Quantum Computing

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Quantum mechanics—the theory describing the fundamental workings of nature—is famously counterintuitive: it predicts that a particle can be in two places at the same time, and that two remote particles can be inextricably and instantaneously linked. These predictions have been the topic of intense metaphysical debate ever since the theory's inception early last century. However, supreme predictive power combined with direct experimental observation of some of these unusual phenomena leave little doubt as to its fundamental correctness. In fact, without quantum mechanics we could not explain the workings of a laser, nor indeed how a fridge magnet operates. Over the last several decades quantum information science has emerged to seek answers to the question: can we gain some advantage by storing, transmitting and processing information encoded in systems that exhibit these unique quantum properties? Today it is understood that the answer is yes. Many research groups around the world are working towards one of the most ambitious goals humankind has ever embarked upon: a quantum computer that promises to exponentially improve computational power for particular tasks. A number of physical systems, spanning much of modern physics, are being developed for this task—ranging from single particles of light to superconducting circuits—and it is not yet clear which, if any, will ultimately prove successful. Here we describe the latest developments for each of the leading approaches and explain what the major challenges are for the future.

I. INTRODUCTION

One of the most bizarre and fascinating predictions of the theory of quantum mechanics is that the information processing capability of the universe is much larger than it seems. As the theory goes, a collection of quantum objects inside a closed box will in general proceed to do everything they are physically capable of, all at the same time. This closed system is described by a "wave function", which for more than a few particles is an incredibly large mathematical entity describing states of matter and energy far beyond experience and intuition. The wave function, however, is only maintained until the box is opened and the system "collapses" randomly into one particular "classical" outcome. Erwin Schrödinger attempted to reduce these notions to absurdity by connecting the known quantum behavior of an atomic nucleus to a cat in a box that becomes simultaneously alive and dead before the box is opened. Schrödinger intended for the difficulty of imagining a cat in a "superposition" of alive and dead to make us question whether this quantum theory could possibly be correct.

And yet, nearly a century later, quantum theory has yet to fail in predicting an experiment. Although observing an actual "alive and dead" cat is still beyond experimental capabilities, a number of useful technologies have arisen from the counterintuitive quantum world. The quantum computer, a device which uses the full complexity of a many-particle wavefunction to solve a computational problem, may soon be one of these technologies.

The nature and purpose of quantum computation are often misunderstood. The context for the development of quantum computers may be clarified by comparison to a more familiar quantum technology: the laser. Before the invention of the laser we had the sun, and fire, and the lantern, and then the lightbulb. Despite these advances in making light, until the laser this light was always "incoherent", meaning that the many electromagnetic waves generated by the source were emitted at completely random times with respect to each other. One possibility allowed by quantum mechanics, however, is for these waves to be generated in phase, and by engineering and ingenuity methods were discovered for doing so, and hence came about the laser. But lasers do not replace light bulbs for most applications; instead, they produce a different kind of light—coherent light—which is useful for thousands of applications from eye surgery to cat toys, most of which were unimagined by the first laser physicists.

Likewise, a quantum computer will not necessarily be faster, bigger, or smaller than an ordinary computer. Rather, it will be a different kind of computer, engineered to control coherent quantum mechanical waves for different applications. The result will be a "closed box", designed to simultaneously perform everything it is physically capable of, all at once, with all of those possibilities focused toward a computational problem whose solution will be observable after the box is opened.

So what will be in the box, and what will it be able to do? Both questions are currently subjects of ongoing research. The first question will be addressed in ensuing sections; the second is worthy of a review of comparable size, and interested readers are advised to see Ref. 1. For now, we provide only a brief synopsis of quantum computer "software".

One example of a task for a quantum computer is the quantum fourier transform, which continues the exponential increase in computational efficiency begun by the fast fourier transform[2]. This subroutine is at the core of Peter Shor's seminal quantum algorithm for factoring large numbers[3], which is one among several quantum algorithms that would allow modestly sized quantum computers to outperform the largest classical supercomputers in solving the specific problems required for decrypting encoded information. Although these algorithms have done much to spur the development of quantum computers, another application is likely to be far more important in the long term. This application is the first envisioned for quantum computers, by Richard Feynman in the early 1980s[4]: the efficient simulation of that large quantum universe underlying all matter. Such simulations may seem to lie in the esoteric domain of research physics, but these same quantum laws govern the behavior of the many emerging forms of nanotechnology, including nature's nanomachinery of biological molecules. The engineering of the ultra-small will continue to advance and change our world in coming decades, and as this happens we will likely use quantum computers to understand and engineer such technology at the atomic level.

Quantum information research promises more than computers, as well. Similar technology allows quantum communication, which enables the sharing of secrets with security guaranteed by the laws of physics. It also allows quantum metrology, in which distance and time are measured with higher precision than would be possible otherwise. The full gamut of potential technologies have probably not yet been imagined, nor will it be until actual quantum information hardware is available for future generations of quantum engineers.

This brings us to the central question of this review: what form will quantum hardware take? Here there are no easy answers. Quantum computers are often imagined to be constructed by controlling the smallest form of matter, isolated atoms, as in ion traps and optical lattices, but they may likewise be made from electrical components far larger than routine electronic components, as in superconducting phase qubits, or even from a vial of liquid, as in Nuclear Magnetic Resonance (NMR). Of course it would be convenient if a quantum computer can be made out of the same material that current computers are made out of, i.e. silicon, but it may be that they will be made out of some other material entirely, such as InAs quantum dots or microchips made of diamond.

In fact, very little ties together the different implementations of quantum computers currently under consideration. We provide a few general statements about requirements in the next section, and then describe the diverse technological approaches for satisfying these requirements.

II. REQUIREMENTS FOR QUANTUM COMPUTING

Perhaps the most critical, universal aspect of the various implementations of quantum computers is the "closed box" requirement: a quantum computer's internal operation, while under the programmer's control, must otherwise be out of contact with the rest of the universe. Small amounts of information-exchange into and out of the box can disturb the fragile, quantum mechanical waves that the quantum computer depends on, causing the quantum mechanically destructive process known as decoherence, discussed further in Sec. III. Unfortunately no system is fully free of decoherence, but a critical development in quantum computer theory is the ability to correct for small amounts of it through various techniques under the name of Quantum Error Correction (QEC). In QEC, entropy introduced from the outside world is flushed from the computer through the discrete processes of measuring and re-initializing qubits, much as digital information today protects against the noise sources problematic to analog technology. Of course, the correction of errors may be useless if the act of correcting them creates more errors. The ability to correct errors using error-prone resources is called fault-tolerance[5]. Fault-tolerance has been shown to be theoretically possible for error rates beneath a critical threshold that depends on the computer hardware, the sources of error, and the protocols used for QEC. Realistically, most of the resources a fault-tolerant quantum computer will use will be in place to correct its own errors. If computational resources are unconstrained, the fault-tolerant threshold can be as high as 3%[6].

An early characterization of the physical requirements for an implementation of a fault-tolerant quantum computer was carried out by David DiVincenzo[7]. However, since that time the ideas for implementing quantum computing have diversified, and the DiVincenzo criteria as originally stated are difficult to apply to many emerging concepts. Here, we rephrase DiVincenzo's original considerations into three, more abstract criteria, and in so doing introduce a number of critical concepts common to most quantum technologies.

1. Scalability: the computer must operate in a Hilbert space whose dimensions may be grown exponentially without an exponential cost in resources (such as time, space or energy.

The standard way to achieve this follows the first DiVincenzo criterion: one may simply add well-characterized *qubits* to a system. A qubit is a quantum system with two states, $|0\rangle$ and $|1\rangle$, such as a quantum spin with $S = 1/2$. The logic space available on a quantum system of N qubits is described by a very large group [known as SU(2^N)], which is much larger than the comparable group [SU$(2)^{\otimes N}$] for N unentangled spins or for N classical bits. Ultimately, it is this large space that provides a quantum computer its power. For qubits, the size and energy of a quantum computer generally grows linearly with N.

Although qubits are a convenient way to envision a quantum computer, they are not a prerequisite. One could use quantum d-state systems (qudits) instead, or even the continuous degrees of freedom available in laser-light. In all cases, however, an exponentially large space of accessible quantum states must be available.

In principle, there is an exponentially large Hilbert space in the bound states a single hydrogen atom, a system which is clearly bounded by the Rydberg energy of 13.6 eV and consists of only two particles! However, the states of a hydrogen atom in any realistic experiment have a finite width due to decoherence, limiting the useful Hilbert space (for which DiVincenzo introduced his third criterion; see Sec. III). Further, access to an exponentially large set of a hydrogen atom's states comes at the exponentially large cost in the size of that atom and the time required to excite it to any arbitrary state[8].

While it is straightforward to see why a single-atom quantum computer is "unscalable", declaring a technology "scalable" is a tricky business, since the resources used to define and control a qubit are diverse. They may include space on a microchip, classical microwave electronics, dedicated lasers, cryogenic refrigerators, etc. For a system to be scalable, these "classical" resources must be made scalable as well, which tie into complex engineering issues and the infrastructure available for large-scale technologies.

2. Universal Logic: the large Hilbert space must be accessible using a finite set of control operations; the resources for this set must also not grow exponentially.

In the most standard picture of computing, this criterion (DiVincenzo's fourth) means that a system must have available a universal set of quantum logic gates. In the case of qubits, it is sufficient to have available any "analog" single-qubit gate (e.g. an arbitrary rotation of a spin-qubit), and almost any "digital" two-qubit logic operation, such as the controlled-NOT gate.

But quantum computers need not be made with gates. In *adiabatic quantum computation*[9], one defines the answer to a computational problem as the ground state of a complex network of interactions between qubits, and then one adiabatically evolves those qubits into that ground state by slowly turning on the interactions. In this case, evaluation of this second criterion requires that one must ask whether the available set of interactions is complex enough, how long it takes to turn on those interactions, and how cold the system must be maintained. As another example, in *cluster-state quantum computation*[10], one particular quantum state (the cluster state) is generated in the computer through a very small set of non-universal quantum gates, and then computation is performed by changing the way in which the resulting wave function is measured. Here, the measurements provide the "analog" component that completes the universal logic. Adiabatic and cluster-state quantum computers are provably equivalent in power to gate-based quantum computers[11], but their implementation may be simpler for some technologies.

One theoretical issue in the design of fault-tolerant quantum computers is that for most QEC protocols, "digital" quantum gates (or, more precisely, those in the Clifford group) are relatively easy to perform fault-tolerantly on encoded qubits, while the "analog" (non-Clifford) quantum gates are substantially more challenging. In other protocols, the analog gates may become easy, and then the digital ones become difficult. The modern design of fault-tolerant protocols centers around maintaining universality and balancing the difficulties between the two types of operations.

No matter what scheme is used, however, QEC fundamentally requires the third abstract criterion:

3. Correctability: It must be possible to extract the entropy of the computer to maintain the computer's quantum state.

Regardless of QEC protocol, this will require some combination of efficient *initialization* (DiVincenzo's second criterion) and *measurement* (DiVincenzo's fifth criterion). *Initialization* refers to the ability to quickly cool a quantum system into a low-entropy state; for example, the polarization of a spin into its ground state. *Measurement* refers to the ability to quickly determine the state of a quantum system with the accuracy allowed by quantum mechanics. It is possible that these two abilities are the same. For example, a *quantum non-demolition* (QND) measurement alters the quantum state by projecting to the measured state, which remains the same even after repeated measurements. Clearly, performing a QND measurement also initializes the quantum system into the state measured. Some QND measurements also allow quantum logic; they are therefore quite powerful for quantum computing. The relationship between the need for initialization and measurement is complex; depending on the scheme used for fault-tolerance, one may generally be replaced by the other. Of course, some form of measurement is always needed to read out the state of the computer at the end of a computation. Notably, the amount of required physical initialization is not obvious, as schemes have been developed to quantum compute with states of high entropy[12].

Quantum computation is difficult because the three basic criteria we have discussed appear to be conflicted. For example, those parts of the system in place to achieve rapid measurement must be turned strongly "on" for error correction and read-out, but must be turned strongly "off" to preserve the coherences in the large Hilbert space. Generally, neither the "on" state nor the "off" state are as difficult to implement as the ability to switch between the two!

DiVincenzo introduced extra criteria related to the ability to communicate quantum information between distant qubits, for example by converting stationary qubits to "flying qubits" such as photons. This ability is important for other applications of quantum processors such as quantum repeaters[13], but the ability to add non-local quantum communication also substantially aids the scalability of a quantum computer technology. Quantum communication allows small quantum computers to be "wired together" to make larger ones, it allows specialized measurement hardware to be located distant from sensitive quantum memories, and it makes it easier to achieve the strong qubit-connectivity required by most schemes for fault-tolerance.

Evaluating the resources required to make a quantum technology truly scalable is an emerging field of quantum computer research, known as quantum computer architecture. Successful development of quantum computers will require not only further hardware development, but also the continued theoretical development of algorithms and QEC, and the architecture connections between the theory and the hardware. These efforts strive to find ways to maintain the simultaneous abilities to control quantum systems, to measure them, and to preserve their strong isolation from uncontrolled parts of their environment. The simultaneity of these aspects forms the central challenge in actually building quantum computers, and in the ensuing sections, we introduce the various technologies researchers are currently employing to solve this challenge.

III. QUANTIFYING NOISE IN QUANTUM SYSTEMS

A key challenge in quantum computation is handling noise. For a single qubit, noise processes lead to two types of relaxation. First, the energy of a qubit may be changed by its environment in a random way which, on-average, brings the qubit to thermal equilibrium with its environment. The timescale for this equilibration is T_1. Typically, systems used for qubits have long T_1 timescales, which means that T_1 can usually be ignored as a computation error. However, in many experimental systems, T_1 sets the timescale for initialization.

More dangerous for quantum computing are processes which randomly change the phase of a qubit; i.e. processes that scatter a superposition such as $|0\rangle + |1\rangle$ into $|0\rangle + \exp(i\phi)|1\rangle$, for an unknown value of ϕ. This is known as decoherence, and the timescale for phase randomization by decoherence is called T_2. The processes leading to T_1 also contribute to T_2, resulting in T_2 being upper bounded by $2T_1$. But T_2 processes cost no energy, and as a result may be much more frequent than T_1 processes.

In studying noise, one must average over a large ensemble of measurements. It is frequently the case that in this ensemble of measurements, the energy of a qubit is slightly different in each measurement. As a result, superpositions again develop unknown phases, and as a result effects appear which resemble those contributing to T_2. This process is known as dephasing, and it occurs on a timescale $T_2^* \leq T_2$. However, the phase evolution that contributes to T_2^* is constant for each member of the ensemble, and may therefore be reversed. The standard method for doing so is known as the spin-echo, following the NMR technique developed in 1950[14]. By unconditionally flipping the state of a qubit after a time τ, and then allowing evolution for another time τ, any static phase evolution is reversed, leading to an apparent "rephasing." Through spin-echo techniques, the effects of decoherence (T_2) can be distinguished from those of dephasing (T_2^*).

The value of T_2 is used as an initial characterization of many qubits, since, at a bare minimum, qubits need to be operated much faster than T_2 to allow fault-tolerant quantum computation. This is the third DiVincenzo criterion. However, T_2 is *not* the timescale in which an entire computation takes place, since QEC may correct for phase errors. Also, the measured values of T_2 are not fundamental to a material and a technology. Generally, T_2 can be extended by a variety of means, such as defining qubits with *decoherence free subspaces*[15] which are less sensitive to noise; applying *dynamic decoupling techniques*[16–21], such as the spin-echo itself, to periodically reverse the effects of environmental noise; or simply improving those aspects of the apparatus or material that leads to the T_2 noise process in the first place.

Other noise processes exist besides T_1 and T_2 relaxation. Large-dimensional systems, such as multiple-coupled qubits, may be hurt by noise processes distinct from single-qubit T_1 and T_2 processes. Also, some qubits suffer noise processes that effectively remove the qubit from the computer, such as loss of a photon in a photonic computer or the scattering of an atom into a state other than a qubit state. These processes may also be handled by error correction techniques.

In practice, once relaxation times are long enough to allow fault-tolerant operation, imperfections in the coherent control of qubits are more likely to limit a computer's performance. As devices are scaled up to a dozen of qubits, the use of state and process tomography, useful to fully understand the evolution of very small quantum systems, becomes impractical. For this reason, protocols that assess the quality of control in larger quantum processors have been developed. These enable a characterisation of gate fidelity that can be used to benchmark various technologies.

The table below gives measured T_2 decoherence times and the results of one-qubit and multi-qubit benchmarking or tomography for several technologies.

	Type of Matter Qubit	Coherence			Benchmarking	
		$\omega_0/2\pi$	T_2	Q	1 qbit	2 qbit
AMO	Trapped Optical Ion[22,23] ($^{40}\mathrm{Ca}^+$)	400 THz	1 ms	10^{12}	0.1%	0.7%*
	Trapped Microwave Ion[24–26] ($^{9}\mathrm{Be}^+$)	300 MHz	10 sec	10^{10}	0.48%†	3%
	Trapped Neutral Atoms[27] ($^{87}\mathrm{Rb}$)	7 GHz	3 sec	10^{11}	5%	
	Liquid Molecule Nuclear Spins[28]	500 MHz	2 sec	10^{9}	0.01%†	0.47%†
Solid-State	e^- Spin in GaAs Quantum Dot[29–31]	10 GHz	3 μs	10^{5}	5%	
	e^- Spins Bound to $^{31}\mathrm{P}$:$^{28}\mathrm{Si}$[32,33]	10 GHz	60 ms	10^{9}	5%	10%
	Nuclear Spins in Si[34]	60 MHz	25 sec	10^{9}	5%	
	NV^- Center in Diamond[35–37]	3 GHz	2 ms	10^{7}	2%	5%
	Superconducting Phase Qubit[38–40]	10 GHz	350 ns	10^{4}	2%*	24%*
	Superconducting Charge Qubit[41–43]	10 GHz	2 μs	10^{5}	1.1%†	10%*
	Superconducting Flux Qubit[44,45]	10 GHz	4 μs	10^{5}	3%	60%

Table comparing the current performance of various matter qubits. The approximate resonant frequency of each qubit is listed as $\omega_0/2\pi$; this is not necessarily the speed of operation, but sets a limit for defining the phase of a single qubit. Therefore, $Q = \omega_0 T_2$ is a very rough quality factor. Benchmarking values show approximate error rates for single or multi-qubit gates. Values marked with * are found by state tomography, and give the departure of the fidelity from 100%. Values marked with † are found with randomized benchmarking. Other values are rough experimental gate error estimates.

IV. CAVITY QUANTUM ELECTRODYNAMICS

Many concepts for scalable quantum computer architectures involve wiring distant qubits via communication using the electromagnetic field, e.g. infrared photons in fiber-optic waveguides or microwave photons in superconducting transmission lines. Unfortunately, the interaction between a single qubit and the electromagnetic field is generally very weak. For applications such as measurement, in which quantum coherence is deliberately discarded, using more and more photons in the electromagnetic field can sometimes be enough. However, photons easily get lost into the environment, which causes decoherence, and this happens more quickly with stronger fields. Coherent operation requires coupling qubits to weak, single-photon fields with very low optical loss. Such coupling becomes available when discrete, atom-like systems are placed between mirrors that form a high-quality cavity, introducing the physics known as cavity quantum electrodynamics (cQED)[46]. Cavity QED has been an important topic of fundamental research for many years[47–50], and was employed for one of the earliest proposals for quantum computing[51].

A cavity enables quantum information processes for several reasons. First, one may imagine that a photon in a cavity bounces between its mirrors a large number of times before leaking out; this number is called the quality factor Q. If Q is high, one single photon may interact Q times with a single atom, and if each interaction accomplishes a weak, QND measurement (see Sec. II), then the measurement strength is enhanced by Q.

But a cavity does more than this. It also confines the electromagnetic field into a small volume. One manifestation of this is evident in the spontaneous emission of atoms. Spontaneous emission can be considered as the simultaneous coupling of an atom to an infinite continuum of modes of the electromagnetic field. A cavity makes the coupling to one particular mode — the cavity mode — substantially stronger than other, free space modes. This mode is emitted from the cavity at a rate $\kappa = \omega_0/Q$, where ω_0 is the resonant frequency of the cavity. The coupling of the atom to the cavity mode, g, is proportional to $\sqrt{f/V}$. Here f is the oscillator strength of the atom, a measure of its general coupling to electromagnetic fields irrespective of the cavity, which depends on details such as the size and resonant frequency of the atom. The mode-volume of the cavity, V, is a critical parameter to minimize for strong interactions. If the energy levels of the atom are matched to the cavity photon energy $\hbar\omega_0$, the rate at which the combined atom/cavity system emits photons is approximately $4g^2/\kappa$. It is possible for this rate to be much larger than the rate of emission into non-cavity modes, γ, leading to a very large resonant *Purcell factor*:

$$\text{Purcell factor} = \frac{4g^2}{\kappa\gamma} = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{Q}{V}, \quad (1)$$

where λ/n is the wavelength of the emitted photons in the material of refractive index n. A large Purcell factor roughly means that when an atom emits a photon, it is very likely that the emitted photon enters the cavity mode. This cavity mode may then be well coupled to a waveguide, which strongly directs that photon to an engineered destination. This parameter is critical for a large variety of proposals using cQED, even those not involving Purcell-enhanced spontaneous emission of the atom. The Purcell factor for a resonant atom/cavity system is also known as the *cooperativity factor*, and its inverse is known as the critical atom number[47], i.e. the number of atoms in a cavity needed to have a profound effect on its optical characteristics.

Large Purcell factors are generally observed in cavities in the *weak* or *intermediate coupling regime*, also known as the *bad cavity limit*, in which $\kappa > g$. This regime is useful for applications such as single photon sources, in which the cavity increases the speed, coherence, and directionality of emitted photons. It is also the appropriate regime for schemes in which distant qubits are probabilistically entangled by heralded photon scattering[52–55] (as opposed to photon absorption/emission[56]). However, a variety of schemes are enabled by the *strong coupling* limit, in which $g \gg \kappa, \gamma$, meaning that energy oscillates between the atom and the cavity field many times before it leaks away as cavity loss or emission into non-cavity modes. The number κ/g is known as the critical photon number, i.e. the number of photons needed in the cavity to strongly affect the atom[47]. In the strong-coupling regime, the atom-cavity system may be highly nonlinear, introducing remarkable possibilities for engineering states of the electromagnetic field and its entanglement with atoms.

Cavity QED impacts every physical proposal discussed in this review. Single photon sources enhanced by the Purcell effect may be critical for quantum computing with photons, and potentially scalable methods for logic between photonic qubits may be mediated by a cQED system. Ions and atoms in distant traps as well as distant self-assembled quantum dots or nitrogen-vacancy centers may be entangled via cQED techniques. Purcell-enhanced emission may improve the measurement of electron and nuclear spins, possibly even in the optically dark system of P:Si. One of the most striking recent developments in superconducting qubit systems is the coupling of these qubits to microwave cavities far into the strong coupling regime; much farther than any atomic system has been able to obtain. This regime is enabled in part by the large oscillator strengths of superconducting qubits, but more dramatically by the small cavity mode volumes V available from the combination of μm-wide, lithographically fabricated one-dimensional superconducting waveguides with centimeter-scale wavelengths[57]. These developments have enabled researchers to revisit cQED techniques anew and test the relevant ideas for enabling photon-mediated quantum computation.

V. SINGLE PHOTONS

Realizing a qubit as the polarization state of a photon (horizontal $|H\rangle \equiv |0\rangle$ and vertical $|V\rangle \equiv |1\rangle$) is appealing since photons are relatively free of the noise that plagues other quantum systems, and polarization rotations (equivalent to one qubit gates) can be easily done using "waveplates" made of birefringent material (whose refractive index is slightly different for the two polarizations)[58]. Photons also admit encoding of quantum information in other degrees of freedom, including time-bin and path. Of course a potential drawback is the light-speed propagation of the qubit, although this is a tremendous advantage in distributing quantum information.

A major hurdle for quantum computing with photons is realising the interactions between two photons for two-qubit gates. Such interactions require a giant optical nonlinearity stronger than that available in conventional nonlinear media, leading to the consideration of electromagnetically induced transparency (EIT)[59] and atom-cavity systems[48]. In 2001, a major breakthrough known as the KLM scheme showed that scalable quantum computing is possible using only single-photon sources and detectors, and linear optical circuits[60]. It relied on quantum interference of photons at a beamsplitter (see Fig. 1a,b) to achieve nondeterministic interactions.

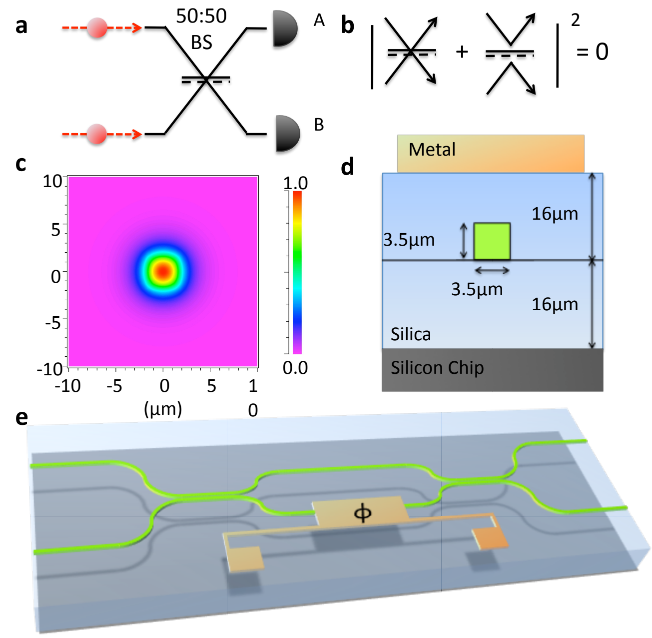

FIG. 1: Quantum computing with photons. **a**, Two photons entering a 50:50 beamsplitter (50:50 BS) undergo quantum interference. **b**, The probability amplitudes for the two photons to be transmitted and reflected are indistinguishable and interfere. **c**, Intensity profile of a photon in a waveguide. **d**, Silica-on-silicon waveguide structure. **e**, An interferometer with controlled phase shift for single qubit operations and multi-photon entangled state manipulation.

Although the KLM scheme was mathematically shown to be "in-principle" possible, initially few people believed it was a 'practical' approach, owing to the large resource overhead arising from the nondeterministic interactions and the difficulty of controlling photons moving at the speed of light. This situation has changed over the past five years[58]: Experimental proof-of-principle demonstrations of two-[61–64] and three-qubit gates[65], were followed by demonstrations of simple-error-correcting codes[66–68] and simple quantum algorithms[69,70]. New theoretical schemes, which dramatically reduced the considerable resource overhead[71–74] by applying the previously abstract ideas of measurement-based quantum computing[10], were soon followed by experimental demonstrations[75,76]. Today, research efforts are focussed on quantum circuits that can be fabricated on the chip-scale[77], high efficiency single photon detectors[78] and sources[79], and devices that would enable a deterministic interaction between photons[48].

The photonic quantum circuits described above were constructed from large-scale (cm's) optical elements bolted to large optical tables. While suitable for proof-of-principle demonstrations, this approach will not lead to miniaturized and scalable circuits, and is also limited in performance due to imperfect alignment for quantum interference (Fig. 1a,b). Recently it has been demonstrated that waveguiedes on chip (Fig. 1c,d), which act much like optical fibres, can be used to implement these circuits[77], and that integrated phase shifters can be used for one-qubit gates and manipulating entangled states on-chip[80] (Fig. 1e). Laser direct-write techniques are also being pursued for three-dimensional circuits[81]. Future challenges include developing large-scale circuits with fast switching and integrating them with sources and detectors.

Ideal single photon detectors have high efficiency, high counting rate, low noise, and can resolve the number of photons in a single pulse[78]. Commercial silicon single photon detectors (Si-APDs) have have a peak intrinsic efficiency of ∼70% and (like photomultipliers) cannot discriminate between one or more photons. However, work is being done to increase efficiency and achieve photon number resolution with Si-APDs[82,83], which offer room-temperature operation and semiconductor integration. Semiconductor visible light photon counters (VLPCs) operate at cryogenic temperatures, have photon number resolution and high efficiency, but generate a relatively large amount of noise[84]. Nanowire superconducting single-photon detectors absorb a single photon to create a local resistive "hotspot", detected as a voltage pulse. The temperature change, and consequently the voltage change depends on the absorbed energy. As a result, the number of photons can be resolved. Low noise and high efficiency (95%) have been achieved for tungsten-based devices[85,86], although they require cooling below the critical temperature of 100 mK and are relatively slow. Superconducting detectors based on nanostructured NbN are fast (100s MHz), low noise, sensitive from visible wavelengths to far into the infrared, have achieved efficiencies of 67% and photon number resolution[87–89].

An ideal single photon source is triggered, frequency-bandwidth-limited, emits into a single spatio-temporal mode, and has high repetition rate. These exacting requirements suggest the need for a single quantum system that emits photons upon transition from an excited to a ground state. (The excited and grounds states could themselves be used to encode a qubit, and in fact many of the qubits described in the following sections have been used to emit single photons.) Controlling the emission can most conveniently be achieved by coupling the system to a high-Q optical cavity (see Sec. IV); emission of single photons from single atoms has been demonstrated in this way[90–92]. A technical difficulty is holding the atom in the optical cavity, leading to solid state "atom" approaches, such as quantum dots, and nitrogen vacancies (NVs) in diamond (see Sec. XI)[79,93] embedded in semiconductor microcavities (see Sec. IV). A key challenge in these solid-state sources is to maintain the indistinguishability of the generated photons[94], which is difficult in solid-state sources due to spectral jumps and other effects. An alternative approach is to use the nonlinear optical materials currently used to emit pairs of photons spontaneously: detection of one photon heralds the generation of the other, which can in principle be switched into an optical delay or multiplexed[95].

While the KLM and subsequent schemes circumvent the need for deterministic interactions between photons there are several schemes for such interactions involving atom-cavity systems[51,96], which are similar to approaches to single photon sources (see Sec. IV). Pioneering work showed that atom-cavity systems can be used to implement an optical nonlinearity between photons[48]. It has been shown that such an atom-cavity system is capable of implementing arbitrary deterministic interactions[97,98].

The photonic approach to quantum computing remains a leading one. (Related approaches based on encoding quantum information in the continuous phase and amplitude variables of continuous-wave[99] or mode-locked[100] laser beams offer some key advantages, but these are beyond the scope of this review.) Achieving scalability will depend on advancements in waveguides, single-photon sources, and detectors, but whatever the future holds for photonic quantum computing, it is clear that photons will continue to play a key role as an information carrier in quantum technologies.

VI. TRAPPED ATOMIC IONS

The best time and frequency standards are based on isolated atomic systems, owing to the excellent coherence properties of certain energy levels within atoms[101]. Likewise, trapped atoms are among the most reliable type of quantum bit. Trapped atom qubits can also be measured with nearly 100% efficiency through the use of state-dependent fluorescence detection[102,103]. Current effort with atomic qubits concentrates on the linking of atoms in a controlled fashion for the generation of entanglement and the scaling to larger numbers of qubits.

Trapped atomic ions are particularly attractive quantum computer architectures, because the individual charged atoms can be confined in free space to nanometer precision, and nearby ions interact strongly through their mutual Coulomb repulsion[104,105]. A collection of atomic ions can be confined with appropriate electric fields from nearby electrodes, forming a 3-D harmonic confinement potential, as depicted in Fig. 2. When the ions are laser cooled to near the center of the trap, the balance between the confinement and the Coulomb repulsion forms a stationary atomic crystal. The most typical geometry is a 1-D linear atomic crystal, where one dimension is made significantly weaker than the other two[104]. In such a linear trap, the collective motion of the ion chain can be described accurately by quantized normal modes of harmonic oscillation, and these modes can couple the individual ions to form entangled states and quantum gates.

Multiple trapped ion qubits can be entangled through a laser-induced coupling of the spins mediated by a collective mode of motion in the trap. Laser interactions can be used to simply flip the state of the qubit, or more generally flip the state of the qubit while simultaneously changing the quantum state of collective motion. Such a coupling arises due to effective frequency modulation of a laser beam in the rest frame of the oscillating ion and the dipole force from the laser electric field gradient. We label the internal qubit states

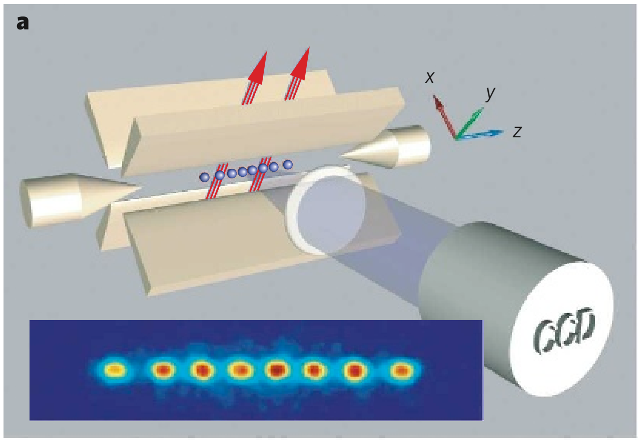

FIG. 2: Schematic of ion trap apparatus. Electric potentials are applied to appropriate electrodes in order to confine a 1-D crystal of individual atomic ions. Lasers affect coherent spin-dependent forces to the ions that can entangle their internal qubit levels through their Coulomb-coupled motion. Resonant lasers can also cause spin-dependent flourescence for the efficient detection of the trapped ion qubit states. The inset shows a collection of atomic Ca^+ ions fluorescing (courtesy R. Blatt, University of Innsbruck).

of ion i as $|\uparrow\rangle_i$ and $|\downarrow\rangle_i$, the quantum state of a Coulomb-coupled mode of collective motion (e.g., the center-of-mass mode) as $|n\rangle_m$, where n is the harmonic vibrational index of motion of that particular mode. By driving ion i on a first order frequency-modulated sideband of the spin-flip transition, the ion system will undergo Rabi oscillations between $|\downarrow\rangle_i|n\rangle_m$ and $|\uparrow\rangle_i|n\pm 1\rangle_m$, where the plus sign denotes the upper sideband and the minus demotes the lower sideband[106]. We assume that the sidebands are sufficiently resolved, or equivalently that the Rabi frequency of the transition is small compared with the frequency of motion.

The simplest realization of this interaction to form entangling quantum gates was first proposed[107] in 1995 and demonstrated in the laboratory later that year[108]. The Cirac-Zoller gate maps a qubit from the the internal levels within a single trapped ion to the external levels of harmonic motion, and similarly applies a laser interaction to affect a second trapped ion qubit conditioned upon the state of motion. The entangling action of the Cirac-Zoller gate can easily be seen by considering two successive laser pulses to the two ions in turn. We start with the ion pair in the state $|\downarrow\rangle_1|\downarrow\rangle_2|0\rangle_m$ through optical pumping of the qubits and laser cooling to the ground state of motion. The first laser pulse is tuned to drive on the first upper sideband of the first ion, for a duration that is half of the time required to completely flip the spin (a $\pi/2-$pulse), and the laser pulse then drives on the first lower sideband of the second ion, for a duration set to the time required to completely flip the spin (a $\pi-$pulse):

$$|\downarrow\rangle_1|\downarrow\rangle_2|0\rangle_m \xrightarrow{\text{pulse 1}} |\downarrow\rangle_1|\downarrow\rangle_2|0\rangle_m + |\uparrow\rangle_1|\downarrow\rangle_2|1\rangle_m \quad (2)$$

$$\xrightarrow{\text{pulse 2}} |\downarrow\rangle_1|\downarrow\rangle_2|0\rangle_m + |\uparrow\rangle_1|\uparrow\rangle_2|0\rangle_m$$

$$= \left(|\downarrow\rangle_1|\downarrow\rangle_2 + |\uparrow\rangle_1|\uparrow\rangle_2\right)|0\rangle_m. \quad (3)$$

These laser interactions entangle the trapped ion qubits, while the final quantum state of motion is unchanged from its initial condition.

Extensions to this approach rely on optical spin-dependent forces that do not require individual optical addressing of the ions or the preparation of the ions a pure quantum state, and are thus favored in current experiments[105]. There are also proposals to use radiofrequency magnetic field gradients[109] or ultrafast spin-dependent optical forces[110] that do not even require the ions to be localized to under an optical wavelength (the Lamb-Dicke limit).

The scaling of trapped-ion Coulomb gates becomes difficult when large numbers of ions participate in the collective motion for several reasons: laser-cooling becomes inefficient, the ions become more susceptible to noisy electric fields and decoherence of the motional modes[106], and the densely-packed motional spectrum can potentially degrade quantum gates through mode crosstalk and nonlinearities[104]. One promising approach to circumvent these difficulties is the "Quantum CCD"[111], where individual ions can be shuttled between various zones of a complex trap structure through the application of controlled electrical forces from the trap electrodes, as depicted in Fig. 3a. In this architecture, entangling gates are operated on only a small number of ions (perhaps 5–10), where the collective motional modes can be cold and coherent. Because the motional state factors from gate operations, the ions can be moved to different locations to propagate the entanglement. Auxiliary ions, perhaps of a different species, can be used as refrigerators to quench the residual shuttling motion of the ions through sympathetic laser cooling[105]. There has been great progress in recent years in the demonstration of multizone ion traps and chip ion traps (Fig. 3b)[112–116].

Another method for scaling ion trap qubits is to couple small collections of Coulomb-coupled ions through photonic interactions, as shown in Fig. 3c. Photonic ion trap networking offers the significant advantage of having a communication channel that can easily traverse large distances, unlike the phonons used in the Coulomb-based quantum gates. While other matter qubits such as quantum dots and optically-active impurities can also be coupled in this way, the use of atoms has the great advantage of reproducibility: each atom or ion in the network has almost exactly the same energy spectrum and optical characteristics. Recently, single atomic ions have been entangled with the polarization or frequency of single emitted photons, allowing the entanglement of ions over macroscopic distances[117,118]. This type of protocol is similar to probabilistic linear optics quantum computing schemes discussed above[60], but with the use of stable qubit memories in the network, this system can be efficiently scaled to large distance communication through quantum repeater circuits, and can moreover be scaled to large numbers of qubits for distributed probabilistic quantum computing[119,120].

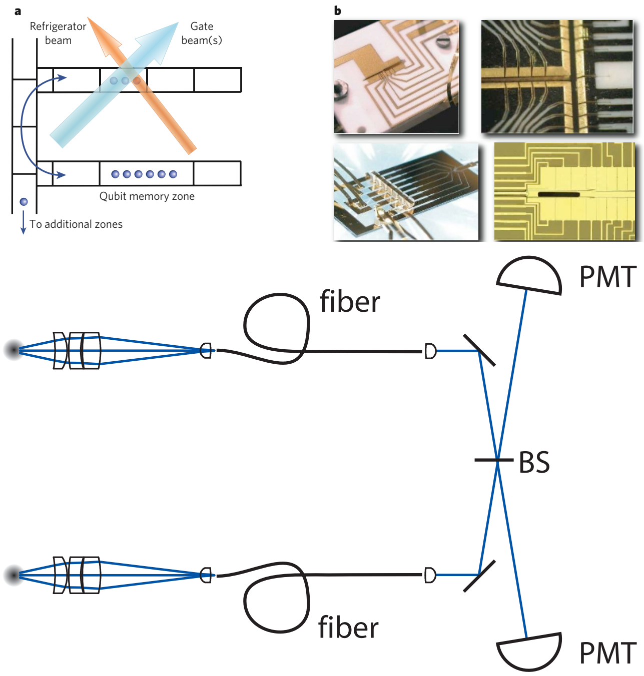

FIG. 3: Ion trap multiplexing. (a) Entanglement can be propagated to larger collections of trapped ions by performing quantum gates on small collections of ions (where the motion is under quantum control) and then physically shuttling the ions to different trapping regions. (b) This approach may require more advanced trapping structures that will likely be fabricated on chip structures (courtesy, D. J. Wineland, NIST). (c) Atoms can be entangled over remote distances through the emission, interference, and detection of photons, depicted with a beamsplitter (BS) and photomultiplier detectors (PMT).

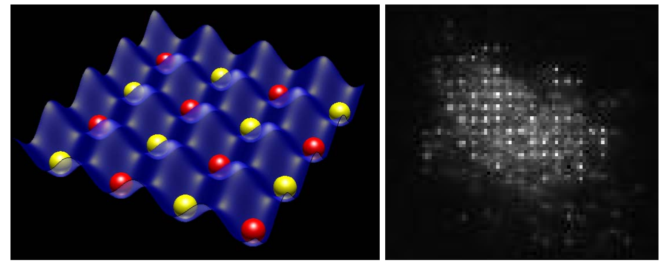

FIG. 4: (a) Optical Lattice of cold atoms formed by multi-dimensional optical standing wave potentials (courtesy J. V. Porto, NIST). (b) Image of atoms confined in an optical lattice (courtesy D. Weiss, Penn State University).

VII. NEUTRAL ATOMS AND OPTICAL LATTICES

A natural host of neutral atoms for quantum information purposes is the optical lattice - an array of cold atoms confined in free space by a pattern of crossed laser beams[121]. The lasers are typically applied far from atomic resonance, and the resulting ac Stark shifts in the atoms results in an effective external trapping potential for the atoms that is proportional to the squared optical electric field amplitude. For appropriate standing wave laser beam geometries, this can result in a regular pattern of potential wells in any number of dimensions, with lattice sites spaced by roughly an optical wavelength (Fig. 4). Perhaps the most intriguing aspect of optical lattices is that the dimensionality, form, depth, and position of optical lattices can be precisely controlled through the geometry, polarization, and intensity of the external laser beams defining the lattice. The central challenges in using optical lattices for quantum computing are the controlled initialization, interaction, and measurement of the atomic qubits. However, there has been much recent progress on all of these fronts in recent years.

Optical lattices are typically loaded with 10^3-10^6 identical atoms, typically with nonuniform packing of lattice sites for thermal atoms. However, when a Bose condensate is loaded in an optical lattice, the competition between intrasite tunnelling and the on-site interaction between multiple atoms can result in a Mott-insulator transition where the same number of atoms (e.g., one) reside in every lattice site[121,122]. Given this external initialization of the atomic qubits, the initialization and measurement of internal atomic qubit states in optical lattices can in principle follow exactly from optical pumping and fluorescence techniques in ion traps described above.

The interaction between atomic qubits in optical lattices can be realized in several ways. Optical lattice potentials can depend upon the internal qubit level (e.g., one state's valley can be another state's hill), so that atoms in lattices can be shifted to nearly overlap with their neighbors conditioned upon their internal qubit state through a simple modulation of the lattice light polarization or intensity. Adjacent atoms can thus be brought together depending on their internal qubit levels, and through contact interactions, entanglement can be formed between the atoms. This approach has been exploited for the realization of entangling quantum gate operations between atoms and their neighbors, as depicted in (Fig 4a)[123]. Another approach exploits the observation that when atoms are promoted to Rydberg states, they possess very large electric dipole moments. The Rydberg "dipole blockade" mechanism prevents more than one atom from being promoted to a Rydberg state, owing to the induced level shift of the Rydberg state in nearby atoms[124]. This effect therefore allows the possibility of controlled interactions and entanglement. Recently, the Rydberg blockade effect was observed in exactly two atoms confined in two separate optical dipole traps[125,126], and it should be possible to observe this between atoms in an optical lattice.

Applying optical lattices to quantum computing involves a general tradeoff in the atom spacing. With the natural spacing of order the wavelength of light, the atoms are close enough for large interactions, but they are too close to spatially resolve for individual initialization and addressing. On the other hand, larger optical lattice spacings allow the individual addressing and imaging of the atoms (Fig 4b), at the expense of much smaller interactions for the generation of entanglement. In any case, optical lattices continue to hold great promise for the generation of large-scale global entangled states that could be exploited in alternative quantum computing models, such as cluster-state quantum computing[10].

VIII. NUCLEAR MAGNETIC RESONANCE

More than 50 years after its discovery[127,128], research in nuclear magnetic resonance research is still bringing new insight on quantum dynamics and control. In 1996, Cory et al.[129] as well as Gershenfeld and Chuang[130] suggested how to use the nuclear spins in a liquid to build a quantum processor. The idea sprang from the realization that nuclear magnetic moments are well suited to bear quantum information for several reasons. They can be idealized as two level systems, isolated from their environment, and controlled with relative ease, taking advantage of the many years of engineering developed in MRI and related technologies.

Immersed in strong magnetic field, nuclear spins can be identified through their Larmor frequency. In a molecule, nuclear Larmor frequencies vary from atom to atom due to shielding effects from electrons in molecular bonds. Irradiating the nuclei with resonant radio-frequency (RF) pulses allows manipulating them one at a time, inducing generic one-qubit gates. Two qubit interactions are implemented using the indirect coupling mediated through electrons. In the liquid state, the rapid tumbling of the molecules effectively cancels the direct dipolar coupling between nuclei, which is especially important for eliminating intermolecular interactions. Measurement is achieved by observing the induced current in a coil surrounding the sample of an ensemble of such qubits.

The other required element is to prepare a fiducial state to initiate the information processing. It was suggested to turn a thermal state into a *pseudo-pure* state, i.e. an ensemble consisting of the desired initial pure state and the total mixed one. It was quickly noticed that the proposed procedure was exponentially inefficient. The problem was resolved, at least in theory, through the discovery of algorithmic cooling[131,132]. The use of highly mixed states also raised questions about the quantumness of NMR[133] and the origin of the power of quantum computers. This spurred research leading to new models of computation[12] and algorithms[134,135], suggesting that there is quantumness despite the use of high-entropy initial states.

The exquisite control of liquid-state NMR has allowed the implementation of small algorithms, providing proof-of-principle of control of quantum processors. This improvement came not only because of the dramatic development of the hardware but also the "software", i.e. using astute pulse generation, such as composite pulses or shaped pulses to make them more precise and robust to imperfection. The long history of pulse techniques from NMR spectroscopy and MRI have recently been augmented by the new quantum information focus. Examples include strongly modulated pulses[136] and gradient ascent pulse engineering (GRAPE)[137].

This improved control allowed NMR quantum computation to manipulate quantum processors of up to a dozen qubits[138–141]. Important steps towards the implementation of quantum error correcting protocols have also been made with NMR. Despite the loss of polarization in the preparation of the initial pseudo-pure states, these experiments showed that there was sufficient control to demonstrate the fundamental workings of QEC, but not yet enough for fault tolerance.

Despite its exquisite control, NMR in the liquid state has its limitations. The key problem is the scalability limitation arising from the inefficiency of pseudo-pure-state preparation. One direction to address this limitation is to move to solid-state NMR. A variety of dynamic nuclear polarization techniques exist in the solid-state, which partially helps NMR's principal limitation to scalability. The lack of molecular motion allows the use of nuclear dipole-dipole couplings, which may speed up gates by one or two orders of magnitudes. A recent example of a step toward solid-state NMR quantum computation can be found in implementation of many rounds of heat bath algorithmic cooling[131,132] using specially made crystal of crotonic acid. Different issues of quantum control arise for this type of technology, and lessons learned from solid-state NMR experiments may easily be transferred to the solid state silicon devices discussed in Sec. X, and to other technologies. Another possibility to extend solid-state NMR systems is to include electrons to assist in nuclear control[142,143]. These techniques have possible application in the diamond-NV system, to be discussed in Sec. XI.

Despite its limitations, liquid-state NMR has played and continues to play an important role in the development of quantum control. However, the future of NMR lies in the solid-state, in low temperatures, and in the ability to better control electrons and their interactions with the nuclei. In this way, the lessons learned in NMR quantum computation research are merging with the solid-state proposals of the ensuing sections.

IX. QUANTUM DOTS

Quantum dots often go by the name "artificial atoms." This terminology highlights their most obvious feature for use in quantum computing. They occur when a small nanostructure (in analogy to a single atomic nucleus) binds one or more electrons or "holes" (absences of electrons) in a semiconductor. They have discrete energy levels that allow coherent control in the similar ways that trapped ions and neutral atoms are controlled, and hence their promise for providing useful qubits is similar. However, unlike atoms, they do not need to be cooled and trapped; they are usually born already integrated into a solid-state host which may be appropriately refrigerated.

Quantum dots come in many varieties, depending on how they are grown. In all cases, they confine electrons or holes in a small region of a semiconductor. Some quantum dots are semiconductor nanostructures grown in chemical solution; these dots are then deposited onto another surface, which may or may not be another semiconductor. More common for quantum computation research are dots

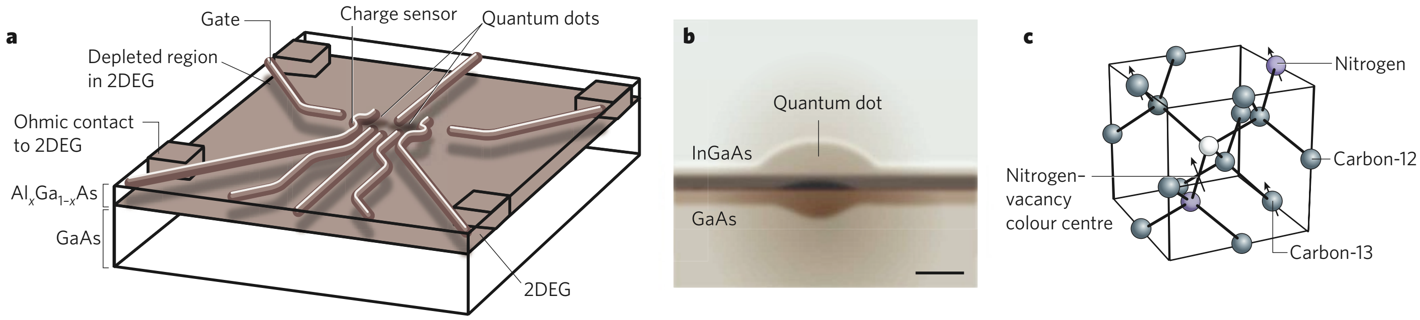

FIG. 5: (a) An electrostatically confined quantum dot. (b) A self-assembled quantum dot. (c) The atomic structure of a nitrogen-vacancy center.

grown by molecular beam epitaxy (MBE), in which semiconductor crystals are grown layer by layer, allowing the stacking of different kinds of semiconductor. A quantum well is defined by a two-dimensional plane of a lower bandgap semiconductor (for example, GaAs) embedded in a larger-bandgap semiconductor (e.g. AlGaAs); electrons become confined in the lower bandgap layers, which may be only a few atomic layers thick. Those electrons might originate from controlled optical excitation or current injection. In some devices they spontaneously "fall" into the well from a nearby layer of n-type dopants which give up their electrons for the lower potential of the quantum well. A quantum well becomes a quantum dot when an additional confinement in the remaining two dimensions is added. Two important differing classes of quantum dots are *self-assembled quantum dots*, where a random semiconductor growth process creates that two-dimensional confinement, or *electrostatically defined quantum dots*, in which that confinement is defined by electrostatic potentials created by lithographically fabricated metallic gates.

One key difference between these two types of quantum dots is the depth of the atom-like potential they create. Electrostatically defined quantum dots are typically defined by small regions in which a two-dimensional electron gas is depleted. These dots behave well when the distance electrons may travel in the two-dimensional electron gas before scattering is larger than the spatial scale of the structures defining the dot; these devices therefore require the very low temperatures (<1 K) accessible with dilution refrigerators. Loading and measuring electrons trapped in these dots is accomplished by dynamically altering the dot potential by changing gate voltages. Self-assembled quantum dots, in contrast, typically trap electrons with energies much larger than thermal energies at temperatures several times larger than a bath of liquid helium (4 K). Their potentials may be electrically controllable but coherent manipulation is generally performed using optical rather than electrical techniques.

One of the earliest proposals for quantum computation in semiconductors, that of Loss and DiVincenzo,[144] suggested the use of electrostatically defined quantum dots, whose key advantages over self-assembled dots is that their location on a semiconductor wafer may be carefully designed. This proposal envisioned arrays of dots each containing a single electron, whose two spin states provide qubits. Quantum logic would be accomplished by changing voltages on the electrostatic gates to move electrons closer and further from each other. As the electron wave functions begin to overlap, they form molecular-like orbitals. These depend on electron spin due to the Pauli exclusion principle, preventing symmetric spin-states from occupying the same molecular orbital. This combination of Coulomb repulsion with quantum mechanical Fermi-Dirac statistics is known as the exchange interaction, and in the Loss and DiVincenzo scheme it is tuned to provide universal quantum logic. In their proposal, individual electron spins could be controlled via microwave transitions tuned to the spin-splitting in a magnetic field, and spin measurement could occur via spin-dependent tunneling processes, reminiscent of technologies in modern magnetic memory.

Since this seminal proposal, substantial progress toward these goals has been reached. The spin-dependent tunneling processes[145,146] needed for the measurement of single spins in quantum dots were demonstrated, and such work has since evolved to employ a *quantum point contact* (QPC), which is a one-dimensional constriction in the potential seen by an electronic current. This constriction is sufficiently sensitive that it may be opened and closed by the charge of a single trapped electron in a nearby quantum dot. The QPC thereby allows the measurement of a single electron charge; to measure a spin, the ability of a single electron to tunnel into or out of a quantum dot must be altered by its spin state. This has been done by changing the magnetic field to alter the energy of a single quantum dot[147], and by changing the potential between two-quantum dots[29,148]. The control of individual spins in these quantum dots has also been demonstrated via direct generation of microwave magnetic fields[149] and by applying microwave electric fields in conjunction with the spin-orbit interaction[150]. These techniques have allowed measurement of single spin dephasing (T_2^*) and decoherence (T_2) times by spin-echo techniques[151]. This single-spin control turns out to not be necessary for quantum computation; qubits may be defined by clusters of exchanged-coupled spins, with effective single-qubit logic controlled by the pairwise exchange interaction[152]. The T_2 decoherence of a qubit defined by an exchange-coupled electron-pair was measured, also using the spin-echo technique[29]. Voltage control of a two-electron qubit by the exchange interaction has the particular advantage of being fast; the single-qubit gates accomplished this way occur in hundreds of picoseconds, which is faster than a direct microwave transition for a single spin.

Most of the work described so far has occurred in dots made in group III-V semiconductors. A critical limitation to these types of quantum dots is the inevitable presence of nuclear spins in the semiconductor substrate. Their hyperfine interactions with the quantum-dot electron spins cause a variety of interactions. Energy exchange between electron spins and nuclei is important at low magnetic fields, as observed experimentally[146,148], but more critical are dephasing effects. The random orientation of nuclear spins at even relatively low temperature creates an effective inhomogeneous magnetic field, which leads spins to dephase at a rate of $T_2^* \sim$10 ns. This static dephasing may be refocused by spin-echo techniques, and may also be suppressed by recently discovered effects in which electrically induced electron spin flips pump nuclear spins to alter the hyperfine gradient[153].

But decoherence is still limited by the dynamic spin-diffusion due to nuclear dipole-dipole interactions. This process has been known in the field of electron spin resonance for over 50 years[154], but has been revisited by modern quantum information research[155], where it is found that in GaAs, nuclear spin diffusion should limit electron spin decoherence times (T_2) of a few μs, close to the values observed in Refs. 29 and 151. Suppressing this decoherence requires either extraordinary levels of nuclear polarization, or the dynamic decoupling of nuclear spin noise by rapid sequences of spin rotations[18]. The latter approach stems from a long history in magnetic resonance[16,17], and recent theoretical developments in this area suggest a promising future for extending decoherence times due to nuclear spin-diffusion noise[19–21].

One way to eliminate nuclear spins is to define similar dots in nuclear-spin-free group-IV semiconductors (i.e. silicon and germanium). Many of the accomplishments demonstrated in GaAs have recently been duplicated in SiGe-based[156–158] or metal-oxide-semiconductor silicon (MOS)-based[159,160] quantum dots, including single electron charge sensing[161] and the control of tunnel coupling in double dots[162].

Given the experimental progress in the development of electrostatically defined quantum dots, it is natural to ask what remains to be done to reach the type of quantum computer envisioned a decade ago[144]. Unfortunately, the demonstrated interactions between these types of quantum dots are extremely short-range, and suggest a quantum-computer architecture with nearest-neighbor interactions only. When considering the requirements of fault-tolerant QEC, this provides a substantial constraint[163]. Although fault-tolerant operation may be reasonable with a dense, two-dimensional network of neighbor-coupled qubits[164,165], such a network may not be possible due to the space required for the electrical leads required to define each qubit. It seems inevitable that a scalable architecture will require the transport of coherent quantum information over longer distances. A number of methods for accomplishing this in electrostatically defined quantum dot systems have been proposed, for example using the coherent shuttling of spins in charge-density waves[166]. However, it remains experimentally uncertain how far spin coherence may be reliably transferred on a chip.

Photonic connections between quantum dots may ultimately prove more reliable, and for this reason optically controlled, self-assembled quantum dots have also undergone substantial development. These quantum dots have a few advantages over atoms. Besides the lack of need for motional cooling, their large size increases their coupling to photons (known as the "mesoscopic enhancement" of the oscillator strength.) For some devices they may be electrically pumped into their excited states[167], which may have architectural advantages in future devices. One potential use for these quantum dots in quantum information technologies is as a single photon source, since after optical or electrical pumping they efficiently emit one and only photon[94,167] which may be used for such applications as quantum secret sharing[168] or photonic quantum computers as discussed above.

The earliest proposals for the use of optically controlled quantum dots for quantum computing[169–171] stressed the importance of optical microcavities for allowing photons to mediate quantum logic between the dots (see Sec. IV). Many schemes have been devised, often based on early proposals for establishing entanglement between atoms[56]. Recently, it has been realized that the photonic wiring of quantum-dot-based quantum computers should be possible with experimentally realistic cavities[54,55,172]. The strong-coupling regime is particularly challenging in solid-state settings where surface effects on lithographically defined microstructures degrade the cavity Q. Most schemes for optically connecting quantum dots via microcavities and waveguides only require a high Purcell factor or cooperativity parameter. Although solid-state microcavities may have smaller Q, Q/V may be very large due to very small mode volumes, on the scale of a cube of the optical wavelength. For this reason, there has been substantial development of systems incorporating a quantum dot in a microcavity. There are a variety of microcavity designs; those that have demonstrated strong-coupling operation include distributed Bragg reflector micropillars[173], microdisks/microrings[174], and defects in photonic bandgap crystals[175,176].

The control and measurement of self-assembled quantum dots has also made recent progress. This research is hindered by the random nature of these quantum dots; unlike atoms, their optical characteristics vary from dot to dot, so many experiments that work for one device may fail for another. Nonetheless, rapid optical initialization of spin-qubits in quantum dots has been demonstrated for both electrons and holes[31,177,178]. Optical quantum non-demolition measurements have been demonstrated[179,180], and single-spin control via ultrafast pulses has been developed[30,31,181]. A remarkable feature of this optical control is that these qubits may be controlled very quickly, on the order of picoseconds, potentially enabling extremely fast quantum computers. Initial demonstrations of quantum logic between single quantum dots in microcavities and single photons have also begun[182].

Although single qubit preparation, control, and measurement in single, self-assembled quantum dots are now well established, substantial challenges remain in scaling to larger systems. First, the many schemes for establishing entanglement between quantum dots are either probabilistic or insufficiently robust to photon loss, which is typically a large problem in realistic chip-based devices. Second, self-assembly leads to dots that are randomly placed spatially and spectrally. Emerging fabrication techniques for deterministic placement of dots[183] and dot tuning techniques[182,184] may remedy this problem in the future. Finally, these quantum dots suffer the same nuclear-spin-induced decoherence issues faced by the electrostatically defined quantum dots, and will likely require similar dynamical decoupling methods. Another approach under consideration is the use of a hole spin rather than an electron spin, since in GaAs holes have spatial wavefunctions with substantially smaller overlap with the nuclear spins, weakening the effects of this interaction, and potentially extending decoherence to the lifetime limit[185]. In bulk semiconductors, holes typically have much shorter relaxation times due to stronger spin-orbit relaxation; their utility for quantum-dot qubits remains to be seen. Initial results in the initialization[178] and the measurement of long T_2^* values[186] show remarkable promise. These and other results suggest a long future for improving the viability and scalability of optically controlled quantum dots for large-scale quantum computation.

X. IMPURITIES IN SILICON

In 1998, at the same time as the first demonstrations of quantum computing in NMR systems were being realised and close to the appearance of the Loss and DiVincenzo[144] scheme, Bruce Kane developed a proposal to marry NMR quantum computation with a silicon-based system[187]. The Kane proposal was highly influential, primarily since it seems to be highly consistent with extant silicon-based microelectronic technologies. This proposal embeds quantum information in the state of nuclear-spin ($I = 1/2$) qubits. However, unlike in liquid-state NMR they are *single* nuclear spins of individual phosphorus ^{31}P nuclei embedded in isotopically pure silicon-28 (^{28}Si), which has a nuclear spin $I = 0$. Phosphorus is a standard *donor* in silicon, donating one electron to attain the same electronic configuration as silicon. At low temperatures this donor electron is bound to the phosphorus nucleus. These donor electrons are critical to the operation of the quantum computer: they mediate a nuclear spin interaction, allow qubits to be addressed individually and are integral to measuring the spin state of the qubits.

Coincidental to quantum computing, isotopically purified silicon started to become available[188], and bulk samples of this silicon have now shown remarkable properties supporting the Kane proposal. The electron spins in ^{28}Si show encouragingly long T_2 times, exceeding 60 ms, as demonstrated by electron-spin resonance[32]. This coherence has recently been extended to a few seconds by swapping the electron coherence with the ^{31}P nuclear spin[33]; the potential for much longer nuclear spin decoherence times of minutes or longer has further been seen in NMR dynamic decoupling experiments[34] on ^{29}Si in ^{28}Si. Another remarkable property of isotopically purified silicon is that the optical transitions related to the ^{31}P donor become remarkably sharp in comparison to isotopically natural silicon[189]. Unlike in any other semiconductor to date, the optical transitions are sharp enough to resolve the hyperfine splitting due to the ^{31}P nuclear spin in the optical spectra[189]. This has enabled rapid (less than 1 second) electron and nuclear spin polarization by optical pumping[190], orders of magnitude faster than the polarization obtained in 50 years of research into silicon spin polarization[191,192]. Rapid polarization is critical for the success of proposals such as Kane's, since T_1 times (see Sec. III) for electron and nuclear spins in silicon are notoriously long at low temperature and qubits must be constantly initialized for QEC.

Quantum logic in the Kane proposal is similar to the proposal for quantum dots of Loss and Divincenzo[144] discussed in the previous section. The wave functions of the electrons bound to phosphorus impurities are controlled by nanometer-scale metallic gates, and the resultant exchange-split energy levels in turn affect the energy levels of the nuclear spins, due to the strong Fermi contact hyperfine coupling between the electron spins and the nuclei. This effect, in addition to magnetic resonance techniques using radio-frequency (RF) magnetic fields, allows universal control of single spins and nearest-neighbor two-qubit quantum gates.

Additional ideas for quantum computing in silicon include the 'spin resonance transistor,' in which the varying gyromagnetic ratio of spins in different semiconductors allow the electrical control of donor-bound electronic spins in Si/Ge alloys without the need for RF fields[193]. Further departures[194] include eliminating the electronics altogether and computing with arrays of spin-1/2 ^{29}Si in ^{28}Si, or using dipolar couplings between donor-bound electron spins[195]. Much recent work has focused on silicon-based quantum dots, as discussed in the previous section.

The novel quantum logic ideas of silicon quantum computing proposals have not yet been demonstrated, since single-spin measurement in this system must push existing nanotechnology techniques. Unfortunately, the single-spin measurement techniques described in the other sections of this review, such as those for electrically gated quantum dots (Sec. IX), cannot be easily applied to silicon. Optical detection of single spins, as established for self-assembled quantum dots (Sec. IX) and diamond-NV centers (Sec. XI), is hindered by silicon's indirect bandgap, requiring heroic

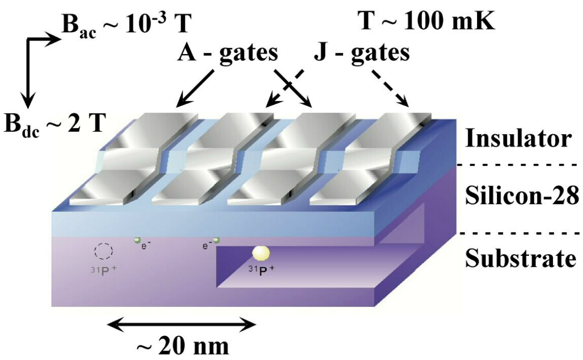

FIG. 6: Schematic of the original Kane architecture

improvement by cavity QED[196] (Sec. IV). Kane's solution to the problem of measurement begins by coherently transferring the state of a single nuclear spin to the donor electron, and then transferring that electron spin to charge by comparing it to the spin of a nearby donor, again relying on the Pauli exclusion principle. Then, single electron charges near a Si/SiO_2 interface must be sensed.

For single-charge sensing in silicon, there is substantial prior art in the development of silicon-based single electron transistors (SETs) operating as extremely sensitive charge amplifiers[197]. Charging of silicon-based quantum dots has been detected by SETs operating at RF frequencies, making critical use of multiple devices for noise cancellation[198]. Recently, silicon-based transistors have aided the detection of the ion-implantation of single dopants[199], a technique which adds to STM techniques[200] for placing phosphorus impurities in prescribed atomic locations. Single spin detection has not yet been accomplished, but innovations in electrically detected magnetic resonance (EDMR) have resolved small ensembles of phosphorous impurity spins[201], and the spin states of single impurities in the oxides of silicon-based field-effect transistors have been successfully detected[202]. Some combination of these techniques are likely to achieve single spin detection in the near future.

What existing measurements with SETs reveal[200], as well as some NMR data[34], is that measurement and decoherence in this system are limited by $1/f$ noise, a familiar noise source in classical silicon-based electronics due to random charge states at silicon/insulator interfaces. This noise source is no surprise, as indicated by Kane[187]. Reduction of this noise source to the small levels required for fault tolerant quantum computing requires the development of clean, high-quality silicon/insulator/metal interfaces. This challenge is expected to be surmountable due to silicon's primary advantage: the massive infrastructure in high-quality silicon microprocessing that already exists for large-scale classical computing. Despite the challenges in measurement and nanofabrication, silicon-based quantum computers maintain substantial hope of "taking off" due to their ability to leverage existing resources for very large scale integration once the fundamental difficulties are solved.

XI. IMPURITIES IN DIAMOND

Diamond is not only the most valuable gemstone, but also an important material for semiconductor technology. It holds promise to replace silicon owing to unprecedented thermal conductivity, high charge carrier mobility, hardness, and chemical inertness. Dopants in diamond can be used as a platform for quantum information processing devices, like the phosphorus impurities in silicon discussed in the previous section.

Diamond hosts more than 500 documented optically active impurities, known as colour centres, since they are responsible for coloration in crystals. Nitrogen, being the most abundant impurity in diamond, forms about ten optically active defects including the nitrogen-vacancy (NV) centre. The structure of the NV centre (shown in Fig. 5c) consists of a substitutional nitrogen at the lattice site neighboring a missing carbon atom. It is established experimentally that these NV centres can exist in two charge states as neutral and negatively charged. Several unique properties make the NV centres particularly suitable for applications related to quantum information processing. First, the NV center exhibits strong optical absorption and high fluorescence yield that allows the detection of a single defect using confocal fluorescence microscopy[203] (and recently developed nonlinear microscopy techniques allow far field addressing of defects with a resolution of about 5.6 nm[204]). Second, it is extraordinarily photostable, meaning that it does not show any photoinduced bleaching upon strong illumination. Third, the paramagnetic ground state of a charged NV defect can be used as a qubit[205]. Finally, the fluorescence intensity of a NV defect is spin-dependent, which allows the readout of its spin state via counting the number of scattered photons[206].

The remarkable properties of the NV centre have already found application as a single photon source for quantum cryptography[207], including the first commercial single photon source device available on the market. Spin-based quantum information processing can also profit from the outstanding properties of the diamond lattice.

The negatively charged state of the NV centre is formed by four electrons associated with dangling bonds of the vacancy, one electron originating from nitrogen, and an additional electron from an external donor. Two out of these six electrons are unpaired forming a triplet spin system. Spin-spin interactions split the energy levels with magnetic quantum numbers $m_s = 0$ and $m_s = 1$ by about 2.88 GHz. The degeneracy of $m_s = \pm 1$ states, arising from C_{3v} symmetry, can be lifted further by applying an external magnetic field. Under optical illumination, spin-selective relaxations lead to an efficient optical pumping of the system into the $m_s = 0$ state, allowing fast (250 ns) initialization of the spin qubit[208]. The spin state of a NV centre can be manipulated by applying resonant microwave fields[36]. Hence all the necessary ingredients to prepare, manipulate and readout single-spin qubits are readily available in diamond. The first demonstration of quantum process tomography in solid state was realized on a single diamond spin shortly after the discovery of spin manipulation techniques in this system[209].

In contrast to GaAs quantum dots, spins in NV centres show long decoherence times, even at room temperature. The observed decoherence times depend on the growth method of the diamond lattice. In low-purity technical grade synthetic material (type 1b diamond), single substitutional nitrogen atoms cause major effects on the electronic spin properties of NV centres. Flip-flop processes from the electron spin bath create fluctuating magnetic fields at the location of the NV centre limiting the coherence time to a few microseconds. It was shown that by applying an external magnetic field, these spin fluctuations can be suppressed substantially[210]. Furthermore, the electron spin bath can be polarized in high magnetic fields leading to complete freezing of nitrogen spin dynamics[211]. Another way to prolong coherence times comes from the possibility to grow ultrapure diamond. Recently, it was shown that a chemical vapor deposition process allows reducing the impurity concentration down to about 0.1 parts per billion. In such materials, the nuclear spin bath formed by ^{13}C nuclei (natural abundance of about 1.1 percent) governs the dynamics of electron spin of NV centres[212]. The decoherence of electron spins can be remarkably long if these nuclei are removed. By growing isotopically enriched ^{12}C diamond it is possible to increase T_2 to 2 ms for 99.7% pure material[35].

In lattices that do contain ^{13}C nuclei, it is found that those nuclear spins located close to the NV centre are excluded from the spin dynamics owing to an energetic detuning from the dipolar interaction with the electron spin. These nuclear spins, located in the "frozen core" extending to about 4 nanometers from the electron spin, can be initialized and controlled by the NV centre. They can themselves be used as a quantum memory, which may be particularly useful in quantum repeaters[213]. For example, the state of the electron spin can be mapped onto the nuclear spin state (which phase memory can be as long as seconds) and retrieved with very high fidelity[214]. Three-spin entanglement was also demonstrated for two nuclei coupled to the electron spin[37].

Intrinsic coupling of stationary qubits (spins) to flying qubits (photons), manifested for example in the effect of electromagnetically induced transparency (EIT)[215], allows coupling between distant NV centres. This capability enables quantum computation schemes based on probabilistic entanglement between distant qubits[53], as discussed above in the context of trapped ions. Optical transitions of NV centres may be sufficiently "atom-like" in that they are not affected by dynamic inhomogeneity (i.e. they have a transform-limited linewidth), potentially enabling interference from two distant defects. Static inhomogeneity caused by strain present in the crystal lattice (which is on the order of 30 GHz for high quality synthetic crystals) can be compensated by applying an external electric field (Stark effect)[216].

Deterministic schemes for creating entanglement between distant spin qubits via a photonic channel require coupling of optical transitions to a high-Q cavity (see Sec. IV). The first experimental demonstration of such coupling was reported for whispering gallery modes of silica microspheres[217]. More recently, monolithic diamond photonic structures were designed and fabricated, including waveguides and photonic crystal cavities[218,219]. When incorporated into photonic structures, diamond defects can provide the platform for an integrated quantum information toolbox, including single photon sources and quantum memory elements.

Many initial benchmark demonstration experiments on coherent control of a diamond quantum register were carried out on naturally formed NV centres. However, for many applications, in particular those related to coupling of NV centres to optical cavities, it is necessary to control the position of NV centres. Although creation of NV centres in nitrogen-rich diamond by electron irradiation is an established technique, its poor positioning accuracy is not suitable for quantum information devices. Recently, implantation techniques relying on atomic and molecular implantation of nitrogen in ultrapure diamond using focused ion beams were reported[212]. Although generation of NV defects remains probabilistic owing to fluctuation of the ion number in the beam, novel approaches involving cold ion traps as a source are also proposed. Note that use of single cold ions not only eliminates statistical fluctuation of the number of implanted ions, but also allow Ångstrom-level accuracy of positioning them into crystal[220,221].

While most of the quantum information processing work was performed on NV centres, new emerging systems based on nickel- and silicon-related defects were also reported recently[222–224]. Optical properties of nickel-related centres outperform NV centres owing to their narrow-band, near-infrared emission at room temperature which is important for free-space and fiber-based quantum communication. The silicon-vacancy defect is particularly interesting because it is known to have paramagnetic ground electron state similar to NV defects. Therefore it is likely that other defect centers in addition to NV centres have strong potential for use in quantum information technology.

XII. SUPERCONDUCTING QUBITS

If you tried to make a quantum computer using classical electronics, you would find that the resistance of normal metals would constantly leak the quantum information into heat, causing rapid decoherence. This problem may be alleviated using zero-resistance superconducting circuits.

The basic physics behind superconducting qubits is most easily explained by analogy to the simpler quantum mechanical system of a single particle in a potential. To begin, an ordinary LC-resonator circuit provides a quantum harmonic oscillator. The magnetic flux across the inductor Φ and the charge on the capacitor plate Q have the commutator $[\Phi, Q] = i\hbar$, and therefore Φ and Q are respectively analogous to the position and momentum of a single quantum particle. The dynamics are determined by the "potential" energy $\Phi^2/2L$ and the "kinetic" energy $Q^2/2C$, which results in the well-known equidistant level quantization of the harmonic oscillator. However, this level structure does not allow universal quantum control. Anharmonicity is needed, which is available from the key component in superconducting qubits: the Josephson junction. A Josephson junction is a thin insulating layer separating sections of the superconductor, in which quantum tunneling of Cooper pairs may still occur. The quantization of the tunneling charge across the junction brings a cosine term in the potential energy. Thus, the total potential in the parallel circuit shown in Fig. 7a is

$$U(\Phi) = E_J \left[1 - \cos\left(2\pi \frac{\Phi_{\rm ex} - \Phi}{\Phi_0}\right)\right] + \frac{\Phi^2}{2L}, \qquad (4)$$

in terms of the flux quantum $\Phi_0 = h/2e$ and the Josephson energy $E_{\rm J}$, which is proportional to the junction critical current. Two of the quantized levels in the anharmonic potential $U(\Phi)$ give rise to a qubit.

There are three basic types of superconducting qubits, *charge*, *flux*, and *phase*, which are conveniently classified by the bias flux $\Phi_{\rm ex}$. The ratio E_J/E_C is also crucial, where $E_C = e^2/2C$ is the single electron charging energy characterizing the charging effect, i.e. the kinetic term.

The *charge* qubit omits the inductance. There is no closed superconducting loop, and the potential is simply a cosine one with a minimum at zero phase. It is sometimes called a *Cooper-pair box*, as it relies ultimately on the quantization of charge into individual Cooper pairs, which becomes a dominant effect when a sufficiently small "box" electrode is defined by a Josephson junction. Qubits of this type were first proposed[225,226] and developed[227,228] in the regime of $E_J/E_C \ll 1$, and later extended to the other limit and named *quantronium*[229] and *transmon*[230]. The nature of the wave functions and their sensitivity to charge fluctuations depend critically on the choice of E_J/E_C.

In the *flux* qubit[231–233],, also known as a *persistent-current qubit*, $\Phi_{\rm ex} \simeq \Phi_0/2$ is chosen to give a double-well potential. The two minima correspond to persistent current going in one direction along the loop or the other. Often, the inductance is substituted by an array of Josephson junctions. The kinetic energy term is kept small, $E_J/E_C \gg 1$.

In the *phase* qubit[234], the potential is biased at a different point, for example $\Phi_{\rm ex} \simeq \Phi_0/4$, and again $E_J/E_C \gg 1$. Unlike the flux qubit, the phase qubit uses the two-lowest energy states in a single metastable potential well which is anharmonic.

All superconducting qubits are realized in electric circuits, in which one may tune the potential and therefore the wave function by changing the macroscopically fabricated inductance, capacitance, and the barrier configuration of the qubits. Likewise, this potential may be dynamically altered by various means to give complete quantum control. Typically, the qubit excitation frequency is designed at 5–10 GHz, which is high enough to avoid thermal population at the low temperatures available in dilution refrigerators ($\sim$ 10 mK; $k_B T/h \sim 0.2$ GHz) and low enough for ease of microwave engineering. The single-qubit gates are implemented with a resonant microwave pulse of 1–10 ns inducing Rabi oscillations. Such pulses are delivered to the qubit locally using on-chip wires.

Thanks to their macroscopic nature, it is straightforward to couple superconducting qubits to each other; neighboring qubits couple strongly either capacitively or inductively. These direct couplings have allowed simple quantum logic gates[45,235,236], and well-controlled generation of entangled states studied by quantum state tomography[40]. However, for large-scale quantum computer architectures, more adjustable coupling schemes are desirable. Indirect couplings mediated by a tunable coupler have been developed for switching on and off the interaction between qubits[237,238]. The application of such tunably coupled qubits to adiabatic quantum computing is also under investigation[239–241].

Exchange of quantum information between arbitrary pairs of distant qubits may be possible by using a quantum bus, or *qubus*. Coupling between superconducting qubits and a microwave transmission-line resonator is a powerful tool for this purpose. The one-dimensional resonators have an extremely small mode volume and thus strong cooperativity factor[242] (see Sec. IV). Qubits can interact via real- or virtual-photon exchange through the resonant/off-resonant resonator. Such systems have allowed two-qubit gate operations between qubits several millimeters apart[243–245], and also a variety of cQED-type experiments in the strong coupling regime[242,246–253].

The development of coupling schemes with transmission lines and resonators has opened new and large potentials for quantum microwave optics on a chip. Josephson junctions play multiple roles in these experiments; they are used to create qubits as artificial atoms, as discussed, but they also act as nonlinear inductors. The strong qubit-resonator coupling as well as the strong nonlinearity of resonators involving Josephson junctions may allow the exploration of unprecedented regimes of quantum optics, which may, for example, lead to the use of continuous-variable quantum information in superconducting circuits. Still to be demonstrated, for example, are a single microwave photon detector and on-chip homodyne mixing, which would further enrich the microwave quantum-optics tool box.

Adding a measuring device to superconducting circuits without introducing extra decoherence can be challenging. The switching behavior of a current-biased Josephson junction at its critical current is commonly used as a threshold discriminator of the two qubit states. Such schemes have been successfully used in many experiments[229,233,234] and achieved a high measurement fidelity above 90%[39], though the qubit state after the readout is randomized due to measurement back-action. A recent, promising development is the demonstration of QND measurements in which a qubit provides a state-dependent phase shift for an electromagnetic wave in a transmission line[254–256]. This shift is then read out by electronics far from the qubit itself, projecting the qubit into the eigenstate corresponding to the measurement result. Again, nearly 90% fidelity has been demonstrated with non-demolition properties[256]. Highly efficient amplifiers are crucial for further improvement of the measurement fidelity. Integrations of quantum-limited amplifiers employing Josephson junctions may bring huge impact in this direction[257,258].

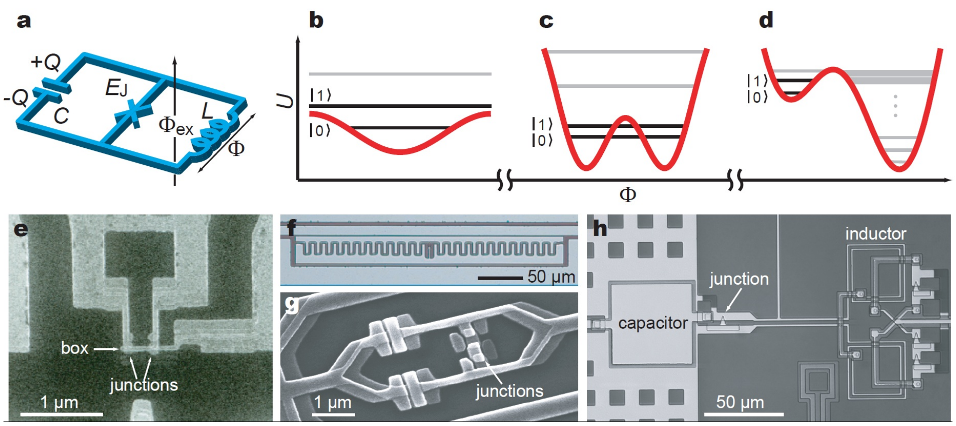

FIG. 7: (a) Minimal circuit model of superconducting qubits. Josephson junction is denoted by X. The capacitance C includes a contribution from the junction itself. (b)-(d) Potential energy $U(\Phi)$ (red) and qubit energy levels (black) for (b) charge, (c) flux, and (d) phase qubit, respectively. The potential for charge qubit is under a periodic boundary condition. (e)-(h) Micrographs of superconducting qubits. The circuits are made of Al films. The Josephson junctions consist of Al_2O_3 tunnel barrier between two layers of Al. (e) Charge qubit, or a Cooper pair box. (f) Transmon, a derivative of charge qubit with large E_J/E_C. The Josephson junction in the middle is not visible in this scale. The large interdigitated structure is a shunt capacitor. (g) Flux qubit. Two of the three junctions in the series provide inductance. (h) Phase qubit.

For effective fault-tolerant quantum computing, it is important to rapidly initialize qubits. QND measurements followed by feedback operations may enable this. Rapid cooling of qubits may also be induced by microwaves[259,260].

A notable feature of superconducting qubits is their macroscopic scale: they involve the collective motion of a large number ($\sim 10^{10}$) of conduction electrons in devices as large as 100 μm. Common wisdom is that superpositions of these larger, more “macroscopic” states should suffer faster decoherence than more “microscopic” systems, and indeed superconducting qubits have typically had the fastest decoherence times of all qubits under widespread development. However, the distressingly short decoherence times of a few nanoseconds observed in the earliest experiments have recently been extended to the range of many microseconds. The enhancement was accomplished by improved circuit designs to make the qubits more robust[41,44,229], by decoupling from the environment[230], and by reducing the noise processes that contribute to decoherence[261]. Much current work in superconducting circuit development deals with understanding and eliminating the noise still remaining. These noise processes vary for each qubit, but often seem to be connected to microscopic origins such as charge traps and spins in the amorphous oxides at the tunnel barriers and at the metal surfaces, or in the dielectrics for the insulating layers of capacitances and substrates[261,262]. This kind of process is common to multiple solid-state implementations of qubits; for example, phosphorous in silicon suffers a similar problem from the SiO_2 barrier, even though SiO_2 provides the “cleanest” insulating layer among semiconductors. Intensive material engineering research may eventually solve these problems.

Superconducting qubits provide a wide variety of promising tools for quantum state manipulations in electric circuits. Beautiful demonstrations of two-qubit quantum algorithms (Deutsch-Jozsa and Grover search) were reported recently[43]. With careful engineering, the fidelities for control and readout will be increased further. As the observed decoherence rates improve, these tools will allow more and more complex circuits, providing an optimistic future for large-scale quantum computation.

XIII. OTHER TECHNOLOGIES

The technologies we have discussed for implementing quantum computers are by no means the only routes under consideration. A large number of other technologies exhibiting quantum coherence have been proposed and tested for quantum computers.

As one example, the single photons in photonic quantum computers could be replaced by single, ballistic electrons in low-temperature semiconductor nanostructures, which may offer advantages in the availability of nonlinearities for interations and in detection. As another emerging example, quantum computers based on ions and atoms may benefit from using small, polar molecules instead of single atoms, as the rotational degrees of freedom of molecules offer more possibilities for coherent control[263,264].

New materials beyond those we have discussed are also being investigated in the context of quantum computing. For example, some researchers continue to search for new systems that display the positive optical features of self-assembled quantum dots and diamond NV centres discussed above (atom-like behavior, semiconductor host, large oscillator strength) while exhibiting better homogeneity and coherence than quantum dots and easier routes to integration than diamond. Shallow, substitutional semiconductor impurities, for example, exhibit sharp optical bound states near the bandgap and have the advantages of being substantially more homogeneous and potentially easier to place with atomic-scale fabrication techniques, as in the example of phosphorous in silicon. The fluorine impurity in ZnSe is one impurity with a similar binding energy to phosphorous in silicon and a comparable possibility for isotopic depletion of nuclear spins from the substrate. Unlike in silicon, the direct, wide bandgap of ZnSe affords it an oscillator strength comparable to a quantum dot. Further, the II-VI semiconductor system allows MBE-based semiconductor alloying techniques not currently available in diamond. The electron bound to F:ZnSe and the ^{19}F nuclear spin may therefore provide excellent optically controlled qubits; already it has shown promise as a scalable single photon source[265].

Another system under investigation for optically controlled, solid-state quantum computation is provided by rare earth ions in crystalline hosts. These systems have been known for many years to show long coherence times for their hyperfine states. Unfortunately, these impurity ions usually have weak optical transitions and and therefore cannot be detected at the single atom level like quantum dots, NV centres in diamond, or fluorine impurities in ZnSe. Therefore, like NMR quantum computing, this approach employs an ensemble. Isolating the degrees of freedom to define qubits in this ensemble benefits from the large inhomogeneous broadening of the system, caused by shifts of the optical transitions of the impurities due to imperfections of the crystalline host. Remarkably, these static shifts only weakly affect the width of transition of individual ions, which may have optical coherence times of milliseconds. The extremely high ratio of homogeneous to inhomogeneous broadening (typically 1 kHz vs. 10 GHz for Eu doped $YAlO_3$) potentially allows the realization of up to 10^7 readout channels in the inhomogeneous ensemble. Qubits can be defined as groups of ions having a well defined optical transition frequency, isolated by a narrow bandwidth laser. Unlike in the case of liquid state NMR quantum registers, the initial state of rare-earth qubits can be initialized via optical pumping of hyperfine sublevels of the ground state.

This system has recently seen a demonstration of single-qubit state tomography[266,267]. Multi-qubit gates are also possible via the large permanent dipole moment in both ground and excited electronic states. Very long coherence times of the ground state also enable the use of rare earth qubits as an efficient interface between flying and matter qubits[268–270] with unprecedented storage times for photons up to 10 sec[271], which is many orders of magnitude longer than achieved for atomic systems.

Other materials for hosting single-electron-based qubits are also under consideration. The carbon-based nanomaterials of fullerenes[272,273], nanotubes[274], and graphene[275] have excellent properties for hosting arrays of electron-based qubits. Electrons for quantum computing may also be held in a low-decoherence environment on the surface of liquid helium[276]. Another spin-based aproach is the use of molecular magnets. Although these molecules contain many atoms and many electrons, their magnetic degrees of freedom at low temperature behave as a single quantum particle, but with a much stronger and therefore easier-to-measure magnetic moment[277].

A further category of exploration for quantum computation is new methods to mediate quantum logic between qubits, often of existing types. A key example of this is the use of superconducting transmission line cavities and resonators for qubits other than those based on Josephson junctions, such as ions[278], polar molecules[279] and quantum dots[280]. Edge-currents in quantum-hall systems present another type of coherent current which may be useful for wiring quantum computers[281]. In fact, nearly every type of bosonic field has been explored for quantum wiring, including lattice phonons in semiconductors[282], phonons in micromechanical oscillators[283], free excitons[284] or hybridizations between excitons and cavity photons in semiconductors[285], and spin-waves in magnetic crystals[286]. Other ideas in this category include surface-acoustic waves for shuttling spin qubits[287] and plasmonic technologies for shuttling photonic qubits at sub-wavelength scales[288].

Other areas of diverse development in quantum computation are novel means for measurement. Ultra-sensitive magnetic field detection techniques with Ångstrom-resolution such as magnetic resonance force microscopy (MRFM) and spin-dependent scanning-tunneling microscopy (STM) may play a role in future quantum computers. In the other direction, technologies developed for qubits such as the NV centre in diamond are finding new roles as magnetic field sensors in diverse applications[289,290].

A final development in quantum computation deserving of mention here is the use of topologically defined quantum gates to preserve quantum information. Such concepts are used to define fault-tolerant QEC schemes among ordinary qubits[165], but have also been proposed as a method of physical computation should a physical system be found to implement them. For example, a type of quantum excitation with fractional quantum statistics known as the anyon has been predicted to play a role in condensed matter systems (in particular, certain aspects of the fractional quantum-Hall effect). Theoretical ideas in implementing quantum logic by the topological braiding of such particles may offer more advanced future routes to robust quantum computation[291].

XIV. OUTLOOK

In the last 15 years we have discovered that quantum information is fundamentally more powerful than classical information, challenging the tenets of computer science. We have also learned that it is possible, in principle at least, to quantum compute reliably in the presence of the imperfection of real devices. As demonstrated in this article, we have learned that we do indeed have enough control today to implement rudimentary quantum algorithms. These elements form the foundation of a new kind of science and technology based on those quantum properties of nature that have no classical analog.

The challenge for the years to come will be to go from proof-of-principle demonstrations to the engineering of devices based on quantum principles that are actually more powerful, more efficient or less costly than their classical counterparts. A quantum computer is perhaps the most ambitious goal of this new science, and it will probably require a few more decades to come to fruition. On the way to this goal, however, we will grow accustomed to controlling the counterintuitive properties of quantum mechanics, and we will develop new materials and make new types of sensors and other technologies. As we proceed, we will tame the quantum world and become inured with a new form of technological reality.

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