

# AFTER THE TRANSISTOR, THE QUBIT?

*Attention is increasingly focused on quantum computing as a path to the continued rapid growth of information-processing technology. But like other physical circuitry, quantum computers must face the uncomfortable fact that man-made objects aren't exact reproductions of idealized devices and aren't invariably perfectly reproducible. The consequences of this imperfection threaten the future of quantum computing.*

**E**lectronic technology using solid-state devices has advanced us toward increasingly faster and more powerful systems for half a century. The invention of the integrated circuit opened the door to miniaturization, which, by making capacitances smaller and reducing distances between devices, has proven to be the key to faster operation.

However, some of the problems associated with further miniaturization are beginning to appear insoluble:

- More devices per unit area have raised the density of power dissipation to higher than stove-top densities, making heat removal a major problem.
- Greater component densities call for greater wiring densities, taxing interconnection technology.
- Smaller separations between a device's elements increase the tunneling and leakage currents that add to power usage, hurting device performance.

The formidable barriers to the continued im-

provements in silicon technology have intensified the attention paid to alternatives such as quantum computing. Unfortunately, troubling obstacles still stand in the way of physically implementing useful quantum computers.

## Quantum Computing

The initial discovery of quantum algorithms promising giant leaps forward in the attempts to tackle important computing applications gave a powerful impetus to the current interest in quantum computing. New basic physics emerging from the investigation of quantum phenomena in macroscopic devices also adds to the allure.

Like more familiar computers, a quantum computer would be built as a collection of elementary devices. Qubits, physical systems that can exist in either of two distinguishable quantum states, are quantum computing's elementary devices. A qubit's two quantum states are conveniently labeled 0 and 1; their associated wave functions can be called  $\psi_0$  and  $\psi_1$ . The inferred power of quantum computing with qubits depends on a phenomenon unknown in classical physics: information stored in superpositions of quantum states. For example, a qubit can be in a state

$$\Psi = \alpha\psi_0 + \beta\psi_1, \quad (1)$$

where  $\alpha$  and  $\beta$  are complex coefficients and must

satisfy  $|\alpha|^2 + |\beta|^2 = 1$ . Reading a qubit in the superposition of Equation 1 yields a 0 with probability  $|\alpha|^2$  and a 1 with probability  $|\beta|^2$ . In practice, information would be held in a superposition of the states of a register of many qubits. Each member of a superposition would represent a separate sample of information; processing the qubit register would process all the information simultaneously.

Like digital computing, quantum computing holds information in zeroes and ones, but unlike digital computing, it also contains information in coefficients drawn from a continuum of numbers, as in Equation 1. The accuracy of representation is limited by the precision of the physical components that hold the information. Another writer clearly states this issue:<sup>1</sup>

“[Q]ubits are just quantum two-level systems such as the spin of an electron or the polarization of a photon. They can be prepared in a coherent superposition state of 0 and 1:

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle,$$

where  $\alpha$  and  $\beta$  are the complex amplitudes of qubit states  $|0\rangle$  and  $|1\rangle$ , and the superposition is resolved in either definite state  $|0\rangle$  or  $|1\rangle$  upon measurement with respective probabilities  $|\alpha|^2$  and  $|\beta|^2 = 1 - |\alpha|^2$ . In one sense, this is just a single bit of information, but in another sense the continuous amplitudes  $\alpha$  and  $\beta$  carry an infinite amount of information, similar to that of analog information carriers such as the continuous voltage stored on capacitors.”

Clearly, the infinite information is that contained in  $\alpha$  and  $\beta$ , coefficients that are drawn from a continuum of numbers. To be fair, the quoted author is aware of the existence of limitations to the amount of information that can be represented: “analogue systems are known to suffer from the cumulative build-up of noise ... Quantum bits are similarly vulnerable to analogue noise.”<sup>1</sup>

Much about quantum computing is a “riddle wrapped in a mystery inside an enigma,” to borrow Winston Churchill’s famous phrase, and the above explanations of quantum computing’s power are too simplistic. However, since questions about the exact meaning of quantum concepts don’t (at present) obviously bear on the prospects for physically implementing a quantum computer or on its operability, they won’t intrude here.

### Real Qubits

Researchers have explored physical realizations of qubits both theoretically and experimentally for several years. The largest quantum computations

to date used the precision methods of nuclear magnetic resonance (NMR), with spin 1/2 atomic nuclei as qubits and a magnetic field establishing two distinct nuclear states. Seven nuclei in a molecule made a 7-qubit quantum computer that exercised the factoring algorithm on a 4-bit number; macroscopic samples contained millions of the molecules working in parallel.<sup>2</sup> However, the NMR method seems to be limited to roughly 10 qubits,<sup>3</sup> whereas attacking worthwhile problems would require systems of thousands or tens of thousands of them.

Quantum computing thus seeks qubits in other physical forms. Experience in preparing large numbers of solid-state devices makes them almost certainly the medium with which to fabricate the thousands of qubits needed for a useful quantum computer. Unfortunately, other technologies for making qubits won’t be able to duplicate the very high quantitative precision of NMR experiments, and error-correction schemes, to be discussed later, will increase the number of physical qubits needed by a factor of 10 or more. The economic and performance advantages derived from transistor miniaturization propelled a long-enduring evolution of integrated circuit fabrication that routinely produced wafers with hundreds of chips, each one containing millions of devices. Although most qubit technologies lack such ready extensibility to large numbers of devices, several laboratories have demonstrated solid-state qubits created from well-established integrated circuit technology.<sup>4-7</sup>

Qubits based on the phenomena of superconductivity provide the principal realizations of solid-state qubits to date. Such devices are relatively easy to make and don’t require any modification of the underlying substrate. In fact, superconducting qubits have advanced to enable two qubits coupled by a capacitor on the chip to interact.<sup>6,7</sup> Energetics favors the quantization of magnetic flux in superconducting loops; setting a flux to a half-integral number of flux quanta allows the integer flux quanta energy minima on either side to be used as qubits.<sup>5</sup> The union of superconducting electrons into Cooper pairs provides a similar opportunity: inducing an odd electron in a small superconducting capacitor (called a *Coulomb box*) yields a state that can lower its energy by adding or removing an electron to reestablish pairing.<sup>6</sup>

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Bruce Kane's proposal for another kind of solid-state device, a silicon qubit, stimulated wide interest in quantum devices in silicon.<sup>8</sup> This method used spins in semiconductor silicon as the qubits and as a means of controlling qubit–qubit interactions. The spins of phosphorus nuclei imbedded close to the surface in silicon are the qubits. Phosphorus is a donor in silicon, and its nucleus can be controlled through the wave functions of the trapped electrons that contact it. Qubits interact via the overlap in the neighboring donors' wave functions.

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As ingenious as these concepts are, they must still be translated into physical devices. Modern solid-state devices are patterns in layers of material deposited on a planar substrate; the lithographic processes that control the removal, deposition, or alteration of material in selected regions impose these patterns. A lengthy series of such steps is required to make devices and circuits. Moreover, the processes involve chemical and physical treatments that must be performed at elevated temperatures in reaction vessels and ovens. Perfect control of all the many parameters is not attainable for many reasons:

- Temperature gradients in a substrate cause differences in the rate at which thermally activated processes proceed.
- Reagents might be depleted unevenly because of local patterns.
- Materials with different thermal expansion coefficients cause strains in the devices and in the substrate during heating and cooling that the finished product retains.
- The patterns in devices and interconnections lead to complex inhomogeneities in the strains, which in turn can distort the substrate and cause focusing errors during lithographic operations.

The result of the inability to exercise perfect control over a substrate is that each device is unique. This variability in solid-state devices for electronics is typically measured in percents, and it degrades conventional computing systems' performance.<sup>9,10</sup> Similar variability is to be expected in qubit characteristics.

The lack of quantitative precision in the fabrication process affects device properties in different

ways. The variability of superconducting qubits' lateral dimensions causes inconsistencies in inductance and capacitance values, and uncertainty in film thickness contributes to the well-known spread in the characteristics of Josephson devices.<sup>9</sup> Although strain has minor effects on metal properties, its large effects in silicon lead to faulty knowledge of the electronic wave functions and uncertainty in the methods used to control donor electrons. As mentioned earlier, voltages applied to electrodes on the silicon's surface influence electronic wave functions and their density at the phosphorus nuclei in the Kane computer.<sup>8</sup> The effect of the electrodes on the wave functions depends on their exact size and placement, but variability of such physical dimensions is common in device processing, so it affects the electrodes placed between donors to control qubit–qubit interactions.

Remember the previously mentioned superconducting qubit experiments? For systems of only two qubits, the differences between the devices are easily measured and handled.<sup>6,7</sup> The differences between nominally identical qubits are determined and explicitly stated as differences in critical currents and Josephson energies. Differences between only two devices are easily taken into account in laboratory experiments.

Although Kane's silicon/P-donor proposal is being actively pursued<sup>11</sup> and is widely cited in suggestions for other devices in silicon, all approaches must contend with the variability of nominally identical devices. Silicon is the favored device-fabrication technology, but the requirements for fabricating digital computing devices differ from those for quantum computing, and certain properties of elemental silicon don't favor its use as a material for qubits in computers. Silicon is a multivalley semiconductor, a feature that renders its wave functions particularly sensitive to strain.<sup>12</sup> The random strains that remain after processing alter the mixture of valleys in the donor wave functions, causing the electronic states to differ from one donor to another. Additionally, an isotope with nuclear spin 1/2 constitutes almost 5 percent of natural silicon. Because silicon qubit proposals involve nuclear and electronic spins, the presence of isotope <sup>29</sup>Si interferes with the operation of spin-dependent qubits. The original proposal for a silicon quantum computer assumed isotopic separation to eliminate <sup>29</sup>Si,<sup>8</sup> but the localized donor state's wave function (contacts a nuclear qubit) spans approximately 20,000 silicon atoms, of which roughly 1,000 would be randomly distributed atoms of <sup>29</sup>Si. Elimination of <sup>29</sup>Si from a system of 1,000 devices would strain separation technology.

Although each qubit in a group of different qubits can hold information, the lack of detailed knowledge about each one's properties inhibits their manipulation via control signals. Superpositions start with a qubit in a known state; after applying a perturbation that causes the device to evolve toward the other state, we stop the change when the device's state reaches the desired mixture of the two wave functions. In NMR, quantum computing electromagnetic radiation at a selected frequency is the perturbation that causes spin 1/2 nuclei in a magnetic field to rotate at a finite rate between the states parallel and antiparallel to the magnetic field. By removing the perturbation when the nucleus is between the two states, the qubit remains in a superposition of those states.

Looking at Equation 1, we might want a superposition with equal parts of  $\psi_0$  and  $\psi_1$ ,  $\alpha = \beta = 2^{-1/2}$ . Ideally, this could be formed by applying a perturbation to a qubit in state 0 for some time and turning the perturbation off when  $\alpha = \beta = 2^{-1/2}$ . The rate at which a qubit evolves between its states depends on the wave functions that represent the 0 and 1, but the qubit's physical properties determine the wave functions: variability in the physical properties of manufactured qubits leads to variability in the wave functions as well as in the rate at which they evolve under a perturbation. However, when the wave functions  $\psi_0$  and  $\psi_1$  aren't accurately known, the perturbation's effect is uncertain, the time period needed would likewise be in doubt, and  $\alpha$  and  $\beta$  could have substantial errors.

The pioneers of NMR computing knew about the timing problem. They reported that, "The single most important source of errors in the experiments was ... field inhomogeneity and pulse-length calibration imperfections."<sup>3</sup> (Inhomogeneity here refers to the magnetic field, which was required to be homogeneous to within one part in  $10^9$  over the sample's volume.)

The fact that each qubit is a different physical entity with distinct properties might be acceptable in a sufficiently small system. The 7-qubit NMR computer used both carbon and fluorine nuclei as qubits, and each nucleus was in a different position in the molecule. The point is that with just seven qubits and NMR methodology, each qubit could be characterized with parts-per-million accuracy and the differences accounted for during operations.

### Error Correction

The world in which quantum computing will have to function offers opportunities for interaction of quantum information with extraneous entities that alter that information, an event known as *decoher-*

*ence*. Some argue that decoherence tolls quantum computing's death knell.<sup>13</sup> A solid-state quantum computer would have to be operated at a temperature well below one degree Kelvin, for example, to minimize thermally stimulated sources of decoherence. Changes introduced in solid-state qubits by repeated cycling between cryogenic and room temperatures would thus be an indirect consequence of decoherence.

Recent research found a response to the decoherence threat in the correction of errors by comparing redundant qubits at each step in a computation.<sup>14</sup> Error correction assumes that the probability of an error at each step, including the correcting actions, is small enough to greatly reduce the probability of an error remaining after correction. Estimates of what "sufficiently small" means vary from  $10^{-2}$  to  $10^{-9}$ . Other research suggests that too large an error probability per operation can be handled by applying another level of error correction to the error correction itself, which further complicates the physical computer.<sup>14,15</sup>

Error correction through redundancy increases the number of devices needed for a computer by a factor of something like 10 or even 100,<sup>15</sup> and a correspondingly large amount of communication between devices and control hardware will also be needed. An assumption that errors are uncorrelated, which won't necessarily be the case with the differences that arise during fabrication, is a weakness of today's error-correction methods. Gradients in process parameters might affect nearby devices in much the same way. The interesting questions are twofold: Can errors caused by the faulty timing of interactions be corrected? Can the imperfect knowledge of qubit characteristics be managed with error correction designed for decoherence?

### Communication

The wires that enable interaction between components by carrying information from place to place play a major role in shaping a computer's physical form. Fabrication of the wires on a chip is part of the chip manufacturing process, and communication hardware beyond the chip belongs to the discipline of packaging.

Quantum computers must also have a way to bring together information from distant parts of the substrate. The requirement for interactions in quantum logic has been stated fairly specifically: "it

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should be possible to apply the CNOT gate to any pair of qubits in the quantum computer.”<sup>16</sup> (The CNOT gate operates on a pair of binary digits, A and B. If A is 1, B is changed from 1 to 0 or from 0 to 1. If A is 0, B is unchanged. The operation is equivalent to  $B = A \text{ XOR } B$ .) This is quite a demanding requirement for interconnection, implying, for example, that a 1,000-qubit system would need to provide for 500,000 qubit–qubit interactions. However, the 7-qubit NMR computer did it: interaction of each of the 21 ways in which a pair of nuclei could be chosen was brought about by one of 21 different frequencies.<sup>2</sup>

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There will be many orders of magnitude more possible pairwise interactions in a useful quantum computer than in the 7-qubit example, and each will differ from every other one. Characterizing and accounting for each qubit and 10,000 or more possible different interactions seems out of the question.

The ability of qubits to influence one another through overlapping wave functions, as in the silicon–phosphorous donor proposal,<sup>8</sup> or through a mutual capacitance, as in some superconducting experiments,<sup>4–7</sup> won’t be possible when qubits are far apart. Every qubit won’t adjoin every other qubit in a computer that contains thousands of devices, so something will have to be invoked to satisfy the demand for interaction—and this interaction must be specific to each pair of qubits. A means of point-to-point communication functionally comparable to the wires used in conventional computers will be needed, but wires themselves seem to be out of the question. Besides the question of how a superposition of states could be carried by a wire, their capacitive and inductive couplings would be intolerable in an environment that requires careful control of interactions.

A state might be transmitted through a distance along a chain of neighboring qubits, but that would hardly be possible in a dense system where crossings of information-bearing paths would be encountered. Long series of transfers would be slow and inhibit operation synchronization. Quantum teleportation offers a communication technology, but implementing it for the large number of connections needed in a small space seems unlikely. The need to support each transfer of information with error correction would greatly complicate a communication system.

## Digital Computing

Similar obstacles have long plagued information-processing systems, including the computers on our desks. Through the ages, devices have had to handle information and transmit it with inexactly specified components, noise, delay, signal degradation, and distortion. The not-so-secret key to dealing with this uncertainty is binary digital representation. (Witness the abacus, wherein each bead has two positions.) The need to distinguish between only two possible alternatives in binary logic circuits greatly eases the problems posed by variability in devices and degradation of signals on wires.

Standard values for a signal are distributed throughout a system, and signals are reset to the standard value. At each processing step, it’s only necessary to recognize a signal as a 0 or a 1 to be able to correct deviations from its intended value by resetting it to one of the standard values. Strict insistence on one state or the other provides the tolerance of variability and noise that allows systems of millions—even billions—of devices to be assembled and to work together reliably, year after year. The essential element is standardization, the restoration of a signal to its proper value at each step in a procedure. Quantum computing has not yet developed anything of this kind, and small errors can accumulate throughout the many steps in a computation.

Ultimately, we need a means to restore the synchronization of interacting signals. In the digital computers that we know and use every day, signals are periodically stored for short times and released by a clock to synchronize the separate parts of the system.

**T**he concepts of quantum computing are formulated in the framework of the ideal world described by quantum theory—the challenging task is to adapt those concepts to the less than perfect world of manufacturable devices. The potential that quantum computing offers is connected to the ability to form superpositions of quantum states that are defined by coefficients that can have a continuum of possible values. The analog nature of this essential information threatens quantum computing with the same limitations encountered in analog computation: imperfect knowledge of component parameters limits result accuracy.

One answer to the problem of imperfectly known components is binary digital representation of information as used in contemporary electrical computers. The challenge for quantum computing is to find another answer. Can redundancy as

used in quantum error correction provide it? In vain, researchers have devoted massive efforts to technologies aspiring to replace the transistor with solid-state components subject to the same variability as the transistor, but without a way to restore signals to their intended values.<sup>17</sup> The same kinds of difficult problems are present in quantum computing and must be faced if it is to avoid the same fate.

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