40 years of quantum computing

This year we celebrate four decades of quantum computing by looking back at the milestones of the field and forward to the challenges and opportunities that lie ahead.

In science there are few true eureka moments experienced by lone geniuses, but rather a continuous exchange and development of ideas that drive the collective human curiosity in new directions. Before a new field of research is born, there is usually a time when many similar ideas are in the air and scientists start to see something new forming, but cannot quite put their finger on it. Then someone manages to articulate a new concept, opening a new direction. From there, it may take years or even decades until the full implications are grasped. Such is the case of quantum computing.

In the early 1980s a deep connection between physics and computation was becoming evident. Twenty years earlier, Rolf Landauer had linked thermodynamics and information. In 1980, mathematician Yuri Manin mentioned in the introduction of his book *Computable and Uncomputable* (in Russian) the idea of a quantum automaton that used superposition and entanglement (see the English translation in REF.[1]) and Paul Benioff discussed[2] a microscopic quantum mechanical Hamiltonian as a model of Turing machines. Then, in May 1981, a conference on the 'Physics of Computation' organized by MIT and IBM brought together physicists and computer scientists. Among the participants were some well-known scientists like Freeman Dyson, John Archibald Wheeler or Richard Feynman, Landauer and Benioff, and others whose names resonate with anyone having worked in quantum computing: Charles Bennett, Tommaso Toffoli, Edward Fredkin. The talks were published the next year in the *International Journal of Theoretical Physics*.

It is difficult to tell to what extent these papers were influenced by the discussions at the meeting or whether the ideas presented had been articulated by individual scientists beforehand. Most contributors referenced the other papers, except Feynman who did not cite anyone (although he did credit Fredkin for inspiration) and just transcribed his keynote speech with its colloquialisms ("Nature isn't classical, dammit."). His paper[3] has become a landmark in quantum computation and simulation, and has been credited for the birth of these fields. Feynman took the ideas that were in the air — computation is a physical process, perhaps even a quantum mechanical one — then turned them around by asking how to compute (simulate) physics. He showed that "quantum mechanics can't seem to be imitable by a local classical computer", but could be tacked by "quantum computers — universal quantum simulators". Manin had had a similar intuition[1] ("the quantum behaviour of the system might be much more complex than its classical simulation"), but he did not develop it further.

Although it is hard to assign a single moment in time as the starting point of quantum computing, as a journal, we like to take the 1982 issue of the *International Journal of Theoretical Physics* as the crystallization of the idea of a quantum computer. We would also like to credit all the pioneers whose ideas connected quantum mechanics with computing.

From 1982 to today quantum computing has been on a journey with many ups and downs and unexpected encounters. It saw great excitement after Shor's quantum algorithm for factorization in 1994, followed by the first proposals for building a quantum computer. Hopes were high, but then came the realization of how difficult it would be in practice. No other algorithms to rival the potential of Shor's were found. Despite disappointment, momentum was not lost and the field branched into different directions. Unexpected connections to fundamental physics and insight into the foundations of quantum mechanics were uncovered and numerous advances were made both in theory and experiment. Things started to pick up again for quantum computing and the past five years have witnessed a renewed commercial interest and the first demonstrations of quantum computers performing tasks that are hard for classical computers, a quantum advantage.

To celebrate four decades of quantum computing we put together a Collection of relevant content from our pages. As we have done in the past, we will revisit milestone papers and their legacy in 'then and now'-type retrospective pieces. We will also look ahead with a Roadmap article and other upcoming content. Watch this space.

1. *Mathematics as Metaphor. Selected Essays of Yuri I. Manin* 77–78 (American Mathematical Society, 2007).
2. Benioff, P. The computer as a physical system: A microscopic quantum mechanical Hamiltonian model of computers as represented by Turing machines. *J. Stat. Phys.* **22**, 563–591 (1980).
3. Feynman, R. P. Simulating physics with computers. *Int. J. Theor. Phys.* **21**, 467–488 (1982).