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Analogue simulation with the use of artificial quantum coherent structures

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ABSTRACT

An explosive development of quantum technologies since 1999 allowed the creation of arrays of natural and artificial quantum unit elements (viz. trapped ions and superconducting qubits), which maintain certain degree of quantum coherence and allow a degree of control over their quantum state. A natural application of such structures is towards simulating quantum systems, which are too big or too complex to allow a simulation with the means of classical computers. A digital quantum simulation promises a controlled accuracy, scalability and versatility, but it imposes practically as strict requirements on the hardware as a universal quantum computation. The other approach, analogue quantum simulation, is less demanding and thus more promising in short-to-medium term. It has already provided interesting results within the current experimental means and can be used as a stopgap approach as well as the means towards the perfecting of quantum technologies. Here I review the status of the field and discuss its prospects and the role it will play in the development of digital quantum simulation, universal quantum computing and, more broadly, quantum engineering.

1. Introduction

In their paper [1] Dowling and Milburn proclaimed the advent of the Second Quantum Revolution and pinned its true beginning on 1994, when the Shor algorithm for breaking the RSA cryptosystem was discovered [2] and quantum entanglement between photons was demonstrated over 4 km of optical-fiber [3]. The first of these breakthroughs threatened one of the cornerstones of secure data transmission, on which much of the world economy came to depend in a short time; the second provided means of avoiding this danger; this naturally made the topic attractive to both researchers and funding bodies and spurred the further development of the field. One could take instead the year 1999, when the first superconducting qubits were realized (charge [4] and flux [5]) and D-Wave Systems Inc. was founded [6], but this would not change much.

As pointed out in [1], “in the Second Quantum Revolution we are now actively employing quantum mechanics to alter the quantum face of our physical world”. But, to a degree, this can be also said about the First Quantum Revolution (which can be symbolically pinned on 2 December 1942, when the first nuclear reactor achieved criticality), which encompassed nuclear power, semiconductor devices, lasers and superconductors. The key difference between the two is rather that the First Revolution and the corresponding “Quantum Technologies 1.0” employed quantum effects on microscopic scale only, that is, the quantum states of the corresponding systems included quantum superpositions and entanglement of only a small number of microscopic quantum states

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across microscopic distances. For example, the order parameter, which characterizes a superconductor, is often described as its “macroscopic wave function”, but it has just a single degree of freedom, like a single quantum particle. Quantum superpositions involved in the operation of a dc or rf SQUID in its standard regime, as described in, e.g., [7], only concern quantum states differing by a single Cooper pair per Josephson junction (see [8], Section 3). “Quantum Technologies 2.0” (QT2.0), on the other hand, use quantum superpositions and/or entanglement of quantum states of artificial structures on a macroscopic (or at least mesoscopic) scale.

This definition should not be applied too strictly. For example, quantum communications do not require entanglement between a macroscopic number of photons, though its spatial scale must be macroscopic. Superconducting or semiconductor charge qubits for their operation require quantum superpositions of states differing only by a single Cooper pair or electron (while in superconducting flux qubits the difference is at least $10^5 - 10^6$ single particle states) [9]. Qubits based on nitrogen-vacancy (NV^-) centres in diamond [10,11], divacancies in silicon carbide [12] or two-level systems in tunneling barriers of Josephson junctions[13,14] exploit microscopic degrees of freedom of natural systems. Still, such a definition is convenient, clear enough and gives the gist of what the Second Quantum Revolution and QT2.0 are about.

The main directions of development of QT2.0 outlined in 2002 [1] did not essentially change by now. The 2014 report by the UK Defense Science and Technology Laboratory [15], the 2016 UK Government Blackett report [16] and the 2016 EU Quantum Manifesto [17] list such applications as quantum clocks, quantum imaging, quantum sensing and measurement, quantum computing and simulation, and quantum communication, and estimate that it will take from 5 to 15 plus years for different sections of QT2.0 to be realized. Similar time scales are indicated in the Innovate UK report on commercialization of quantum technologies in the finance sector [18]. It is also predicted [17] that by 2035 a quantum computer will exceed the power of conventional computers. The global market for different quantum technologies is estimated at anything from 1–10 million to 0.1–10 billion pounds (for the long-term), and is, of course, predicated on the absence of any fundamental barrier on the way towards the realization of large-scale quantum coherent systems (e.g., due to a gravitational quantum state reduction [19]). So far no indication of such a barrier was detected.

The prevailing classification of QT2.0 by application is not the most logical approach from the point of view of physics, but it reflects the important fact that the development and investigation of such quantum structures takes on features of engineering, when for the first time quantum coherence, entanglement and superposition must be treated as material parameters determining the performance, on par with Young’s modulus or electrical resistivity.

The engineering aspects of QT2.0 pose formidable challenges. For example, it is necessary to maintain quantum coherence of the system (which demands its insulation from the environment) while simultaneously manipulating its quantum state (which a connection to the environment and extra circuitry being an additional source of decoherence). This is a typical engineering task of meeting mutually incompatible requirements. There is also a novel challenge, the fundamental impossibility of modeling large enough quantum structures with classical means, pointed out by Feynman as the motivation for developing quantum computing (see, e.g., [20]). At the moment the limit is (very optimistically) about a hundred qubits, and it is unlikely that it can be pushed much farther. On the other side, a universal quantum computer should contain thousands of *logic* qubits (and at least an order of magnitude more *physical* qubits), far exceeding this limit. This makes the development of new methods specific for quantum engineering an urgent and challenging task [21].

Analogue quantum simulation and computation is one way of meeting these challenges. Analogue devices operate by a direct simulation: they are designed in such a way that their natural evolution is described by approximately the same equations as that of the simulated system. For example, slide rules used the rigidity of solids to calculate $\ln(ab) = \ln a + \ln b$ and specially designed scales to realize the input and output, $a \to \ln a$, $b \to \ln b$, $\ln(ab) \to ab$. They are by definition not universal, unlike digital computers, and must be specifically designed for a certain class of problems. Their accuracy is limited by the accuracy of input and readout and by the intrinsic accuracy of its operation, i.e., by how well the natural evolution of the analogue device approximates that of the simulated system. In the case of a slide rule, the former is determined by the width of the marks on the scales and the cursor, and the latter by the accuracy of scales and the rigidity of the structure. The accuracy of an analogue quantum computer is thus hardware-determined and cannot be increased at will. On the other hand, its operation being the natural evolution, it does not demand a precise time-domain control of its individual elements, and being designed for a specific task, it can benefit from problem-specific design shortcuts. This loosens the requirements to the analogue quantum hardware and allows to simplify the design, thus reducing the scale and complexity of the device and with it the sources of decoherence, compared to a digital quantum computer.

The use of analogue quantum devices for quantum optimization, modeling complex natural processes and the evaluation of artificial quantum structures brings additional benefits of perfecting the quantum technologies themselves. In the following we will review these applications, realizations of quantum analogue devices, and possible directions of their further development. This is a very quickly developing area of research, and here we can only cover the indicative directions, in order to give the reader a general overview.

We will concentrate on the most advanced quantum hardware, which combines the control over individual qubits with the best promise of scalability. Arguably, these include superconducting quantum structures [22,23], trapped ions [23,24], optical lattices [25,26] and spins in solid state (e.g., NV^--centres in diamond [10,11]).

2. Digital quantum simulation

Simulation of quantum systems with the use of artificial quantum structures is arguably the most natural application of QT2.0 and is a popular and quickly expanding field of research [27,28]. In the most direct approach, given the initial state of a quantum system, $|\psi(0)\rangle$, and its Hamiltonian $\widehat{H}(t)$, one would reproduce the unitary evolution of the system via simulating the action of the evolution