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Introduction

The IEEE Future Directions Committee has a long history of working with industry, academia and national laboratories to use its role as an impartial player to catalyze the development of important new technologies. The Committee brings together stakeholders for meetings in new areas of interest to the IEEE to determine where the Institute might make a contribution. Once the meeting has concluded, the Committee uses a summit output whitepaper to help it decide what technologies to incubate.

This whitepaper is the output of an IEEE Future Directions Quantum Computing Summit (QCS), held in Atlanta in August, 2018. It was attended by 40 major players in quantum sciences from both the public and private sectors. The summit chairs are Travis Humble and Erik DeBenedictis,.

Their original plan called for the group to deal with nine different quantum-related issues. The QCS, though, developed a consensus for a different approach, focusing on three areas where participants believed the IEEE could be especially impactful. The three are:

1) *Benchmarking*: Development of a benchmarking effort to help track quantum computing's progress.
2) *Publications:* Provide authors a place to publish scholarly articles about quantum computing that provide markers for the field's current state of progress.
3) *Education:* Develop a quantum computing education component that would, among other things, help interest college students in quantum sciences and, eventually, assist them in preparing for a career in a quantum industry.

What follows is an in-depth exploration of each of these recommendations, as explained by the conference participants tasked with turning each of them into reality.

(This whitepaper was written by Lee Gomes, (lee@leegomes.com) a long-time technology journalist who lives in San Francisco. If you have questions on how it is positioned for future actions within IEEE Future Directions, please send an email to FD@ieee.org.)

Recommendation I: Benchmarking

When we want to keep score with technology, we make use of benchmarks; measurements by which products from entirely different vendors can be compared without worrying about mixing apples and oranges. Thus can the owners of two different computers know they have the same amounts of hard disk storage; or two different mobile phone users be confident that their headsets contain CPUs of roughly the same processing power, despite being sold by different manufacturers.

The early histories of new technologies commonly contain a chapter in which industry participants come together to jointly develop independently-verifiable benchmarks by which progress in the field can be fairly measured. The IEEE is no stranger to these benchmarking efforts; it played a prominent role in one of the most important benchmarking episodes in computer history: The lengthy and intricate process during the 1990s and 2000s that led to benchmarks for reliable, high-performance microprocessors, one of the foundations of modern computing.

As quantum computers slowly morph from being theoretical lab projects to working, real-world systems, the need for a set of benchmarks to allow comparisons among and between quantum systems is acute. This is true for two reasons. First, the half dozen or so quantum computer designs that are now receiving the most attention have very little in common with each other, meaning it is impossible to get any sense of how the absolute performance of one stacks up with another. Second, the single "benchmark" currently in widespread use with quantum machines -- the number of qubits the system contains -- is wholly inadequate, and indeed even misleading. Most lay readers would assume that a 100-qubit computer would be more powerful than one with only 50 qubits. In fact, this is not necessarily the case, for as it turns out, not all qubits are created equal. Rigorous benchmarking will be required to determine the relative quality of a particular qubit.

It was thus only natural that given the IEEE's role as a facilitator of community consensus, one of the most important contributions it could make to foster the emergence of a robust quantum computing sector would be to create of a suite of benchmarks. Consensus on this matter was quickly reached at the Atlanta summit. A special working group on benchmarking was created, co-chaired by Travis S. Humble, director of the Quantum Computing Institute at Oak Ridge National Laboratory, and Bruce Kraemer, past president of the Standards Association of the IEEE.

"With quantum computing, we are in unchartered territory," said Humble. "We need benchmarks to understand where we are on the map."

The actual process of creating benchmarks often involves designing deeply technical analyses that make rigorous measurements using sophisticated test and measurement hardware; it's a job for experts, and requires lengthy planning and prep work. For the benchmarking study group, that effort will be occurring in the months ahead, as input from a wide range of industry experts is solicited. For now, the group is concentrating on categories of benchmark tests; it will transition shortly to *what* exactly is going to be benchmarked.

The group decided to make use of the framework of a "stack." All computer systems can be conceptualized as some form of stack; the specific quantum stack developed by the working group is shown in this chart.

1) Qubit-level and type
2) Gate-level
3) Architecture-level
4) System-level
5) User-level
6) Application-level

The list starts with the most basic hardware units of the machine, and then progresses in increasing complexity to encompass what the machine can actually do. A similarly-conceived stack for a traditional desktop PC might start with measuring the specs of the individual components of the CPU at Level One, then working all the way up to questions such as "How fast can the computer run Excel?" at Level Six.

Drilling down from the desktop level one would look at the base transistor, the Static Ram Memory cache up to the slower onboard Dynamic Random Access Memory. The argument is parallel to the Qubit-level and type. It also bridges into the Architecture-level.

Here is a closer look at the six levels, and a sketch of the benchmarking efforts that will be undertaken at each of them.

1) **Qubit level.** It's beyond the charter of this paper to explain the workings of quantum computing, much less the larger world of quantum mechanics. But understanding qubit-level benchmarking issues involves appreciating one of the field's core concepts: the way a particle can simultaneously be in a state where,

among other things, it is both a zero and a one. It is because an (unobserved) quantum particle exists in this "superposition" that it is able to act as both a wave and a particle in the famous double-slit experiment of quantum mechanics. (It's also the reason why the cat in Schrödinger's famous thought experiment is both alive and dead.)

Unfortunately, an object doesn't last in this mysterious state forever. Any number of factors, but especially some sort of "noise" from the outside world, can cause it to fall out of its "all of the above" quantum state and become instead like a standard computer bit, equal to either a traditional one or a zero. The length of time for which an object maintains its quantum nature is called its "coherence time;" one analogy to coherence time is the duration for which a coin set spinning on a table will maintain its perfectly upright rotation before it starts to slow down, wobble, and eventually collapse.

A qubit is only useful while it is still "coherent." Unfortunately, coherence times in quantum computing are currently quite short, for example, in the range of 25-100 microseconds for some quantum technologies. What's more, the interval between errors in a single qubit is different each time it is accessed. Worse still, in a multi-qubit system, the different qubits will all display different coherence times, and in a largely random fashion; these mainly-random differences can be as much as 25% among different qubits. (That is just one reason that the current generation of very early quantum computers is often referred to by the acronym NISQ, which stands for Noisy Intermediate-Scale Quantum technology.) Every quantum computing research team has a good understanding of the coherence times of its qubits, and all of them are working to both lengthen coherence and to make the process of decoherence less random and more predictable.

Creating an accurate measure of coherence time, to better follow overall progress in quantum systems, is thus one of the primary benchmarking challenges at this level of the quantum "stack." This task is complicated by the fact that different quantum research projects use very different physics to create their qubits. IBM, Rigetti, and D-Wave for example use a specially-fabricated "superconducting circuit" that, at the chip level, demonstrates quantum properties that can be exploited for the purposes of computation. An entirely different qubit technology, trapped ion quantum computing, isolates a single atom and presses it into duty as a qubit. Naturally, each will require benchmarking tests relevant to their relevant electric engineering.

2) **Gate level and equivalents for other quantum computing paradigms.** The concerns at this level are most easily described for gate-model quantum computers, so we will describe these first. It was mentioned previously that a particular 50-qubit computer perhaps would be more useful than one with twice as many. We just got a hint of one of the reasons that's true: qubits with longer coherence times are far more valuable. The other half of the story is that the true usefulness of a qubit depends on how many "operations" one can do on it while it is still in its perfect quantum state, which means each operation must be performed rapidly. Being able to count the number of successful operations is the main goal of device-level benchmarking.

To perform calculations with gate-model quantum computers, engineers apply some sort of charge to its qubits; RF pulses and lasers are common ways of interacting with them. Physicists, both applied and theoretical, have an increasingly complete understanding of how these "gate operations" affect the value of the qubit, and how they can be strung together in order to perform an actual quantum calculation. (A somewhat imperfect analogy involves the way traditional computer scientists have learned which commands they need to send to a CPU in order to get a desired answer.) Naturally, quantum researchers want to be able to send as many of these pulses/gate operations as they can while the qubit is still in its quantum state. And thus, the ratio of the number of gate operations, divided by the coherence time, is one of the most important metrics in quantum computer science. Hence, a 50-qubit machine that allows thousands of gate operations during the "useful life" of its qubits could be significantly more useful than a 100-qubit device that only allowed a few dozen.

Being able to reliably measure this gate operation/coherence time ratio is the main challenge of this level of benchmarking. Currently, an individual gate operation in superconducting technologies requires about 100 nanoseconds, meaning that today's quantum machines can typically perform from 100 to 1,000 gate operations before the qubit decoheres. (Again, these figures are accompanied by considerable randomness.) As quantum scientists work to increase that figure, the gate-level benchmark will be tracking their progress.

Quantum annealers, like those manufactured by D-Wave, do all their operations at the same time, so when discussing these systems, the same underlying issue has to be described somewhat differently. These systems start out in a random initial superposition, essentially "everywhere" in the space of possible configurations, and then cool down in a way similar to the formation of a crystal, where the structure of atoms in the crystal is the "answer" returned by the computation. If cool-down is too fast, the crystallization becomes imperfect -- like a diamond with imperfections -- and the answer incorrect. The proper rate for both an annealer and a crystal depends on the relative speed of the interactions -- between qubits or molecules -- compared to the size of the problem. Thus, an annealer works better with strong, fast interactions between qubits compared to their decay time.

3) **Architecture level.** At this level, we begin to think less about the specs of individual qubits, and more about how they are arranged into an actual computer. (The obvious traditional computer analogy is that we are moving from considering transistors and logic gates, and to instead start to think about the entire CPU as an integrated device.)

One of the crucial issues in quantum computing involves how easily one qubit can interact with another qubit located elsewhere on the device. Much of this is determined by how the qubits are physically laid out. Different grid-style topologies have been adopted by different quantum research labs and companies; all have their own strengths and weaknesses. Quantifying those differences is one of the main goals of architecture-level benchmarking. What is especially challenging about this topology problem is that the I/O mechanisms for qubits are, relatively speaking, large and bulky; they take up vastly more space than the actual qubits themselves. And as topologies grow in size and complexity, noise and errors tend to accumulate. Appreciating the trade-offs involved with different qubit layouts is thus a central concern of this level of benchmarking.

4) **System level to application level.** Until now, the benchmarking efforts being discussed have been squarely in the province of physicists and electrical engineers. But now, as we move "up the stack," new disciplines begin to enter the picture, notably theoreticians, computer scientists and programmers. That is only natural considering the questions being asked as we arrive in this new benchmarking territory.

At the system level, a typical relevant question might be, "How easy is it for this computer to be actually deployed in the real world?" A user-level benchmark would seek to appreciate the robustness of the programming tools that are available to those wishing to make use of the machine. Finally, the application level deals with what for many people is the only relevant question about quantum computing: What useful things will these machines be able to do for us ... and when?

Rather than addressing each of these benchmarking levels individually, as we did with qubits, gates and architectures, a more productive approach will be to deal with a number of disparate issues that, in one way or another, touch on all of them.

A) Qubits: "Regular" and "error-corrected." Until now, this discussion paper of qubits has referred to a single, actual physical qubit. But, as we have noted, qubits are susceptible to decoherence, noise, loss of quantum "superposition" and other random events that can interfere with accurate computation. That is why, when quantum scientists envision a useful quantum machine sometime in the future, they contemplate the use of what are called "error corrected" qubits. Giving qubits error correction is an especially critical issue in gate-model quantum computing because qubits are currently too unreliable to be depended on for day-in, day-out practical computation. (Indeed, none of the gate model quantum systems currently in the news are equipped with any error-corrected qubits at all.)

Error correction in quantum computing is similar to error correction in a desktop PC: You accompany every piece of information with extra bits, and in the event something goes awry, use the extra bits and well-understood algorithms to reconstruct the correct information. What is different in the quantum world is the large number of "spare" qubits that will need to be standing by to "back up" a single "working" qubit. A single, dependable, error-corrected qubit is known as a "logical" qubit; at the moment, the best guess is that between 10 and 100 "physical" qubits will be required to create a single, dependable "logical" qubit. Advances in both theoretical and applied physics are continuing to bring the physical-logical ratio down, but the ratio is expected to remain quite large.

Although quantum annealing systems are more robust against these types of failures, error-correction is sometimes necessary to maintain a target threshold of success probability. In cases that have been studied (on small working systems) the ratio of error-correction qubits to logical qubit is typically less than four. In any fixed-size machine there is a tradeoff between the number of qubits used in the logical problem versus the number used for backup purposes, since a given qubit can be deployed for either purpose. Applications being solved on current D-Wave systems often make use of error-mitigation schemes (which do not require extra qubits), but in typical use do not assign qubits for error correction duties.

B) Error correction: What price to pay? The need for error correction is one of the most sobering aspects of quantum computing research, and is the reason why many involved in the field say it remains an open question whether quantum can "scale" in the same way as more familiar technologies, especially CMOS semiconductors. Consider the numbers. At the moment, the biggest quantum system in gate model computation is a chip with 72 physical, uncorrected qubits. But that is just a tiny fraction of what will be required to solve some of the "Holy Grail" problems of the field. The best known is Shor's Algorithm, which would allow the breaking of Internet encryption; it was the 1992 discovery that quantum computers could indeed accomplish this task that set off most of the current interest in the field. But a full implementation of Shor's algorithm would likely require millions of physical qubits -- a daunting figure indeed.

C) Will useful quantum computing be possible with fewer qubits? There are reasons to be hopeful that quantum computers will be able to tackle important real-world problems without requiring millions of physical qubits. One example comes from the field of chemistry. Converting nitrogen into ammonia for use in fertilizer is a crucial link in the world's food production system, and anything that would make the process more efficient could have major benefits to the planet. An enzyme crucial to the process, nitrogenase, contains a metallic structure that chemists have not been able to duplicate. But it's been estimated that a quantum machine with 200 logical qubits might be able to unlock its secrets, and thus make substantial progress on synthetic ammonia production. Of course, 200 logical qubits are still far more than is available on any current gate model system. But it's still a more attainable goal than tackling Shor's algorithm.

D) How "quantum" is a particular quantum computer? The work on quantum systems being undertaken by the likes of IBM and Google involve what might be considered general purpose quantum machines that, researchers hope, will one day be capable of handling any algorithm that itself allows for a faster-than-classical quantum solution, including, for example, Shor's algorithm. But other companies, most notably D-Wave are now marketing a different type of quantum systems tailored for specialized problems, especially those involving optimization. It will be up to the benchmarking group to determine how to measure the relative utility of each of these systems, having as they do fundamentally different operational principles. This might seem to be a task for the upper levels of the benchmarking stack, especially the application layer. But it is a pervasive issue that testers will need to confront at every step of their work. Indeed, one proposed benchmark for the qubit level involves the "quantum volume" of a qubit, which can be taken, roughly speaking, as a measure of the qubit's "computational horsepower." Those benchmarks are likely to be different with a general purpose and a specialized quantum machine, making it necessary to develop an interpretative framework for the tests.

E) If we build it, will they come? One of the main challenges in any industry-wide collaboration, including one for benchmarking, involves securing the involvement of all the major participants. Often, this includes economic competitors, some of who may decline to become involved lest they forfeit some kind of competitive advantage. Will this occur with the still-nascent field of quantum computing?

Co-chair Humble is optimistic on that front, certainly for the foreseeable future. "The quantum community is still very open-minded and research-oriented. Many of the leading efforts are headed by scientists and engineers who believe in the technology but who understand that it is still in its early days. Companies are still being very open and sharing their information, and there are multiple universities pursuing the same lines of inquiry. No one has made a breakthrough in terms of scalability or controllability that would warrant a concern about keeping the information proprietary. We will have a more competitive space once competing products start to appear, but I don't think we are there yet."

Recommendation II: Publications

Scholarly journals play a universally-acknowledged role in chronicling the progress of the sciences. In this regard, they are best-known for the articles that announce important new results, be they Einstein's four *Annus Mirabilis* papers in *Annalen der Physik* in 1905 or the 1948 write-up in *The Physical Review* of Bell Labs' new "transistor."

But there is another venerable tradition for scientific journals: The special issue. These special issues don't necessarily announce new results. Instead, they are published at some historical juncture when a field has seen important advances; their goal is to capture that moment, explain its significance, review the basic science, and contemplate where the field might be headed. IEEE publications have published numerous special issues over the years. For example, *Computer* had a special issue on "Rebooting Computing" in 2015, and *Computing in Science and Engineering* had a special issue in 2017 on "The End of Moore's Law."

A consensus emerged at the IEEE Quantum Computing Summit that with the field on the cusp of the breakthrough known as "quantum supremacy," quantum computing had reached the point where it warranted a special issue of its own. Not just one, in fact, but a pair of them, each covering a different aspect of quantum sciences and each running in a journal that had expressed an interest in hosting a special quantum issue.

Atlanta conference attendee Elie K. Track, co-chair of the IEEE Rebooting Computing Initiative, CEO of photovoltaic start-up nVizix, and past president of the IEEE Council on Superconductivity, was given the task of helping shepherd the two publications into being.

"There are many articles about quantum computing being published today," said Track. "But the problem is that they are scattered across different journals from different fields, mostly in fundamental science journals. The value of a special issue of an IEEE journal is that it would provide an overview of the new technology as it starts to make the transition out of the laboratory. This would be valuable for someone who is just entering the field. And it will also be a great reference for someone five or 10 years from now, providing a historical record of where we were and the direction in which we were moving."

The publications that will be hosting the special quantum issues are *Computer*, the IEEE Computer Society prestigious and practitioner-oriented magazine, and *Transactions on Applied Superconductivity*, published by the IEEE Council on Superconductivity. *Computer* is directed to the entire computing community, while the *Transactions* is directed toward specialists in superconducting devices and systems. *Computer,* said Track, concerns itself with computer systems and applications; its articles tend to involve the sorts of issues that a computer scientist might be interested in, such as algorithms and architectures. Possible topics for its quantum special issue might be a discussion of the types of problems that a first-generation quantum computer might be able to deal with and the programming languages that might be employed as it does so.

Transactions on Applied Superconductivity, by contrast, is concerned, as its name suggests, with implementations of superconducting technology. The interest of the journal's editors in quantum computing is due to the fact that many of the best-publicized quantum computing efforts, including those at IBM, Google and D-Wave Systems, use a superconducting circuit as the quantum bit or "qubit" which forms the basic element of a quantum computer. Topics will include designs of current superconducting circuits and the challenges involved in scaling them to robust, field-ready commercial systems. Other quantum hardware approaches, such as those employing trapped ions, might also be covered by the issue, Track said.

Erik P. DeBenedictis, a volunteer from Sandia National Laboratories, will be co-editing the two special issues. In the case of *Applied Superconductivity*, he will be joined by D. Scott Holmes, of Booz Allen Hamilton. In the case of *Computer*, he will be joined by Dr. Travis Humble of Oak Ridge National Laboratory.

Computer has already issued its call for papers, which is available here (https://publications.computer.org/computer-magazine/2018/08/09/quantum-realism-realistic-future-quantum-computing-call-papers/). Contributions are due by Dec. 1, 2018, with publication expected in June 2019. The call for papers by *Applied Superconductivity* will be issued soon.

Recommendation III: Education

Quantum computing technology is at a historically important juncture. Its laboratory bona fides have been firmly established; now, scientists and engineers at scores of companies and institutes are racing to transform lab projects into scalable, production-ready systems that can be turned loose on real-world problems.

The situation gives rise to a number of questions. What expectations should society, especially those involved in setting government policy, have for the near- and longer-term future of quantum machines? What should today's science and engineering students be taught about the growing body of quantum information sciences? Might a shortage of skilled workers hamper the roll-out of robust quantum systems?

Some of these problems are already upon us. There is rapid funding growth planned in quantum computing, such as the the billion-dollar National Quantum Initiative, along with likely industry co-investment. But there might not by an adequate supply of workers trained in quantum information to effectively spend the projected funds. One possible solution: incremental education, such as one or two courses that would allow, say, a skilled circuit designer to design quantum circuits, or enable a materials researcher to study quantum information behavior in qubits.

Attendees at the Atlanta conference quickly reached a consensus that some form of IEEE education effort was crucial to dealing with such issues, and the many others that will crop up as quantum computing continues to evolve.

Dr. Scott Koziol, Assistant Professor, Electrical and Computer Engineering at Baylor University's School of Engineering and Computer Science agreed to chair the group charged with drawing up a game plan for what that education effort might look like.

Two ideas involving educational efforts quickly surfaced. One was a lecture series that would develop into a curriculum for interested college students. These lectures would be designed to "evangelize" quantum sciences, both as an intellectual enterprise as well as a possible career choice for engineering, physics or math students.

Since he himself is in a university setting, Koziol is especially interested in how an IEEE education effort could capture the interest of current undergraduates and graduate students. A well-planned lecture series could be a great catalyst, he said. "We'd like to identify leaders in the field, and then go to them and say, 'Hey, we've got a lecture hall full of people curious about quantum computing. Come and inspire us.' We want students to be exposed to this new technology so that they will be excited about it."

A key IEEE strength is the organizing of experts to create an authoritative opinion, such as in peer review. This IEEE strength could be applied to these lectures, perhaps ultimately taking the form of an expert panel to vet a series of lectures -- or other resources -- as a curriculum.

A second approach would be for IEEE to leverage its unique capabilities to create more quantum computing-focused educational resources. IEEE has an eLearning Library and a certificates programs for educational components in specific technology domains. Perhaps quantum computing educational resources could offered to the public utilizing these tools. In addition, IEEE has a social media platform: Collaboratec. Collaboratec community members could be used, for example, to determine what students are looking for in quantum education, and also to point students to IEEE's quantum resources, including publications, standards, existing educational modules and conferences. William Tonti, senior director of IEEE Future Directions, informed the group the IEEE Educational Activities (EA) unit is rolling out a new educational platform, the "IEEE Learning Network." This is a platform to host courses and then provide students with credit after completing a course and passing an exam. This would be of interest to industry, which is looking for opportunities to develop a quantum-trained workforce. Bill took the action item to follow up with EA and investigate if this is an area EA would be interested in should quantum computing become a new initiative. All involved believe it's paramount to provide learning modules (whether they be in the ILN, E-learning modules, or webinars) in a manner that is coordinated with the IEEE Future Directions Committee, the IEEE Educational Activity unit and the individual stakeholders requesting specific courses.

Koziol acknowledged that other groups, both inside and outside the IEEE, have similar endeavors underway and that one of his first priorities would be to reach out to them to better understand their efforts and the ways his own team might be able to contribute to them.

"I'm definitely not the expert here," he said. "We don't have all the answers, but we are getting organized to get those answers."

Since the summit Scott, Bill, Bruce and Erik have met with Jonathan Dahl of IEEE EA. Jonathan is looking at the potential need for quantum education in

EA. More to come on this once IEEE Future Directions makes a decision about a new quantum-related initiative.

In addition, both Bruce and Erik, are adding a special session on Quantum Computing at the upcoming IEEE Future Directions International Conference on Rebooting Computing. They see this as a continuing step in collaborating with the quantum computing community to develop a plan by which the IEEE could complement existing education efforts, such as with a lecture series and on-line content.

Koziol said it was crucial for the IEEE, as it contemplates quantum-related education efforts, to maintain a close partnership with major stakeholders such as industry and the national labs. "We want to make sure that we're helping to train engineers with the specific skill sets that are needed. I'd like to help educate future summer interns so who can hit the ground running when they start working in quantum science. We need to ask ourselves, 'What skills would the 'perfect' quantum computing lab summer intern have? Or the 'perfect' new hire?"

The role of quantum educator is one Koziol, as both an engineer and a teacher, clearly relishes. "Quantum represents a completely new rethinking of computing; it might in fact be the future of computing. It's exciting to think about how I as an educator can be a part of it."