leakage factors taken into consideration, the machine operates with less than one-thousandth of the energy per operation of a conventional circuit implementing the same computational model.

Although all these techniques are becoming more tractable, there is still no sign of any way to break the Turing barrier. Which computational route holds the most promise for the future? In spite of profound differences — in philosophy, methodology, resources — all face a number of similar problems. How should we efficiently encode the data? What architecture should we choose? How is the architecture initially programmed? Can the architecture reconfigure itself? How should we modify the presently known algorithms to fit the new architecture? How should we efficiently read the output?

So it is a matter of some debate whether any of these models will ever leave the lab. But they have helped draw together the disciplines of computing, mathematics, physics, engineering and biology, and already produced new insight. For instance, new ideas have arisen about the evolution of genes and DNA sequences (that life may be seen as a series of complex computations) and in the field of quantum communication; and solutions have been obtained to old problems (for example, the negative solution to Maxwell's demon problem (S. Lloyd, MIT): a perfectly efficient engine is impossible not only for mortals, but even in principle). The real issue might not be the final destination, but the journey, and the understanding of natural phenomena that will necessarily occur along the way. □

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Ozone depletion

A greenhouse warming connection

Ross J. Salawitch

On page 589 of this issue[1], Shindell and colleagues tackle the question of how rising levels of greenhouse gases will affect ozone (O_3) depletion over the Arctic in the years to come. Their conclusion is tentative but worrisome — that despite reductions in emissions of O_3-depleting chlorofluorocarbons (CFCs), levels of O_3 will continue to fall, with especially severe declines occurring in the years 2010 to 2019.

The direct radiative effects of the build-up of carbon dioxide (CO_2) and other greenhouse gases have led to a gradual cooling of the stratosphere, with the largest changes in temperature occurring in the upper stratosphere, well above the region of peak O_3 concentrations[2]. Build-up of greenhouse gases has been associated with global warming, which occurs as more of the heat radiated from Earth's surface is trapped in the troposphere; as a consequence, less heat reaches the overlying stratosphere, which cools. Cooling of the upper stratosphere during the past several decades would lead to slightly higher concentrations of O_3 due to the temperature dependence of the rates of several key reactions. But this effect has been masked by depletion of upper stratospheric O_3 driven by the release of industrial CFCs (ref. 3). It has also been suggested that the abundance of O_3 in the lower stratosphere may be reduced on longer timescales due to changes in circulation induced by the so-called 'doubled CO_2' environment[4]. Because the greatest concentrations of O_3 exist in the lower stratosphere, this region has the strongest influence on the total column abundance of O_3 (the integrated amount of O_3 between the surface and the top of the atmosphere), which in turn affects exposure to ultraviolet radiation.

Shindell *et al.* now describe a previously unappreciated connection between greenhouse gases and O_3 for the contemporary lower stratosphere. They use a general circulation model (GCM) to show that increasing concentrations of greenhouse gases may currently be leading to colder, more stable vortex circulations in winter, accelerating the chemical removal of O_3 at high latitudes. The authors' calculations suggest that, because of the build-up of greenhouse gases, the total column abundance of O_3 in the Arctic vortex will continue to decrease for about 15 years after levels of stratospheric chlorine begin to decline.

Rapid loss of O_3 throughout the winter polar vortices occurs under conditions of high concentrations of chlorine monoxide (ClO), low temperatures and relatively long periods of daylight. The unreactive reservoirs, HCl and $ClNO_3$, are converted to ClO by reactions on the surfaces of polar stratospheric clouds that form when temperature drops below a critical threshold. Sunlight is required for catalytic removal of O_3, but sunlight also leads to the suppression of increased concentrations of ClO. Maintenance of high concentrations of ClO until the equinox, when day and night are of equal duration and rates of O_3 loss tend to maximize in the Antarctic, requires either temperatures persistently low enough to suppress concentrations of gas-phase HNO_3, which photolyses and eventually converts ClO to $ClNO_3$, or temperatures intermittently low enough to allow repeated exposure of air to heterogeneous processing on

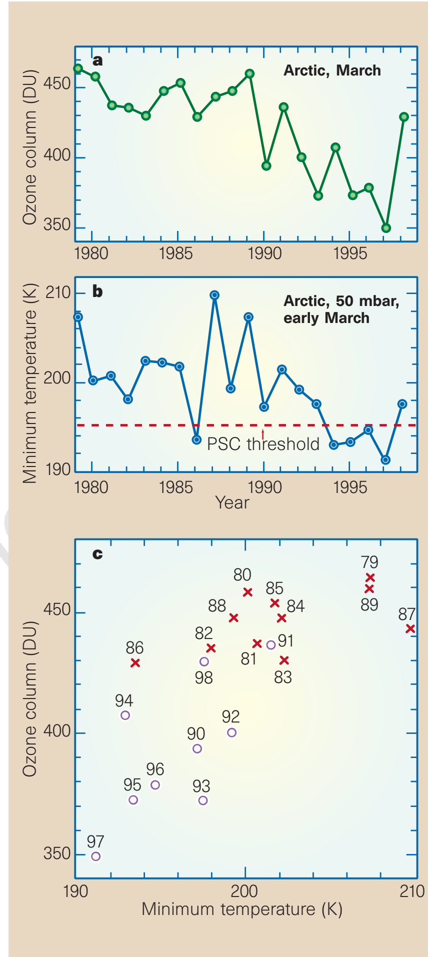

Figure 1 **Ozone levels and minimum temperature over the Arctic (63 to 90° N), 1979–98.** a, **Time series of the average total ozone column during March (from ref. 6). Column O_3 data for 1998 are from Earth Probe TOMS. (One Dobson unit (DU) is the thickness, measured in units of hundredths of a millimetre, that the ozone column would occupy at standard temperature and pressure.)** b, **Minimum temperature on the 50-mbar pressure level in the Arctic vortex during the first two weeks of March, based on data from the National Center for Environmental Prediction; the temperature threshold for formation of polar stratospheric clouds is also shown.** c, **Scatter diagram of these observations, with the data labelled according to the year of observation. Shindell *et al.*[1] show that rising concentrations of greenhouse gases may be the cause of the colder conditions in recent years, accelerating the chemical loss of O_3 by ClO derived from industrial CFCs. Observations for 1998 are preliminary and will be the subject of a future publication by P. A. Newman and R. D. McPeters. I thank them for making these observations available for inclusion in this figure.**