QUANTUM TECHNOLOGY

Quantum Technology: A Brief Introduction
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ABOUT THE AUTHOR

Tina Dekker is an intellectual property lawyer who will be joining the Ottawa office of Borden Ladner Gervais, LLP in September 2023. Tina graduated from the University of Waterloo with an honours degree in Nanotechnology Engineering and specialized in nanoelectronics, semiconductors, and microfabrication. She continued her studies as a Master's student with the Quantum Materials and Devices Lab at the Institute for Quantum Computing in Waterloo. Her work included fabricating quantum devices to examine the optical and electronic properties of materials with reduced dimensionality for applications in quantum information technology. Tina completed her Juris Doctor at the University of Ottawa, where she researched, published, and presented on the legal and ethical implications of quantum technologies as a research fellow with the Centre for Law, Technology and Society.

ABSTRACT

Quantum technologies have become the next hyped technology, and their unique capabilities are expected to disrupt many industries. In view of a rapidly evolving global quantum ecosystem, the Canadian federal government recently released **Canada's National Quantum Strategy**, which commits $360 million to Canada's quantum ecosystem to support the three pillars of research, talent, and commercialization. Canada needs diverse talent to establish a robust quantum workforce that can support its growing quantum ecosystem. Much of this talent can be sourced from Canada's existing professionals, but transitioning into the quantum field can be difficult due to the field's unique concepts and jargon. This two-part paper series introduces the core concepts of quantum technologies and provides an outlook of the role engineers will play in contributing to quantum technology development.

QUANTUM TECHNOLOGY: A BRIEF INTRODUCTION

With Canada's recent publication of a **National Quantum Strategy** [1], combined with the significant hype over quantum technologies, engineers may be wondering what it means to participate in Canada's growing quantum ecosystem. Quantum technology can intersect with an astonishing number of sectors and industries, providing engineers an opportunity to bring their professional knowledge to contribute to the growth of quantum applications in Canadian industry. This paper is the first of a two-part series and introduces quantum technologies to the engineering audience. The second paper expands on the role engineers will play in quantum technology development in Canada.

1. A Primer on Quantum Technology

The term "quantum" generally refers to the physics principles (i.e., quantum mechanics) that apply to systems at the nanoscale and smaller. The wave nature of matter (wave-particle duality) makes possible quantum phenomena like tunnelling, superposition, and entanglement. This contrasts with "classical" physics (e.g., Newtonian physics), which applies to objects larger than the nanoscale.

Engineers have been involved with quantum technologies like transistors and lasers since their development decades ago. These technologies were some of the first applications of our knowledge in quantum mechanics. Now we are working on next-generation technologies that harness quantum phenomena to realize new capabilities in computing, sensing, communication, and materials. An overview of these technologies follows.

a. Quantum Computing

Quantum computers use **qubits** (i.e., quantum bits) to perform computations. Qubits are quantum systems that are prepared in a superposition of the 0 and 1 states. There are various physical implementations of qubits, including superconducting qubits [5], trapped ion qubits [6], photonic qubits [7], spin qubits [8], and more. By leveraging quantum phenomena like superposition and entanglement through qubits, quantum computing methods are expected to advance our ability to simulate, optimize, and model systems. This, in turn, may improve our ability to tackle global, multidimensional problems like climate change [3].

While quantum computation is theoretically capable of completing any classical computation, the point of interest is where a quantum computer outperforms a classical computer on a problem. Demonstrating this "quantum advantage" depends on numerous factors, including the qubit technology used in the processor and the number of stable qubits [4].

Current quantum computing methods are limited by errors stemming from factors like noise and the ability to maintain quantum states long enough to perform computations. However, "quantum simulators" (i.e., quantum computers with restricted operations that target a particular problem) offer near-term quantum computing solutions in lieu of a universal quantum computer [9].

* Wave-particle duality is the ability of matter to behave as either a particle or a wave. Quantum tunnelling is the ability of a particle to transmit (or tunnel) through an energy barrier that the particle otherwise does not have enough energy to overcome. Superposition is the phenomenon whereby a particle exists in multiple states at once until it is measured. Entanglement is the phenomenon whereby two or more particles are correlated such that obtaining information about one particle simultaneously yields information about the other particle. We can describe quantum systems and the properties identified above mathematically using linear algebra. For further detail about these concepts and other quantum principles, see *Quantum Computing for Everyone* by Chris Bernhardt [2].

b. Quantum Software

Much like classical computers, quantum computers also require software to interface with the underlying hardware [10]. Quantum software development kits can be used to implement quantum circuits comprising quantum logic gates [11]. Some examples include **Qiskit** [12], **TKET** [13], **PennyLane** [14], and **Cirq** [15], all of which are conveniently built on the Python programming language. Some of the most advanced quantum processors in the world can be accessed and programmed over cloud services, which is termed **Quantum Computing as a Service (QCaaS)**.

Two important considerations in the evolving quantum software development space are:

1) interoperability with different quantum processors and quantum computing tools; and
2) accessibility for non-quantum trained users who wish to solve problems using quantum computers.

c. Quantum Communication

Quantum communication involves the transfer of information that is encoded into a quantum system over a quantum network [16]. Quantum communication uses physics principles and phenomena to secure information (e.g., in the generation of encryption keys), which prevents the information from being copied or manipulated without detection. A well-known example is **Quantum Key Distribution (QKD)**, which involves the secure generation of encryption keys, and which may provide post-quantum security against cybersecurity threats enabled by quantum computing [17].

A culminating application of quantum communication technology is the development of a quantum internet [18]. Some predicted applications of a quantum internet include secure communication, clock synchronization, quantum sensor networks, and securing cloud access to quantum computing services [18].

d. Quantum Materials

Quantum materials are materials that demonstrate quantum phenomena. Research in quantum materials seeks to harness their unique electronic, magnetic, and optical properties for applications such as batteries and electronic devices. The conditions for demonstrating a specific quantum phenomenon will differ according to the material and its environment.

As quantum physics is related to a system's size, it follows that materials with reduced dimensionality can demonstrate quantum phenomena. A well-known example is graphene, which is a single layer of carbon atoms arranged in a hexagonal lattice [19]. Compared to graphene's macro form, graphite, graphene demonstrates unique electronic and optical properties that can be leveraged in modern electronics [20].

Discovering these materials and their properties is a result of continuous advancements in microfabrication techniques. In addition, the discovery of new materials and/or the development of synthetic materials may be facilitated by the simulation and optimization capabilities of quantum computing, as discussed above.

e. Quantum Sensors

Quantum systems are very sensitive to perturbations in their environment, such as temperature, vibration, and interactions with other matter. While this extreme sensitivity is a challenge in quantum processor development, leading to computational errors and noise, the extreme sensitivity of quantum systems can also be harnessed in the context of metrology for novel or improved detection methods.

The scope of what is detectable is vast and includes applications in bioimaging, spectroscopy, communication, navigation, and environment monitoring, as well as application to fundamental science research [21]. Quantum sensors also underlie the operation of other quantum technologies, with the most notable example being the use of **superconducting quantum interference devices (SQUIDS)**, which can detect magnetic fields on the order of 10-14 Tesla and are a key component of superconducting qubit technology [22].

Quantum sensors are generally considered to be at the highest technology readiness level compared to other quantum technologies and are already being used in commercialized applications. Quantum sensors are also highly favoured for use in military and national defence applications [23] [24].

2. Quantum Technologies with Classical Infrastructure

Engineers in traditional fields may advance quantum technology by innovating the supporting infrastructure. Underlying most quantum technology is classical technology that facilitates (or is a necessary requirement for) operation, such as cryogenics, wiring, optics components, and structures for vibration isolation. For example, most quantum computers operate at cryostat temperatures, which can be a limiting factor for design parameters, such as scalability, processor size (or number of processors), and operating costs. Two additional examples related to quantum computing include the cloud services through which most quantum processors are available and the development of software tools.

CONCLUSION

An important note about quantum technology is that, in most cases, it will not be replacing classical technology like computers and the internet. Instead, quantum technology offers new capabilities that can expand on or complement existing technology.

Canada is a leader in quantum research and is transitioning quantum technologies to higher technology readiness levels. This is an opportunity for the engineering community to bring forth its professional knowledge and deliver commercialized quantum technology to Canadian industry.

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