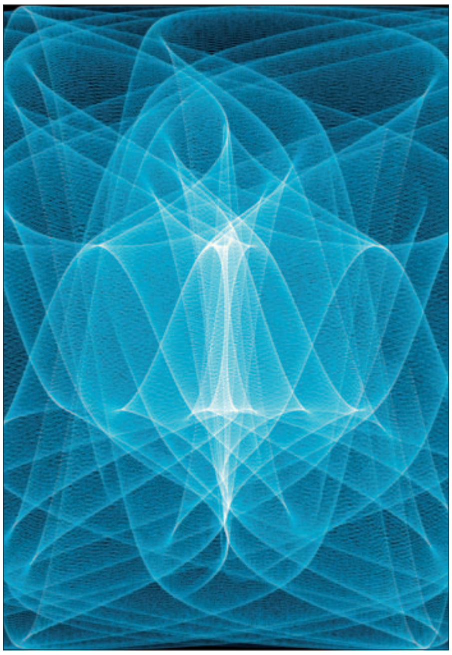
Quantum technologies: an old new story

Technologies based on the properties of quantum mechanics have been around for many years, but **Iulia Georgescu** and **Franco Nori** argue that we need a new definition for "quantum technologies"



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Superposition Quantum mechanics has led to real engineering developments, with more to come.

Quantum technologies have been loosely defined either as the harnessing of "quantum-mechanical effects for its core operation" (*Nature Phonics* **3** 687), or as the control of "the components of a complex system governed by the laws of quantum mechanics" (*Phil. Roy. Soc. A* **361** 1655). The term is usually associated with emerging technologies such as quantum communication, quantum information processing or quantum metrology. However, quantum technologies are not new. They have been around for more than 60 years and we are using them in our everyday lives.

According to the above definitions, nuclear magnetic resonance (NMR), which allows the manipulation of nuclear spin (a very quantum concept) is a quantum technology. So are Josephson junctions and superconducting quantum interference devices (SQUIDs), the basic operating principles of which are based on quantum tunnelling (another very quantum concept) . These technologies have been in use for many decades and more recently have regained attention in the context of building quantum computers. However, these technologies are closer to everyday life than many people may realize.

For instance, MRI scans, routinely done in hospitals, employ several quantum technologies: from nuclear spin resonance to SQUID-based magnetic-field detectors. Even if you have never had an MRI scan, you are most likely making indirect use of quantum technologies, because world time is kept by atomic clocks, some of them harnessing quantum-mechanical effects to achieve increased accuracy and stability.

Terms such as "quantum technologies" and "quantum engineering" are frequently used but they remain vaguely defined. This is not a mere matter of terminology. There is no clear and systematic subject categorization, which leads to confusion and inconsistencies. For instance, one might ask whether quantum technologies should or should not be included in the larger field of nanotechnology (defined as the ability to systematically organize and manipulate properties and behaviour of matter at the atomic and molecular levels). Another question one might ask is why NMR spectroscopy is not regarded as a quantum technology, while an NMR quantum computer is.

So how then do we define quantum technologies? How can we categorize quantum technologies? What quantum technologies are we using today, and what applications should we expect tomorrow? In an attempt to answer these questions, we first propose a more restrictive definition of quantum technologies as "the ability to harness purely quantum-mechanical phenomena to obtain a qualitative advantage over other technologies in performing certain tasks". Classically, these tasks can be performed less efficiently, if at all. We also suggest a definition for quantum engineering that is "the control and manipulation of the quantum-mechanical state(s) of a system". With these definitions in mind, we can explore the world of quantum technologies from a historical perspective.

First-generation quantum technologies

Going back to NMR, the technique was first developed in the 1940s, and has been playing an important role in medical, chemical and magnetic-field-measurement applications ever since. The manipulation of nuclear or electronic spin opened the way to new technologies through the control of a new degree of freedom: the spin. Besides particle spin, one of the earliest quantum concepts to be put into practice was quantum tunnelling (i.e. the ability of quantum particles to pass through an energy barrier).

Quantum tunnelling has important implications for charge transport in electronic devices, such as tunnelling Esaki diodes, which were first produced in the 1950s, or Josephson junctions and SQUIDs, developed in the 1960s. A decade later came scanning tunnelling microscopy, which provides atomic-scale resolution by measuring the tunnelling current between a conducting tip and a surface.

Two other first-generation quantum technologies – spintronics, or "spin electronics", and quantum-dot technologies – appeared in the 1980s and 1990s. Spintronics involves manipulating electron spin in solids and has led to the discovery of quantum effects, such as giant magnetoresistance or tunnel magnetoresistance. Harnessing giant magnetoresistance, for example, allowed the development of magnetic sensors, hard-disk drives and magnetic random-access memory. Unlike the case of quantum information processing, where both the technology and the information being stored are quantum, these quantum technologies are used for the storage and processing of classical bits of information. Taking the engineering of semiconductor structures further, electrons can be confined in all three dimensions in nanoscale structures known as quantum dots. Quantum dots have applications in medical imaging and disease detection, light-emitting diodes, solar cells and photovoltaics, as well as quantum computation.

We refer to the technologies harnessing particle spin or quantum tunnelling, and developed between the 1940s and

Two generations

Concept	Technology
first-generation quantum technologies	
spin	NMR, electron-spin resonance spintronics quantum dots
quantum tunnelling	scanning tunnelling microscopy tunnelling diodes, quantum dots Josephson junctions, SQUIDs
second-generation quantum technologies	
quantum superposition and/or uncertainty (quantum measurements)	quantum computing quantum simulation quantum key distribution quantum random-number generators
quantum correlations (entanglement or discord)	quantum computing quantum key distribution quantum imaging quantum metrology

Heading to market

Technology	Research	Demonstrated or development	Commercial or in use
quantum communication			
quantum key distribution	✓	✓	✓
quantum networks	✓	✓	✓*
quantum random-number generator	✓	✓	✓
quantum information processing			
quantum computation	✓	✓	✓**
quantum simulation	✓	✓	✗
quantum metrology, sensing and imaging			
quantum imaging	✓	✓	✗
time and frequency standards	✓	✓	✓
quantum metrology	✓	✓	✗

* In 2010 an industrial–academic collaboration commissioned by the National Institute of Information and Communications Technology in Japan implemented the world's fastest network protected by quantum encryption technology on 45 km of metropolitan optical fibre network in Tokyo

** The Canadian company D-Wave Systems advertises its superconducting 128-qubit processor chip as "the first commercial quantum computing system on the market"

the 1990s, as "first-generation" quantum technologies. They are commercial technologies with important applications in medicine, industry and research. Note that stimulated or spontaneous emission can be treated semi-classically and therefore we do not include technologies based on these phenomena, such as lasers. In the same spirit, we omit the transistor and most semiconductor technologies even though some currently used electronics are still classified as quantum (e.g. tunnelling diodes or superconducting circuits).

Second-generation quantum technologies

To us, technologies harnessing quantum superposition, uncertainty or quantum correlations are "second-generation" quantum technologies. Having begun to emerge in the 1990s, they make use of more elusive quantum-mechanical phenomena and are the technologies that are normally thought of as "quantum".

Quantum superposition, best known through the famous dead-and-alive Schrödinger's cat, offers the possibility of storing and processing information beyond the limitations of binary bits. Quantum bits are two-level quantum systems, such as nuclear or electron spin, in which information is encoded in the two basis states (spin up and spin down) and their linear superpositions. Computations can be performed on many inputs in parallel, which promises exponential acceleration for some computational tasks. When measured, superposition states decay to one of the basis states with some probability. This can be used to generate truly random numbers, which is important for cryptographic applications.

Furthermore, the information stored in a quantum state cannot be measured faithfully or probed without disturbing the system. Quantum information cannot be perfectly cloned, so in theory quantum bits provide completely secure communication. Controllable quantum systems can be used to emulate other quantum systems in order to explore computationally challenging quantum many-body physics problems.

Quantum computation and quantum cryptography sparked intense interdisciplinary research in the late 1990s. Now, quantum key distribution is the first commercial application of quantum cryptography, and even though not yet fully functional, prototype small-scale quantum computers have been developed.

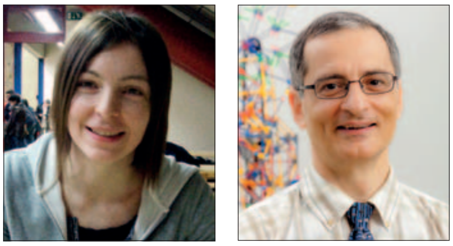
Counterintuitive quantum correlations such as entanglement can be harnessed for information processing and to reach sub-wavelength resolution for imaging and lithography. The idea is to use entangled many-photon states that behave like a single object with a smaller effective wavelength, thus enhancing the spatial resolution of imaging beyond the diffraction limit. Such a technique would be tremendously important for lithography because today's computer-chip manufacturing is struggling to use ever-shorter wavelengths to achieve finer resolution. Similarly, quantum-entangled states could help design improved sensors and lead to higher-accuracy measurements.

The intensive efforts to develop these second-generation quantum technologies have led to important advances in quantum engineering. Exquisite control over the motion and internal energy states of trapped ions and atoms, currents and magnetic fluxes in superconducting circuits, and nuclear or electron spins in solids allows researchers to create many-particle entangled states, or entanglement between very different quantum systems, and perform weak measurements or quantum teleportation. With these well-established quantum-engineering methods, the development of quantum technologies for commercial use requires only time.

Future quantum technologies

By the mid-20th century, manipulating single atoms seemed an impossible feat. However, we can now not only manipulate single atoms or single spins, but also control their quantum states. Harnessing quantum phenomena for new technologies has been done since the 1940s, but it is only relatively recently that single-particle precision and high-accuracy control of quantum systems have been achieved. With such advanced quantum-engineering techniques, more complex quantum phenomena can be exploited for realizing second-generation quantum technologies, such as quantum communication, quantum information processing and quantum metrology, as well as sensing and imaging.

Second-generation quantum technologies promise several killer applications such as perfectly secure communications, tackling exponentially hard problems, sub-wavelength resolutions in imaging and lithography, and high-accuracy measurements and sensors. They are not yet here, but they are getting closer. How soon they will hit the market and whether they will have the same impact as the first generation of quantum technologies is still difficult to predict. But for the moment, we can at least follow the exciting innovations in this multidisciplinary and dynamic field of research.



Iulia Georgescu and **Franco Nori** are at the Advanced Science Institute, RIKEN, Tokyo, e-mail iulia@riken.jp