COMPUTING

Naturally random

Randomly assembled nanoparticle networks can compute two-input Boolean functions by exploiting evolution-based computing algorithms.

Jie Han

Novel electronic devices are actively sought to complement and eventually replace complementary metal–oxide–semiconductor (CMOS) technology. Carbon nanotubes[1] and silicon nanowires[2] may extend the life of conventional transistor structures by reducing the feature size to a few nanometres, whereas spintronic and other unconventional devices have the potential to further enhance the performance and energy efficiency of electronic circuits in the ‘beyond CMOS’ era[3]. None of these devices, however, require a radically different computing architecture. As a result, circuits and systems built from such devices will be likely to suffer from the same problems — imposed by manufacturing variability, reliability and, eventually, fundamental physical limits — as conventional architectures. These limitations could be circumvented by inventing technologies for implementing novel computing paradigms, such as those based on biologically inspired computing, and nanocomputing[4]. Evolution-based computing exploits a unique combination of biologically inspired computing architectures using nanoscale devices and the philosophy that “nothing in biology makes sense except in the light of evolution.”[5] Unfortunately, no systems that exploit the physical properties of materials have been demonstrated for computing with evolution-inspired functional devices.

Writing in *Nature Nanotechnology*, Wilfred van der Wiel and colleagues at the University of Twente now experimentally show that a disordered network of nanoparticles can be evolved to perform functions of Boolean logic[6]. The nanoparticle network covers an area of 200 nm in diameter with a few tens of randomly assembled gold nanoparticles (each 20 nm in diameter) deposited on top of a highly doped Si/SiO$_2$ substrate and connected by insulating molecules. The electron transport across the nanoparticle network is determined by the voltages applied to eight electrodes — two of which are for logic inputs and the other six enable control of the network's logic functionality.

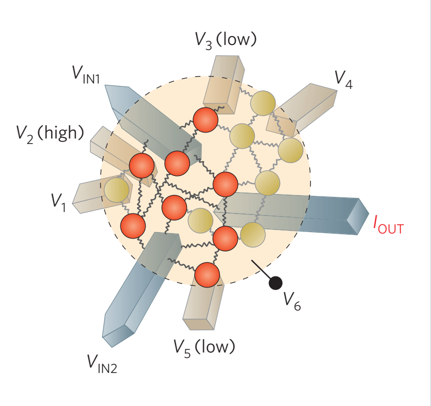

Figure 1 | A plausible circuit diagram for the NOR logic gate using capacitively coupled nanoparticles as single-electron transistors. V_{IN1} and V_{IN2} are input voltages and I_{OUT} is the output current. V_1, V_2 (high), V_3 (low), V_4, V_5 (low) and V_6 are control voltages determined by a genetic algorithm. The shaded circular area is covered by the nanoparticle network. The nanoparticles in red are involved in the NOR function while the nanoparticles in yellow are not.

At temperatures below 5 K, the conductance of a single nanoparticle can be switched on (due to single electron tunnelling) and off (due to Coulomb blockade) by varying the electrostatic potential. Hence, each nanoparticle behaves as a single-electron transistor. As each of the six control voltages spans over a continuous range, a large parameter space exists. A genetic algorithm inspired by the laws of evolution is then utilized to efficiently search for a given logic function within this parameter space. In this algorithm, a set of voltages — much like a genome — determines the output signal as a function of the input signals. All logic functions with two input signals, including AND, NAND, OR, NOR, XOR and XNOR, have been demonstrated by applying the genetic algorithm to the nanoparticle network[6]. A plausible circuit diagram is shown in Fig. 1 for the NOR logic gate.

These results provide experimental support to the earlier idea of computing with molecular ‘nanocells’[7]. A nanocell was first speculated as a programmable 2D network of self-assembled metallic particles interconnected by molecular switches. Experiments have shown a characteristic negative differential resistance of the nanocell at room temperature[8]. Although simulation suggested the feasibility of training the nanocell into a universal NAND gate by using a genetic algorithm, no experimental evidence has been reported.

The logic gates evolved from the nanoparticle network of van der Wiel and colleagues have shown robust operation at temperatures below 5 K. The logic functions can be recovered when the network is thermally cycled back and forth into the operating temperature, although a different genome and thus a new search using the genetic algorithm are required. However, a different function can be obtained by each search, even for the same input signals, which indicates that the logic gate is reconfigurable and versatile for implementing different functions. The evolved network has also shown temporal stability with a functioning time of over 100 hours. The use of the genetic algorithm overcomes the notorious issue of variability due to imperfections in the manufacturing process, operational temperature and supply voltages in conventional nanoscale systems, in which significant redundancy is often required to cope with the problem[9].

While the evolved functions are demonstrated for Boolean logic, the applicability of the nanoparticle network is not limited to it. One can imagine using this system to realize non-Boolean or even analogue computing functions. Questions remain, however, as to the potential for room-temperature operation and the scalability of the network for implementing more complex functions. The prospect seems to be bright for the first question, as Coulomb blockade has been observed at room temperature in gold nanoparticles with a sub-2 nm diameter[10]. To address scalability, the researchers performed additional experiments to evolve the same network into a half adder with two inputs and two outputs. This presents a promising and important step towards building more complex nanocomputers that are naturally evolved from the physical properties of materials. Nonetheless, the types of function that can be realized in a nanoparticle network remain to be investigated, and it is yet to be determined how the network would scale with different numbers of control electrodes and nanoparticles. ❐

Jie Han is in the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, Alberta T6G 1H9, Canada.
e-mail: jhan8@ualberta.ca

References

1. Bachtold, A., Hadley, P., Nakanishi, T. & Dekker, C. *Science* **294,** 1317–1320 (2001).
2. Yan, H. *et al. Nature* **470,** 240–244 (2011).
3. International Technology Roadmap for Semiconductors (ITRS); http://www.itrs.net/
4. Murugesan, S. Radical next-gen computing. *Computing Now* (IEEE Computer Society, 2015); http://go.nature.com/pPHv2A
5. Miller, J. F., Harding, S. L. & Gunnar, T. *Evolutionary Intelligence* **7,** 49–67 (2014).
6. Bose, S. K. *et al. Nature Nanotech.* http://dx.doi.org/10.1038/nnano.2015.207 (2015).
7. Tour, J. M. *et al. IEEE Trans. Nanotechnol.* **1,** 100–109 (2002).
8. Tour, J. M. *et al. J. Am. Chem. Soc.* **125,** 13279–13283 (2003).
9. Han, J. & Jonker, P. *Nanotechnology* **14,** 224–230 (2003).
10. Kano, S., Azuma, Y., Kanehara, M., Teranishi, T. & Majima, Y. *Appl. Phys. Express* **3,** 105003 (2010).