Hybrid Quantum Devices: Guest editorial

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An introduction to the APL Special Issue on "Hybrid Quantum Devices" by the guest editors.

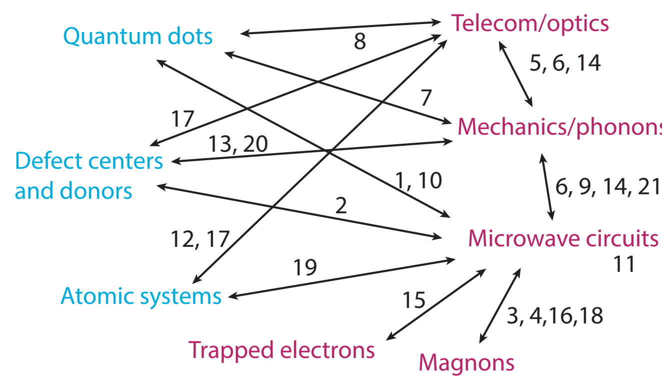

FIG. 1. Connections between different physical systems included in this Special Issue. A approximate distinction is made between qubit-like systems (blue) and harmonic oscillators (magenta).

For applications such as storing quantum states with rapid access, linking remote quantum processors or sensing sound at the quantum limit, quantum hybrids combining two or more physical systems can achieve more than the individual components alone. Interfacing different quantum degrees of freedom leads to new techniques and a better understanding of fundamental physics.

This Special Issue provides researchers and students with a snapshot of today's hybrid quantum devices that are generating a great deal of interest and innovation. It connects atomic and condensed matter physics, quantum optics and nanoscience, highlights recent developments, potentially disruptive technologies, and possible future solutions.

The core building blocks of all quantum devices are qubits and quantum harmonic oscillators, which can be used for encoding, storing and processing quantum information. These have been implemented using a diverse range of physical systems, with each architecture offering its own unique strengths and weaknesses. Hybrid systems allow combination of disparate technologies to exploit the unique advantages of each independent component, for example pairing long coherence atomic qubits for storage with solid state qubits offering fast gates, interfaced using a harmonic oscillator[17].

In this Special Issue we showcase three distinct qubit types including quantum dots[1,7,8,10], defect centres and donors[2,13,17,20] and atomic systems[12,17,19]. Atomic systems are highly scalable, with each qubit being identical and offering long coherence times ideal for quantum memories[12,17], and strong electric dipole matrix elements at both optical wavelengths[12,17] and microwave wavelengths when excited to high-lying Rydberg states[19], however gate times are typically slow compared to other platforms. Quantum dots offer fast gate operations and long coherence times[1], with strong optical transitions enabling coupling to light and opto-mechanical systems[7]. Defect centres and donors in solid state systems similarly offer rapid initialization and gate speeds[17], and can feature long coherence times. These systems are sensitive to magnetic fields, electric fields, and temperature enabling development of precision sensors[13] and coupling to microwave circuits[2]. A common challenge for both quantum dots and defects is the ability to fabricate large numbers of uniform qubits to enable scaling to large qubit numbers.

A wide variety of harmonic oscillators are represented in this collection. In the context of hybrid quantum devices, these linear oscillators often serve as the connection between qubit systems and the classical world, allowing us to, for example, perform sensitive measurements[2,16,18,19] or transfer information between different objects[6,15,17]. Electromagnetic waves in the optical and infrared domain has long been a powerful tool for studying the properties of atoms[12] and solid state emitters such as quantum dots[8], but are now also routinely combined other harmonic oscillator systems in the quantum regime[5,6,14]. Microwave frequency circuits can be designed with a large variety of materials[11] and geometries[4,15], allowing them to be tailored for interfacing with a wide range of other quantum objects. This collection also showcases the diversity of mechanical degrees of freedom that can be used in hybrid systems, ranging from the motion of a single electron in a Penning trap[15] to phonons inside macroscopic, solid-state objects[5,6,9,14,21]. Finally, magnons, which are collective spin excitations, are emerging as a useful new quantum system for hybrid devices due to their high tunability and strong coupling to electromagnetic fields[3,4,16,18]. We

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would also like to point out that most of these oscillators are only approximately harmonic. In fact, some of the works in this collection focus on studying nonlinear effects in these systems and how they might play a role in the performance of hybrid devices[9,11].

Figure 1 schematically shows how the hybrid quantum devices represented in this Special Issue makes connections made between various physical systems. We see that, although certainly not all types of hybrid quantum devices are represented in this collection, it offers some interesting insights into the field. First, microwave circuits are becoming quite ubiquitous in hybrid quantum systems. In addition to perhaps the more straightforward combinations with other solid-state systems, they are now also being used to manipulate and probe Rydberg atoms[19] and single electrons[15]. We speculate that this is not only due to the flexible design of microwave circuits as mentioned above, but also because of the increased interest and new experimental tools generated by the field of quantum information with microwave circuits. Second, the definition of a "hybrid quantum device" has some ambiguity, and this Special Issue presents a broader view of the field than simply linking together different quantum systems. For example, light has been used to probe and control atoms for a long time, but here we highlight new optical devices for cavity QED[12] and using light to connect atoms to other systems[17]. In addition, we include advances in engineering the properties of individual systems to make them more compatible for use in future hybrid quantum devices[11].

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We hope this Special Topic will be relevant and interesting for researchers both in and outside the field.

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