Comments on “IEEE Framework for Metrics and Benchmarks of Quantum computing, v. 0.2”

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1/27/19

This “IEEE Framework” draft document provides a good start, but it seems rather incomplete. It tends to be vague when it really should provide specific examples. I would suggest additions in the following areas:

- Qubits
- Algorithms
- Classical Simulators for Quantum Computers
- Quantum Chemistry Simulations
- Classical and Quantum Ising Simulators

I. Qubits and quantum computers

A qubit consists of a physical device that has at least two stable quantum states, and may exist in a quantum superposition of these quantum states. The quantum state of any given qubit must be sufficiently isolated from its environment so as to maintain coherence for a coherence time that is long enough to carry out at least one operation on the qubit (and preferably many such operations) with high reliability. Transitions between the quantum states may be carried out by using a resonant electromagnetic pulse, where the pulse frequency may lie in the microwave or optical regime, depending on the qubit technology.

A practical quantum computer is a system composed of a large number (greater than 50) of physical qubits, mutually interacting to create an entangled quantum state. The quantum computer will also include classical control hardware to control and read out the states of the qubits. The quantum computer may also include a classical computer and associated software that can translate high-level programs to machine-level commands.

A qubit must be implemented in a specific technology that is scalable to large numbers of interacting qubits. There are two general classes of qubits, based on either microscopic quantum systems, such as atomic states, or macroscopic quantum systems, such as superconducting circuits. Atomic states have energy levels in the eV range corresponding to optical frequencies, for which thermal fluctuations are negligible. In contrast, superconducting circuits have energy levels in the μeV range corresponding to microwave frequencies, requiring cooling down to mK temperatures, far below the superconducting critical temperature, to avoid decoherence from thermal fluctuations.

In some cases, a qubit may operate as a classical bit, enabling a classical mode of operation, without entanglement, even in the presence of noise or fluctuations. Certain computational systems can take advantage of this to enable a smooth transition from classical to quantum operation. In other cases, qubits may be required to maintain coherent entangled operation for an extended period of time, longer than the natural decoherence time. In order to achieve this, a system of quantum error correction must be implemented to correct and restore qubits. This is generally believed to represent a difficult problem that has not yet been implemented or even designed. In the future, benchmarks for quantum error correction techniques will also be required.

Several scalable qubit technologies are currently being explored, as shown in Table I.

Table I: Examples of Types of Qubit Technologies

Technology	Control	Temperature	Players
Josephson Junctions	Microwave	10 mK	Google, IBM, Intel, D-Wave
Trapped Ions	Optical	Room	IonQ, Alpine
Quantum Dots	Infrared	1 K	Intel, SQC

II. Quantum Algorithms and Applications

There are a variety of different types of quantum algorithms which may be implemented on different classes of quantum computing platforms, operating in the presence of different levels of noise. Consider the examples in Table II. Analog quantum annealing reduces to classical annealing in the presence of noise, but a clear advantage of quantum enhancement remains to be established. In the intermediate regime of Noisy Intermediate Scale Quantum Devices (NISQ) with moderate numbers of qubits (50-100), a range of applications in quantum chemistry and quantum machine learning may be possible, and are starting to be addressed. In the other limit, requiring full quantum error correction, is Shor's algorithm for factoring large numbers, which would enable decryption of encrypted signals. Until such quantum error correction becomes feasible, such applications will remain in the distant future.

Table II: Examples of Quantum Algorithms

Algorithm	Application	Noise Environment	Players
Analog Annealing	Optimization	Both Quantum and thermal fluctuations	D-Wave
Analog & Digital Simulation	Quantum Chemistry	NISQ	Google
Neural Networks	Quantum Machine Learning	NISQ	IBM?
Shor's algorithm	Factoring for Decryption	Requires Quantum Error Corr.	?

III. Classical Simulators for Quantum Computers

In order to evaluate the performance of quantum computing systems, appropriate simulations on classical computers are necessary. These simulation systems are non-trivial and not yet standardized. For example, given the central importance of noise in quantum systems, realistic simulators need to include effects of noise and decoherence. Furthermore, given the large degree of parallelism in classical simulation of quantum computers, it is likely that substantial improvement in scale and speed may be obtained using processors such as GPUs, TPUs, etc.

IV. Quantum Chemistry Simulations

It is widely believed that quantum chemistry may provide some of the near-term applications of NISQ quantum computers. There is already an established community of quantum chemistry calculations using classical computers and various levels of approximations. Moderately complex benchmark problems, such as molecular clusters and crystal surfaces, should be established in order to compare classical and quantum solutions.

V. Classical and Quantum Ising Simulators

The D-Wave Quantum Annealer is an analog system designed to map onto a 2D Ising model, which can be used to solve a wide range of optimization problems, such as the Traveling Salesman problem. But the classical 2D Ising model can address the same set of problems, and several types of special-purpose classical digital processors are being developed, such as the Fujitsu Digital Annealer. The same benchmark problems should be used to measure the performance of both classical and quantum systems. Only in this way can the performance enhancements of quantum systems be clearly established.