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Quantum computing: An IBM perspective

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Quantum physics provides an intriguing basis for achieving computational power to address certain categories of mathematical problems that are completely intractable with machine computation as we know it today. We present a brief overview of the current theoretical and experimental works in the emerging field of quantum computing. The implementation of a functioning quantum computer poses tremendous scientific and technological challenges, but current rates of progress suggest that these challenges will be substantively addressed over the next ten years. We provide a sketch of a quantum computing system based on superconducting circuits, which are the current focus of our research. A realistic vision emerges concerning the form of a future scalable fault-tolerant quantum computer.

Introduction to quantum computing

In his famous 1959 after-dinner talk "There is plenty of room at the bottom," Richard Feynman challenged the scientific community to employ quantum mechanical effects in the design of information processing systems:

"When we get to the very, very small world, say, circuits of seven atoms, we have a lot of new things that would happen that represent completely new opportunities for design. Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and we can expect to do different things. We can manufacture in different ways. We can use not just circuits but some system involving the quantized energy levels, or the interactions of quantized spins, etc."

However, at that time, even Feynman could not guess how a quantum system could be used to perform information processing tasks. A greater understanding of the fundamental rules of information processing was first required. In the ensuing years, IBM Research significantly contributed to that understanding. Landauer [1] showed that energy must be dissipated in computing *only* when information is erased and that erasing a *bit* of information must result in an irreducible release of heat to the environment. As a result, whenever an irreversible logic element such as a NAND gate is operated, the computer *must* dissipate energy. Later, Bennett [2], among others, showed that universal computation need not be irreversible. In principle, computations could be performed without erasing information and, thus, without energy dissipation. These insights set the stage for consideration of quantum mechanical systems as computers. Since coherent quantum mechanical operations are energy conserving and time reversible, they are a natural generalization of the reversible classical operations of Bennett.

In the 1980s, it was shown that a quantum mechanical Hamiltonian can represent a universal Turing machine [3]. It was further shown that a quantum machine could efficiently simulate other quantum physical systems. In other words, a quantum machine would use only polynomial resources of time, memory, and space to simulate other quantum systems. By comparison, the simulation of such systems by a classical machine requires an exponential growth of resources for increasingly larger problems [4, 5]. The notion of a quantum Turing machine was subsequently developed, and the concept of quantum parallelism was introduced [6].

A major breakthrough, i.e., the true birth of quantum computing, came in 1994 when Peter Shor showed that a quantum computer could factor integer numbers only in the polynomial time [7]. The quantum algorithm for integer factoring offers an exponential speedup over the best

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known classical algorithm. Since modern encryption is based on the exponential difficulty of factoring large integers on a classical computer, a functioning quantum computer could break such encryption schemes. Consequently, the interest in building such a system has dramatically increased since Shor's discovery.

Aside from code breaking and simulating quantum systems efficiently, quantum computers could prove useful in other important areas. For example, searching unsorted databases, as well as solving a wide range of optimization problems, could be done with a polynomial speedup compared with classical algorithms [8]. The development of new quantum algorithms continues as an active research area in which IBM Research is engaged.

These theoretical results are very appealing, but can a quantum computer actually be built? Experimentalists were quick to point out the analog nature of errors in a quantum system. Despite initial pessimism, quantum error correction (QEC) was soon shown to be possible [9, 10]. With the proper application of these error correction routines, a fault-tolerant quantum computer could be theoretically built [11–15]. QEC enables arbitrarily long computations using faulty components. However, the error rate per gate operation must be below a certain threshold. Early studies gave error thresholds of 10^{-4} to 10^{-5}. Recently, specific 2-D architectures have been shown to relax this threshold to a few times 10^{-3} [16]. As discussed below, the experimental realization of quantum hardware is also advancing rapidly, and demonstrated error rates are now only a factor of about 10 away from this theoretical threshold for fault-tolerant quantum computing. Thus, the realization of a practical quantum computer may be much closer than was thought just a few years ago. With no known fundamental obstacles to continued progress, this is an increasingly exciting field of research with enormous implications for the future of information technology.

Quantum bits: Instantiating digital information in a quantum physical system

How can a quantum physical system represent digital information? A quantum computer consists of quantum bits (i.e., qubits). A qubit can be an entity like a spin-1/2 particle in a magnetic field or a polarized photon. All that is required is that the physical system exhibit at least two orthogonal quantum states. We can refer to these two states as $|0\rangle$ and $|1\rangle$, which encode the classical logical states 0 and 1, respectively. When the laws of quantum mechanics apply, the overall state of a qubit may be written as a linear combination of the states, i.e., $|\psi\rangle = c_0|0\rangle + c_1|1\rangle$, where c_0 and c_1 are complex numbers satisfying the normalization condition $|c_0|^2 + |c_1|^2 = 1$. When $|c_0| = 1$ or $|c_1| = 1$, the system behaves like a classical bit. For all other values, the system is in a quantum superposition with no classical analog. Extending this to multiple qubits, it can be easily shown that an n-qubit system is described by

$$|\psi\rangle = \sum_{i=0}^{2^n-1} c_i|i\rangle,$$

requiring $2^n - 1$ complex numbers to describe the full quantum mechanical system. This is in stark contrast to a classical system with the state specified by a single n-bit number. This gives the first hint of why a quantum computer could be much more powerful than a classical machine.

Over the years, it became clear that it is not quantum superposition itself but rather entanglement that is a necessary ingredient for speeding up quantum algorithms [17]. Entanglement is present when the overall system cannot be simply written as a product of the individual qubit states. An example of an entangled state is $|\psi\rangle = [|00\rangle + |11\rangle]/\sqrt{2}$, which is one of the four famous Bell states that sparked furious philosophical debates over how quantum physics can actually be a correct description of reality [18].

These types of entangled states can be created and manipulated with quantum logic gates. Such gates are unitary operations on the quantum wavefunction. Simple examples are from reversible classical logic, i.e., controlled NOT, NOT, and 3-bit AND (Toffoli gate). There are other quantum gates that take the system from a classical state to a quantum superposition. Further details on quantum operations are discussed elsewhere [19].

Identifying a potentially useful two-level quantum system is the first small step toward building a quantum computer. DiVincenzo focused the worldwide research community on the next steps when he constructed a list of functional requirements that must be met by any practical quantum computer [20]:

1. A scalable system of well-characterized qubits.
2. A universal set of quantum gates composed of interacting qubits.
3. An efficient procedure to initialize the quantum system to a known state.
4. The ability to perform qubit-specific measurements.
5. Long coherence times compared with the average time for an elementary logical operation.

In achieving the DiVincenzo criteria, the most important attribute of any qubit is that it displays a very high degree of quantum coherence. For a single qubit, this quantum coherence is usefully measured by the so-called "T_2" time. T_2 is the characteristic time over which the phase relationship between c_0 and c_1 (previously discussed) is maintained. The essential parameter for successful quantum computation is the error probability e, which can be estimated as $e = T_{\text{clock}}/T_2$, where the "clock" time is the duration of the fundamental one- and two-qubit gate execution times.

Once we consider the coupling of two or more qubits to construct a quantum logical gate, it becomes clear that a more sophisticated set of metrics must supplement the T_2 metric. There are three additional quantities that will certainly require attention.

1. *Off–on ratio R*—A quantum algorithm requires a programmed sequence of quantum gate operations, i.e., specific coherent couplings between specified qubits. Obviously, when the program specifies no operation in a particular clock cycle, this coherent coupling should be zero. R measures the extent to which these couplings can be really turned off. The quantity $1 - R$ should be as close to 1 as possible.
2. *Gate fidelity F*—This quantity is closely related to e, in that $1 - F$ is also an error probability. However, while T_2 provides a measure of how much error occurs in an uncoupled qubit, $1 - F$ more specifically measures the occurrence of error during actual coupled operation, and it is the more relevant error rate for fault-tolerant operation. F encapsulates any type of error that could occur due, for example, to loss of coherence or unwanted coupling. Obviously, F must be very close to 1.
3. *Measurement fidelity M*—The quantity $1 - M$ is another error probability but is related to how well classical information can be extracted from a qubit. Such an operation is frequently required in QEC. Like F, M must be very close to 1.

The community has paid some attention to all of these metrics, and there has been definite progress on all; however, so far, there has been no concerted effort to improve all of them in a coordinated fashion in a single quantum device technology. Now, by focusing on a specific device technology implemented in a specific quantum computing architecture, we hope to increase the rate of progress. Other circuit-oriented metrics will be, no doubt, precisely formulated as experience is gained. We are still a long way from building a practical quantum computer, but the path toward this goal is becoming clearer.

Choosing the qubit

Many very different physical systems have been proposed for the instantiation of qubits. Published proposals include silicon-based nuclear spins [21], trapped ions [22], cavity quantum electrodynamics [23], nuclear spins [24], electron spins in quantum dots [25], superconducting loops and Josephson junctions [26], liquid-state nuclear magnetic resonance (NMR) [27, 28], and electrons suspended above the surface of liquid helium [29], among others. The ultimate success of any of such proposal will depend on the degree to which the chosen system can be engineered to satisfy the five DiVincenzo criteria. Satisfying any of these requirements *individually* can be done with relative ease. Satisfying all of them *simultaneously* is quite experimentally challenging and at the frontier of current research in quantum computing.

Historically, a liquid-state NMR quantum computer (NMRQC) was the first physical system demonstrating many of the main concepts of quantum computing. In such a system, the nuclear spins are placed in a strong magnetic field, creating the "up" and "down" states of the nuclear spin (similar to the north- and south-pole orientations of a bar magnet) representing the logical $|0\rangle$ and $|1\rangle$ states. Separately, IBM [30] and Oxford University [31] were the first to report an experimental realization of a quantum algorithm. The IBM group led by I. Chuang further significantly contributed to this field, with the implementation of a three-qubit quantum search algorithm [32], a five-qubit order-finding algorithm [33], the realization of an adiabatic quantum optimization algorithm [34], and a demonstration of Shor's factoring algorithm [35] (factoring the number 15 using a seven-spin molecule). These demonstrations, together with those of other groups, helped transform experimental quantum computing into a growing field of research.

By the early 2000s, the liquid-state NMRQC had been pushed close to some natural limits to the ability to distinguish increasing numbers of nuclear spins in increasingly large molecules. No path was seen that would allow such systems to be scaled to many qubits and large computations. This ultimately led to a change of direction at IBM. Beginning in 2002, a small research group led by the late Roger Koch began to explore the superconducting Josephson junction technology as the basis for the fabrication of qubits. Since the critical features of a Josephson junction are defined by a lithographic process, it should be possible to build many of such devices using the processes of modern microelectronics manufacturing. This suggests that the technology can ultimately support the construction of large quantum computing systems with complex architecture and comprised of many qubits.

While we focus on this approach to quantum computing in the remainder of this paper, we note that other approaches may ultimately be used. After all, commercially viable classical computers have been built from several fundamentally different types of devices over the years, and we are still searching for new devices with which to build such computers. By analogy, we can expect the continued exploration and the future development of several potentially competing types of quantum devices. Today, in addition to various approaches based on superconducting qubits, the most active areas of research involve trapped ions and quantum dots. The largest quantum computer built in any of these systems to date consists of about ten qubits, and most implementations are focused on the demonstration of a specific quantum algorithm or quantum state.

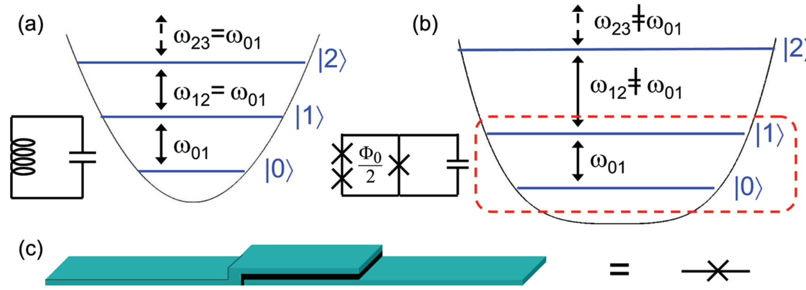

Figure 1

(a) Harmonic oscillator formed by an inductor and a capacitor forms a quantum system in which all energy levels are equally spaced. (b) When adding a Josephson junction, the system becomes anharmonic, giving rise to energy levels that are not equally spaced. (Dashed red box) The lowest two levels are then identified by a unique frequency, allowing the system to be used as a qubit. Sketched is the circuit configuration and corresponding potential energy used at IBM. (c) A Josephson junction is a SIS device where the insulator is very thin, typically 1–2 nm.

Superconducting device toolbox

Usually, we think of electrical circuits as the domain of classical physics, but if the circuits are made of low-loss superconducting components, then a quantum description is appropriate. In fact, these components provide the unique quantum design laboratory that we use to make superconducting qubits. The fundamental circuit elements that we employ—capacitors, inductors, Josephson junctions (described in more detail below), and cavity resonators—are all lossless energy storage elements. Each contributes either to the kinetic or the potential energy terms of a quantum Schrodinger equation [36].

The inductors contribute to the potential energy; the energy storage formula for inductance L is $\Phi^2/2L$, where Φ is the magnetic flux that is related to a quantum mechanical phase $\delta = 2\pi\Phi/\Phi_0$ and $\Phi_0 = h/2e$ is the fundamental quantum unit of magnetic flux. Thus, this contributes a quadratic or "harmonic" potential in the "coordinate" δ. Capacitance C contributes to the quantum kinetic energy; its energy expression $Q^2/2C$ is directly analogous to the kinetic energy $p^2/2m$ of ordinary mechanics. Thus, charge Q plays the role of momentum p, and capacitance C is analogous to the particle mass m. This mass can move according to the potential energy provided by the inductors. In classical physics, a mass placed in a harmonic potential will oscillate back and forth at a frequency that is independent of the amplitude of its oscillations. When the laws of quantum mechanics apply, a quantum harmonic system has energy levels that are separated by a fixed frequency, as shown in **Figure 1(a)**. Such a system cannot be used as a qubit because quantum transitions between the 0 and 1 energy levels cannot be distinguished from other possible transitions. What is needed is a circuit element, i.e., a nonlinear inductor, that alters the potential so that energy levels are unequally spaced, as shown in **Figure 1(b)**. A superconducting tunnel junction, known as a Josephson junction, adds the desired anharmonic contribution to the potential energy. A Josephson junction is a superconductor–insulator–superconductor (SIS) circuit element, as sketched in **Figure 1(c)**. The insulator is very thin, i.e., about 2 nm, in thickness. The energy expression for a single Josephson junction goes like $-I_0\cos(\delta)$, where I_0 is the critical current, i.e., an intrinsic property of the Josephson junction. Note that this expression is harmonic for small δ but becomes highly anharmonic for large δ. Because the energy levels are not equally spaced, the 0–1 transitions can be distinguished in the angular frequency ω, and thus, the system can be used as a qubit. Typically, $\omega_{12} - \omega_{01}$ differs from ω_{01} by a few to 10% [37, 38], although this can be much greater in some qubit designs [39].

For the parameter ranges that are typical for microelectronic superconducting circuits ($C \approx 100$ fF, $L \approx 100$ pH, $I_0 = 0.1$–$1\ \mu$A), the Schrödinger equation gives quantum energy levels separated by frequencies ($\nu = \omega/2\pi$) in the 1–10-GHz range. There are losses in these circuits, but ideally, they are so small (corresponding to shunting resistances in the GΩ range) that they are significant only on time scales much larger than the expected clock times of the quantum computer. Thus, the resulting departures from the coherent quantum behavior can be ultimately dealt with by error-correction techniques.

Low-loss cavity resonators also play a role in superconducting quantum circuits; they constitute additional quantum harmonic oscillator degrees of freedom that can interact with the anharmonic qubit to stabilize its frequency and serve as memory [40], permit transfer to long-lived memory states, mediate coherent interactions with other qubits [38], and provide an effective bandpass filter to reject most of the environmental noise coming in through the control-and-detection circuitry [41].These resonators have permitted a very precise quantum coupling to be achieved between qubits, so that, for example, highly entangled states such as the previously mentioned Bell states are now routinely realized in the laboratory [38, 42].

In summary, the possibility for "designer quantum physics," with the potential energy landscape sculpted by the choice of circuit topology and by the choice of parameter values, makes it possible to craft the system for optimal performance. The anharmonicity of the Josephson element lends great flexibility to the design, permitting quantum energy levels to be spaced almost "at will," so that 0–1 transitions can be uniquely selected by their unique energy. As a result, superconducting qubits are often referred to as "artificial electrical atoms." The possibilities for the functional design of practical quantum computing circuits are being realized in IBM laboratories today.

Engineering superconducting qubits

As previously described, a superconducting qubit is formed by arranging inductors, capacitors, and Josephson junctions to achieve unequal energy level spacings. However, of course, the demonstration of a functional qubit only satisfies one of the required DiVincenzo criteria. It should therefore come as no surprise that the question of how to best arrange such superconducting circuits to simultaneously meet the requirements of all the criteria is at the core of the field.

Superconducting qubits were first demonstrated in 1999 at NEC [26]. Coherence times were only about 1 ns. Over the past 12 years, reported coherence times have increased by more than a factor of 1,000, and $T_2 \sim 1$–$5\ \mu$s can be repeatedly obtained over many devices. For a recent noteworthy case employing a three-dimensional superconducting microwave cavity, an energy relaxation time T_1 of about 60 μs with T_2 of about 20 μs has been demonstrated [43]. This represents an important new direction that IBM is now pursuing as well. The loss mechanisms currently limiting coherence times are not well understood, and much of the current research in the field is geared to further improving these numbers. There is also no definitive understanding of how to build circuits of increasing complexity while maintaining coherence times. We make some general observations here reflecting the latest understanding.

Electromagnetic design

Electromagnetic engineering is a crucial and necessary component because of typical operating frequencies of superconducting qubits. In order to initialize the qubit, we must operate at temperatures such that $kT \ll h\nu$, where k is Boltzmann's constant, T is the temperature, h is Planck's constant, and ν is the frequency. This favors high operating frequencies. Since temperatures in the 10–20-mK range are easily achievable nowadays, operating frequencies are typically placed in the gigahertz regime. Such frequencies will be necessary to achieve the desired nanosecond clock speeds. Furthermore, calculations and experiments show that the coupling of the qubit to much higher frequency modes can reduce coherence times. It is therefore clear that coupling to such parasitic modes must be minimized. As a result, designing the packaging for qubit chips (and the chips themselves) becomes an engineering challenge requiring highly advanced simulation tools that have been developed in communications engineering.

Dielectric loss

For the past several years, it has been known that the dielectric losses in insulating materials can be a dominant source of decoherence [44]. All superconducting qubits require at least one capacitor in order for the system to have "mass," as described earlier. As a result, all superconducting qubits are invariably subject to such loss. Thus, much research is aimed at investigating and improving dielectric properties of materials. The dielectric loss at low power and low temperatures is the quantity that matters most, because the qubit operates at a single photon level and at a temperature of 10–20 mK. We now know that measurements at high power or temperature can provide misleading results, indicating losses that are low by a factor of 1,000 or more [44] compared with actual losses under application conditions.

Most research groups currently fabricate a discrete capacitor structure electrically in parallel with a small or ultrasmall Josephson junction [37]. The junction is so small that only a few microscopic energy dissipating defects are present, are generally not close to the qubit operating frequency, and are thus statistically avoided [44]. For these designs, the qubit coherence is believed to be limited by the dielectric loss of the shunting capacitor. As a result, a large research effort is aimed at reducing dielectric loss at low power and low temperature. In addition, it is notable that for most superconducting qubits employing ultrasmall (0.05 μm^2) Josephson junctions, the junction itself does not appear to presently limit the device performance (as measured by T_2).

Another more challenging approach is to make large Josephson junctions without an explicit shunting capacitor; thus, the desired capacitance is provided by the Josephson junction itself. (Recall that a Josephson junction is a SIS, which has self-capacitance.) In this case, there are many individual energy-dissipating defects that are close to the qubit operating frequency and limit the device performance [37, 44]. As a result, some research efforts are aimed at fabricating Josephson junctions out of a crystalline material instead of an amorphous oxide. A reduced number of defects are indeed observed in experiments [45] for a polycrystalline barrier. However, because of the difficulty of epitaxially growing and patterning such devices, this approach is not widely pursued.

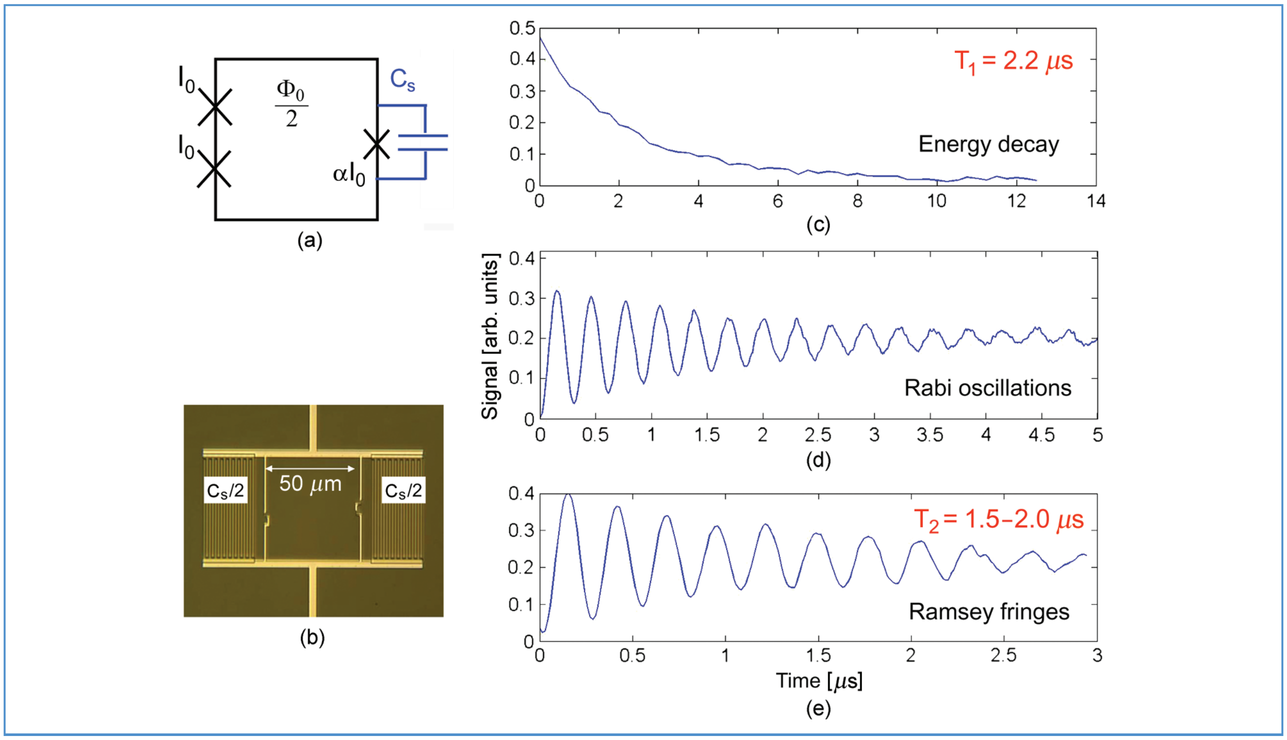

Figure 2

IBM capacitively shunted flux qubit (CSFQ). (a) The circuit diagram shows the qubit. (b) The qubit is fabricated using standard silicon microfabrication techniques. The qubit performance is characterized via several experiments (detailed in [47]). (c) The energy decay is characterized by T_1 time and relates to the decay of the excited state $|1\rangle$ to $|0\rangle$. The T_2 times are measured by observing the decay of (d) Rabi oscillations and (e) Ramsey fringes, because the amplitude of the oscillations are related to the phase coherence between c_0 and c_1 of a quantum superposition state. We note that the device performance is repeatable over many samples and fabrication runs.

Flux noise

Fluctuations of the qubit resonance frequency ω_{01} lead to reduced T_2 times as frequency fluctuations scramble the phase coherence between c_0 and c_1 of a quantum state. Therefore, if the qubit resonance frequency is tunable via a magnetic flux Φ and Φ fluctuates over time, then T_2 is reduced. Magnetic flux noise has a $1/f$ spectral density. Although its source is unknown, it appears to be related to interacting surface spins on the metal [46]. Its magnitude is large enough to limit T_2 for current devices that are tunable in frequency by way of Φ. As a result, many groups are focused on designs that feature a frequency "sweet spot," i.e., a bias point at which the resonance frequency is insensitive to Φ. Another approach is a design for which the qubit resonance frequency is weakly dependent on Φ. Obviously, significantly reducing the amount of flux noise would open the door toward a wider range of qubit designs with improved coherence.

Recent results

Based on what is currently known, our research group has settled on a superconducting qubit design, with the goal of building and demonstrating logical circuits of increasing complexity, ultimately including error correction. Since coherence times of 1–5 μs are sufficient to carry out elementary two-qubit gate operations with high fidelity, we chose small junctions and external shunting capacitors to minimize the dielectric loss. The specific arrangement of junctions and capacitors is shown in **Figure 2(a)** and described in detail elsewhere [47]. The qubit consists of a superconducting loop biased at $\Phi_0/2$, three ultrasmall Josephson junctions, and a shunting capacitor C_s. Two of the junctions are nominally identical, whereas the third has a critical current scaled by factor $\alpha \sim 0.3$. The layout of this qubit is similar to that of a flux qubit [39]. Although it shares some of its properties with the flux qubit, it also has a lot in common with the transmon [41] and phase qubits [44] due to its appreciable shunting capacitance. Thus, we view this qubit as a hybrid of previously existing qubit designs. A micrograph of the actual qubit is also shown in **Figure 2(b)**, featuring an interdigitated shunting capacitor with capacitance $2 \times C_s/2 = 100$ fF and the inductive loop with three Josephson junctions.

This hybrid qubit is initialized by the virtue of cooling it down to very low temperatures (10–20 mK) using a

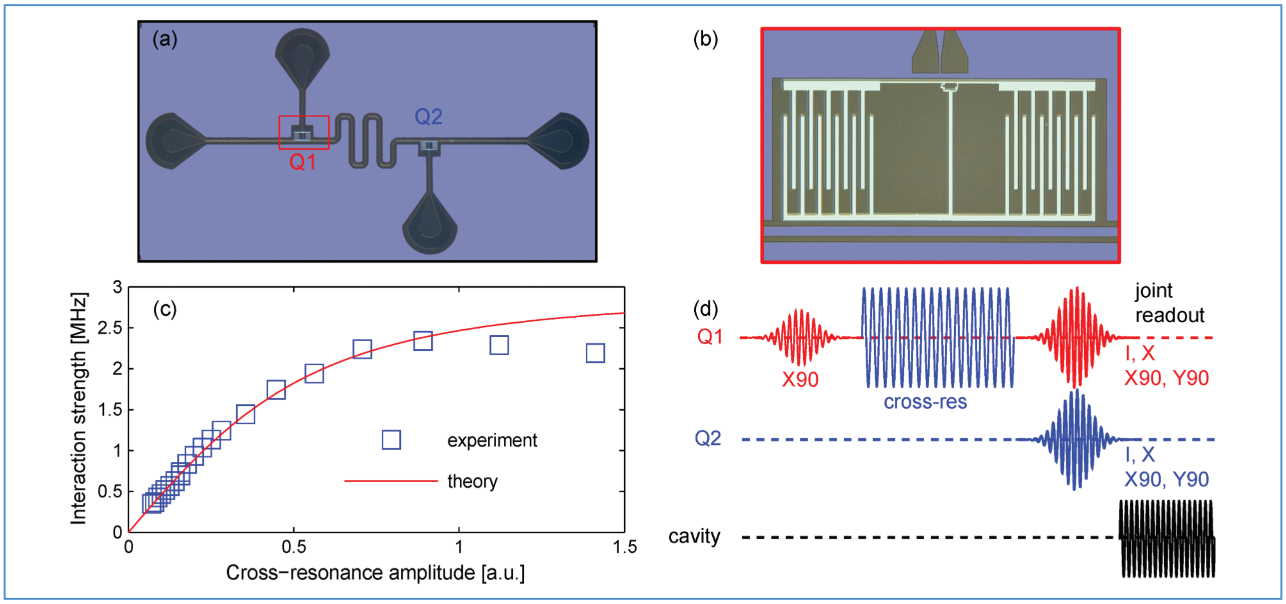

Figure 3

Recent progress toward scalable two-qubit gates at IBM. (a) Two qubits are coupled and measured via a coplanar waveguide resonator. (b) Each qubit is the IBM-style CSFQ designed with smaller loops compared with the single qubits shown earlier. (c) The two-qubit interaction strength is tunable by varying the amplitude of the cross-resonance pulse. (d) A two-qubit gate is generated by applying a microwave pulse to qubit 1 but at the frequency of qubit 2. Together with preparation pulses and measurement pulses, entangled states are prepared and measured.

dilution refrigerator and the appropriate filtering of electrical noise on the bias lines. The qubit is measured by coupling it strongly to a superconducting resonator with a high quality factor Q and observing a shift of the resonator frequency that depends on the qubit state $|0\rangle$ or $|1\rangle$. In essence, the measurement must distinguish between two possible resonant frequencies. This can be accomplished using a variety of techniques, i.e., by measuring the amplitude or the phase of a microwave signal that passes by or is reflected from the resonator (see, e.g., [48]). The current state of the art does not generally permit a single-shot readout of the qubit state (i.e., identifying the qubit state in a single application of a measurement protocol with high fidelity). However, novel measurement protocols, together with ultralow-noise high-frequency amplifiers based on superconducting quantum interference devices, should make this possible.

The team at IBM measured and characterized this qubit in detail. We find that coherence times at the flux sweet spot are consistently 1–2 μs for nominally identical devices from the same wafer and also on wafers from separate fabrication runs [see **Figure 2(c)–2(e)**], thus demonstrating stable reproducible results. These coherence times are comparable with those consistently obtained by the leading research groups (see, e.g., [38, 49]). Although these times are still not sufficiently long for fault-tolerant quantum computing, they are long enough to begin seriously considering and implementing two- and three-qubit gates.

Recently, the IBM team has made progress in implementing a new type of two-qubit gate and using it to generate highly nonclassical quantum states [50]. The approach, known as cross resonance, is based on theoretical work [51, 52] that suggested the ability to turn on a two-qubit interaction between two weakly coupled qubits using only microwave excitations. The interaction can be used to implement a controlled-NOT gate. This scheme stands apart from the standard approaches pursued elsewhere, where two-qubit gates result from tuning the qubits via flux pulses to explicit resonances in the system [38, 42]. Cross resonance is inherently amenable to scaling to larger systems, as with only microwave driving, the qubits can be parked at their bias points, which are optimal for coherence, and interactions are not localized to nearest neighbors in frequency, which is the case with qubit tuning.

Two-qubit experiments are performed on a chip, as shown in **Figure 3(a)**, with two of our hybrid-style qubits [**Figure 3(b)**] coupled to a microwave resonator. Independent flux bias and microwave control of each qubit have been integrated onto the chip. The qubits can be tuned to their points of maximal coherence, where we find $T_2 > 1.5$ μs for both. Cross-resonance gating is enabled by the small fixed mutual coupling of the qubits through the resonator. Microwave radiation, which is resonant with qubit 2, is fed to qubit 1. The resulting interaction can be understood as a qubit-1 state-dependent rotation of qubit 2. **Figure 3(c)** shows the strength of this interaction when varying the amplitude of the cross-resonance microwave drive. The strength of the interaction determines the two-qubit gate time. For our current experiment, we exercise an optimal two-qubit gate, involving microwave pulses as indicated in **Figure 3(d)**, to generate entangled states such as the Bell state $(|00\rangle + |11\rangle)/\sqrt{2}$ with a fidelity to the ideal state of 93%. The further characterization of the gate using the technique of quantum process tomography [19] reveals a two-qubit gate fidelity of 81%. Both of these numbers are on par with the best demonstrated two-qubit gates and entangled states, all of which used the qubit tuning method.

Very recently, the team at IBM has further improved qubit coherence times, which are now above 5 μs for both T_1 and T_2 [53], leading to increased two-qubit gate fidelities that are being quantified in more detail now. Furthermore, the leveling off of the interaction strength in Figure 3(c) should be correctable with optimal control pulse shaping methods currently being developed [54]. Ninety-five percent or higher two-qubit gate fidelity seems well within reach. However, the current results already demonstrate the effectiveness of the cross-resonance gating scheme.

Looking forward toward a quantum computer architecture

With superconducting qubits, controllable two-qubit interactions take place only over a spatial range determined by the size of a superconducting resonator. Based on that fact, new architectures for QEC have been proposed. Employing insights from the theory of topological quantum computation, it is now understood [16] how to use a regular 2-D array of qubits, with only nearest-neighbor couplings, to achieve a fault-tolerance threshold in the neighborhood of $e \sim 0.003$. **Figure 4** shows possible 2-D layouts of qubits coupled by superconducting resonators. The coherent two-qubit logic gates that can be mediated by the presence of these resonators facilitates a local comparison of redundant information in the lattice, permitting errors to be detected and corrected in a way that is analogous to an ordinary digital error-correcting code. The propagation of this information in a 2-D lattice permits very effective error correction, leading to high error-rate thresholds. These insights will guide our research as we seek to demonstrate a practical architecture for QEC.

Assuming a two-qubit gate time of 30 ns, coherence times must be approximately 20 μs or greater to achieve $e \sim 0.003$ or less. Measured coherence times are rapidly improving and are now approaching 20 μs. **Figure 5** illustrates the remarkable progress. A little extrapolation suggests that the reliability of our quantum devices will routinely exceed the threshold for fault-tolerant computing within the next five years. At that point, system architecture and integration will become increasingly important to the further development of quantum computing. Indeed, we are already beginning to consider the broader engineering aspects of the endeavor including input and output, transducers, control circuitry, packaging, refrigeration, and overall integrated system design, build, and test. Individually and collectively, these components will present difficult challenges that must be addressed and concurrently overcome with the development of the quantum devices and circuits.

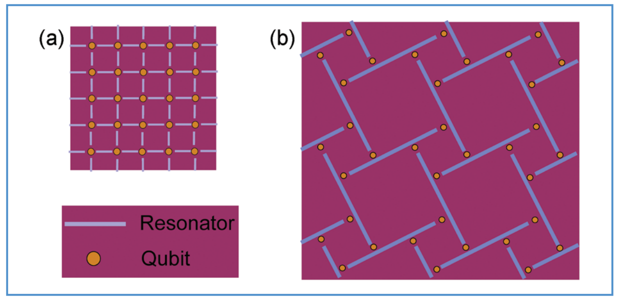

Figure 4

Physical arrangement of square lattices of qubits coupled by superconducting resonators for implementing fault-tolerant quantum computing. (a) A basic 2-D lattice arrangement is shown in which each qubit is coupled to four resonators for communicating with its nearest neighbors. (b) Another lattice structure is achieved with a hardware configuration in which each qubit is coupled to just two resonators forming a "tee" arrangement.

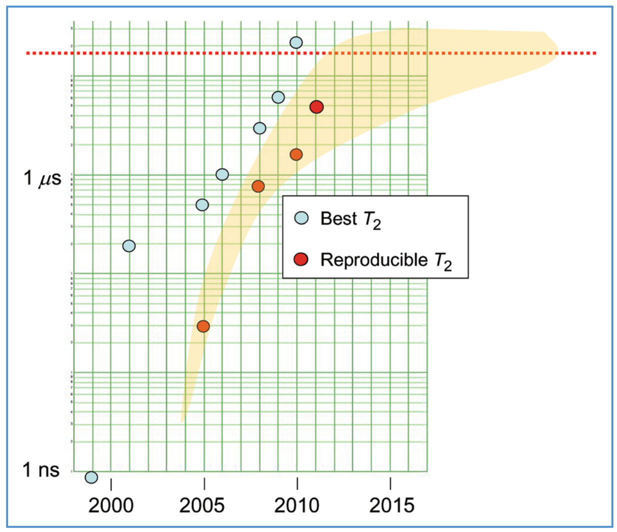

Figure 5

Progress toward reaching long dephasing (T_2) times for superconducting qubits. (Red dashed line) Minimum necessary for fault-tolerant quantum computer, based on a 30-ns two-gate time. (Yellow field) Predicted improvements in T_2.

Indeed, we envision a practical quantum computing system as including a very sophisticated classical system intimately connected to the quantum computing hardware. As presently envisioned, the classical system will have to exchange signals with the quantum subsystem, while maintaining very low noise temperatures so as not to decohere the qubits. The size of the classical data streams involved in the diagnosis and the control of the quantum hardware will ultimately be prodigious. Expertise in communications and packaging technology will be essential at and beyond the level presently practiced in development of today's most sophisticated digital computers. The hardware will probably be situated in multiple temperature zones ranging from 20 mK to room temperature. Several different control circuit technologies may be required to meet the performance and thermal boundary conditions, ranging from room-temperature and cooled (77- and 4-K) complementary metal–oxide–semiconductors to 4- and 20-mK analog and digital Josephson technologies.

Conclusion

While we still have a long way to go and many details to work out, we can see the broad form of tomorrow's quantum computers. The marked progress in the theory of QEC has relaxed the device error rate that must be achieved for fault-tolerant computing. Rapid improvements in experimental quantum hardware suggest that a threshold for the design and the construction of fault-tolerant systems may be reached in the next five years. At that point, the goal of building a useful and reliable quantum computer will be within our reach.

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