The bumpy road to application

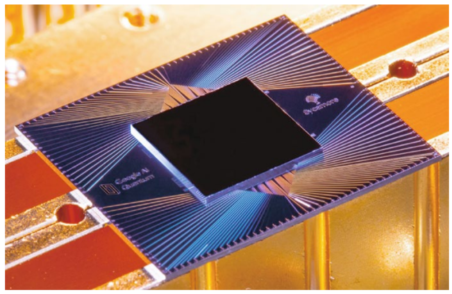
Quantum computing requires time and sustained investment to deliver practical applications — a lesson the development of carbon nanotube electronics illustrates.

The basic building block of a quantum computer is the qubit. With the help of 53 superconducting qubits, researchers led by Google's AI Quantum lab have reported performing a computational task beyond the practical capabilities of a conventional computer — a demonstration referred to as quantum supremacy[1]. The approach uses a quantum processor named Sycamore in which 54 qubits (one was broken) are arranged in a two-dimensional array, with each qubit connected to four nearest neighbours. The task, which was specifically designed to be hard to simulate on a classical computer, involves sampling the output of a pseudo-random quantum circuit. Sycamore takes around 200 seconds to perform the task; the world's leading supercomputer, Summit at Oak Ridge National Laboratory in Tennessee, would, the researchers argue, take 10,000 years.

The work was published in the journal *Nature* on 23 October, though news of the result first emerged back in September when the *Financial Times* reported[2] on a version of the paper that had been posted on, and then quickly removed from, a NASA website. And the achievement has since drawn considerable interest from the research community and beyond. A YouTube video from Google that discusses the work was, for example, viewed more than four million times in less than two weeks.

Researchers at IBM — another tech giant pursuing quantum computing hardware — were, however, quick to dispute the claim. In a blog post[3] and preprint[4] they suggested that the proposed task could, in fact, be simulated by the Summit supercomputer in only two and a half days, rather than millennia. This should be possible by, in particular, exploiting the hard disk space available with Summit — all 250 petabytes of it. The IBM team also highlighted concerns about the use of the term "quantum supremacy": its potential negative connotations (an association with white supremacy), its potential to fuel the hype that already surrounds quantum technology, and its potential for misinterpretation.

The result, nevertheless, remains an inspiring statement of scientific and engineering prowess. At the same time, managing wider expectations about quantum computing — and how quickly its capabilities will progress — is a critical challenge for the field[5]. Money from governments, industry and private investors is currently flowing in[6], but much remains to be done before specific practical applications become a reality (let alone a general-purpose machine). And fears of a 'quantum winter', when results do not arrive as quickly as anticipated and funding dries up, have been raised[6].



Photograph of the quantum processor Sycamore. Image reproduced from ref. [1], Springer Nature Ltd.

Around twenty years ago it was carbon nanotubes experiencing such highs. The first nanotube transistor was reported in 1998[7], only seven years after a report on the synthesis of multiwalled nanotubes had sparked interest in the field. Excitement — and hype — grew. But progress was slower than many had expected and interest in nanotube electronics wavered (ushering in, if not quite a 'nanotube winter', a 'nanotube autumn' perhaps). Researchers, however, continued to make advances and in 2013 a miniature computer made from 178 nanotube field-effect transistors was built[8]. This has now been followed by the creation of a modern microprocessor made from 14,702 complementary metal–oxide–semiconductor (CMOS) nanotube field-effect transistors[9] (see also our Research Highlight on the work).

In a Perspective in this issue of *Nature Electronics*, Lian-Mao Peng, Zhiyong Zhang and Chenguang Qiu at Peking University and Xiangtan University explore the potential of carbon nanotube electronics. They first examine the development of nanotube-based field-effect transistors and integrated circuits, highlighting, for instance, the nanotube transistors with a gate length of only 5 nanometres that have already been built. They then consider the challenges involved in delivering large-scale systems.

One area in which carbon nanotubes could be of practical value in the near future is radio-frequency transistors, which are an important component in wireless communication technology. In an Article elsewhere in this issue, Christopher Rutherglen and colleagues report a wafer-scalable approach for creating nanotube radio-frequency transistors. The researchers — who are based at Carbonics, the University of Southern California and the National Center for MEMS Technologies of Saudi Arabia — show that the resulting devices can offer a higher operating frequency and better linearity than silicon technology.

As Qing Cao at the University of Illinois at Urbana-Champaign argues in an accompanying News & Views article, nanotubes are now close to being a serious competitor to silicon in almost all areas of microelectronics. Furthermore, the recent resurgence of nanotube electronics has, he notes, been driven by researchers in industry, including start-ups such as Carbonics and established companies such as IBM and Analog Devices. This is encouraging for the future of nanotube technology, but continued public investment will still be essential in order for nanotubes to complete the long journey to practical devices. The need for long-term, sustained investment — through the highs and the lows — is a lesson that quantum computing is also likely to need to learn. ❐

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