Technology Assessment

IBM Announces the Next Step in its Plans to Develop a Universal Quantum Computing Ecosystem

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EXECUTIVE SUMMARY

IBM recently announced an addition of important new capabilities in its continual effort to make its universal quantum computer prototype freely available to the global research community as part of its vision to encourage a broad range of potential innovators to explore and develop new quantum applications. Specifically, in March of 2017, IBM continued to demonstrate its commitment to developing a universal quantum computer with the release of two additional upgrades to its Quantum Experience:

- A new application program interface that enables developers and programmers to begin building interfaces between its existing five quantum bit (qubit) cloud-based quantum computer prototype and classical computers, without needing a deep background in quantum physics.
- An upgraded simulator on the IBM Quantum Experience that can model circuits with up to 20 qubits. In the first half of 2017, IBM plans to release a full software development kit on the IBM Quantum Experience for users to build simple quantum applications and software programs.

The IBM-developed five qubit quantum prototype system, along with a wide range of algorithmic and software development tools, is accessible through an IBM-cloud software development environment specifically designed to facilitate such innovation and expand the potential pool of scientists experimenting with the prototype quantum system.

- Giving access to early leading-edge IBM prototypes of advanced quantum systems is a critical step forward in garnering support for the quantum field not only for IBM but for the global quantum computing research community as well.
- The ultimate success of IBM's initiative will be judged primarily by its ability to build a broad base of scientific interest that leads to the creation of a portfolio of quantum computing use cases and a robust quantum computing application development community.

Although the vision of a quantum computer has been around for almost 40 years, it has been only recently that the ability to build and operate a quantum computer has become more feasible. Today, the field is rich with various experimental designs for QC hardware and quantum systems.

- These efforts are complicated by the fact that almost every aspect of quantum computing from the fundamental physics that capture key quantum effects to quantum application development and workflow, requires dealing with wholly new, largely theoretical, and rapidly evolving knowledge and insights into the quantum computing environment.

For its part, over time IBM is targeting development of a fault tolerant universal quantum computer, considered by many to be the most powerful, the most general, and hardest to build flavor of quantum computers.

- The power and flexibility behind a universal quantum computer stems from its ability to tap into a wide variety of quantum logic gates that form the basis for every conventional computational algorithm and related software implementation.
- As such, a universal quantum computer offers a potential speed up over a number of existing algorithms and related applications in the conventional computing world, but more important, it also promises to open up an entire class of new algorithms that are not possible on a conventional system regardless of its ultimate computational capability.
- Because of the demanding requirements to implement, it will likely take more than a decade to develop a fully functioning universal fault-tolerant quantum computer of the scale required to tackle broad classes of problems.
- However, it is expected that so-called quantum superiority — the level at which a quantum computer becomes capable of practical computational tasks impossible on any conventional computing counterpart – may be demonstrated for certain use cases in the next few years on early universal quantum computers without fault-tolerance.

Other flavors of quantum systems, some of which are already available in the commercial sector and being experimented on by early users, include quantum annealers and analog quantum systems. Although each offers its own array of capabilities and tradeoffs in computational capability, generality, complexity in design and manufacture, and depth of application space, these quantum systems currently don't offer the full functionality of a universal quantum system, although that may change in the future.

Despite the daunting tasks ahead in both the hardware and software realm, the promises of a universal quantum computer to address a wide range of new and in many cases previously intractable problems, are considerable. Quantum applications range across a number of scientific disciplines including chemistry, biology, physics and mathematics, and they show significant promise to deliver new important solutions that could be considered the grand challenges of quantum computing.

- Examples of such quantum grand challenges include the development of models of key processes in nitrogen fixation that could allow researchers to manufacture fertilizers using less energy, resulting in cheaper food production around the world, and quantum modeling of catalytic reactions in petrochemical cracking processes that could improve their efficiency to great economic and environmental benefit.

IBM is taking a step forward by working to make its quantum computing prototype solution more accessible to a wide range of developers with the goal of expanding the scope of new quantum-based algorithms and related applications. To that end, a free, ready accessible, and perhaps most important, easy to use quantum computer interface may be the most important element of this recent announcement.

SCOPING OUT THE QUANTUM TECHNOLOGY LANDSCAPE

The vision of a quantum computer has been around for almost 40 years, but it has been only recently that the ability to build and operate a quantum computer has become a reality. Indeed, one company, D-Wave Systems, has sold multiple copies of a quantum annealer computer and a number of other efforts are under way around the world that are looking to define and implement some version of a quantum computer.

Today, the field is rich with various experimental designs for quantum computing hardware, encompassing the development of fundamental representations of quantum bits and quantum logic gates, as well as quantum storage and interconnects schemes. This work is proceeding hand in hand with counterpart efforts in new quantum-friendly algorithms and related applications. These efforts, however, are complicated significantly by the fact that almost every aspect of quantum computing, from the fundamental physics that capture key quantum effects to quantum application development and workflow, requires dealing with wholly new, largely theoretical, and rapidly evolving knowledge and insights into the quantum computing ecosystem.

At their most basic level, quantum computers perform calculations based on the laws of quantum mechanics, which is the complex and ultimately non-intuitive behavior of particles at the sub-atomic level.

- The fundamental building block for a quantum computer are quantum bits (qubits), which represent information in an entirely new way, and that allow problems that would be exponentially harder - if not impossible - on a classical computer to be run efficiently on a quantum computer.
- Indeed, the enormous computational potential of quantum computers comes, in part, from the ability to use a relatively small number of qubits to represent a huge computational space through quantum properties controlled by single or multiple qubit interactions—indeed a space larger than is ever possible conventionally.

In contrast, conventional computing, which encompasses almost all computing capability today, operates on classical electrodynamic theory where information is stored and processed as traditional two-state binary digits or bits expressed in hardware as voltage levels that define the 0 or 1 values.

- Although exceedingly powerful in its own right, conventional computing capabilities are limited by the fundamental bit storage and manipulation capabilities of binary logic.
- However, with its long history as the dominant computing paradigm, conventional computing has built up an impressive base of knowledge and engineering expertise in the design, development, and use of binary computation hardware, software and, perhaps most important, algorithms.

Because conventional and quantum computers operate differently at such a fundamental level, it is no surprise that there are key differences in where each computing paradigm will work best, where they will have only limited utility, and perhaps most important, where they will work together.

First, it is important to consider that despite many claims to the contrary in the press, the power of quantum over binary counterparts leads many to conclude that a quantum computer can provide exponential speed-up over conventional computing for all applications. This is not the case, as the potential span of quantum-only algorithms remains unclear, and according to some, may be quite limited (for example, it is difficult to imagine a quantum computer excelling at word processing).

Likewise, the idea that quantum computing will obviate or even mitigate the issues associated with the much anticipated end of Moore's Law, the idea that silicon-based conventional computers will soon reach a limit on performance growth, is true only for a limited class of quantum friendly applications.

- For most conventional computing algorithms and applications, quantum computing will not address Moore's Law slow-down concerns.
- Ultimately, quantum computing will likely serve as an additional new tool in the computational tool kit that works best in concert with conventional computing and that will be used only when truly required by a particular computational task.

QUANTUM COMPUTING GRAND CHALLENGES

The computational potential of quantum computing opens up a host of new applications and use cases typified by so called grand challenges — those that can significantly advance the state of the art in a wide range of computational scientific research. That potential might translate into dramatic gains in a wide range of applications, to drive new and innovative products and services, generate significant economic benefits across a wide range of industries, around the world, and in general improve the overall quality of life for many millions of people.

In contrast, conventional computing development does not offer clear paths forward for some of these future grand challenges problems. Despite substantial HPC performance gains over the past three plus decades, the ability of HPC s to effectively handle computational problems become increasingly limited as the problem size grows, a critical requirement to solve the fundamentally quantum nature of the many grand challenge problems.

- For example, a first-principles description of quantum effects in nature frequently requires solving an interacting multi-electron system, which is computationally intractable using conventional computing methods. This is caused by the exponential size of the classical description of quantum states.
- This well-known problem has been addressed in the HPC world by employing approximation methods, which are inadequate for some real-world problems of even moderate size.

In contrast, quantum computers offer a compact representation of quantum states, opening the door to fundamentally new solution methods. Even small (50-100 qubits) quantum computers are expected to operate in a regime which is inaccessible to conventional HPC on certain problems.

- For example, the largest next-generation of supercomputers (exascale) would be able to store a general quantum state of at most ~60 qubits, and larger quantum states are likely to be permanently inaccessible on classical supercomputers.

Grand Challenge Problem Types

The following is a partial list of scientific grand challenges that may prove to be solvable only on quantum computers:

Chemistry

- Models of simple heteronuclear diatomic molecules like CaF, which are poorly modeled by conventional approximate methods (off by 100% or a factor of 2 on bond length), will likely be among the first systems where approximate quantum algorithms show real superiority to conventional methods.

Biology

- Models of key processes in nitrogen fixation that allows for the manufacture of fertilizers using less energy.
- An improved understanding of the molecular process of photosynthesis used to improve biofuel production efficiency.
- Improvements in the drug design process made possible with larger quantum systems because of the complexity needed to accurately model drug molecule to binding site interactions as a complete system.

Materials

- Models of catalytic reactions to improve efficiency and allow for finding good candidates for optimization in new catalytic processes.
- Models of substances with mixed-valence (ionic plus covalent mix), which are difficult for conventional methods, are likely made easier with quantum computers.

Physics

- Models that characterize physical properties of strongly correlated materials such as high-temperature superconductors.
  - For example, solving the Fermionic-Hubbard model - a seminal solid state physics model - for may lead to the discovery of even higher-temperature superconducting materials that could potentially have great economic benefit.

Energy

- Models of key reactions in Li-ion and other battery technologies to help improve efficiency and energy density.
- Models that drive similar gains with biofuel production in the biology field.
- Quantum modeling of catalytic reactions in petrochemical cracking processes could improve their efficiency to great economic and environmental benefit. Petrochemicals will likely require hundreds of qubits or more to fully model.

DEFINING THE QUANTUM COMPUTING SPACE

Currently, there is no such single definition as to what constitutes a quantum computer. Quantum systems can be broken up into three main classes: quantum annealing systems, analog quantum systems, and universal quantum systems. Universal quantum systems, in turn, have certain characteristics and use cases based on whether they are fault tolerant or not.

- Each offers its own array of capabilities and tradeoffs in computational capability, generality, complexity in design and manufacture, and depth of application space.

Quantum Annealers

Currently quantum annealing systems seek out the minimum of a specified cost function through a manipulation of the qubits and their couplings.

- Given a set of conditions with many variables, a quantum annealer can quickly find the proper set of number values that result in a global minimum cost, provided that the problem can be represented in terms of its physical Hamiltonian, or total energy.

- Because of the focused functionally of a quantum annealing system, the technical requirements to stand up a working system is currently technologically feasible at useful scales, at least compared with other more complex quantum computing schemes.
- In addition, requirements for constructing workable quantum annealing qubits are well understood; as a result, the current state of the art in quantum annealing development is at 2000 qubits.

Quantum annealing hardware is the least general and powerful type of quantum computer. Quantum annealers solve only one specific problem class, for example the general Ising model (magnetic ions on a specific lattice that interact with near-neighbors).

- The only application that can be run on existing quantum annealing hardware is the general Ising model on a specific graph.
- Other problems can be mapped to the random Ising model, but in some cases at high conventional computational cost. Many practically important problems can be formulated as combinatorial optimization and mapped to a random Ising model.

Those applications that can be mapped include:

- Machine learning
- Sampling / Monte Carlo
- Pattern recognition and anomaly detection
- Cyber security
- Image analysis
- Financial analysis
- Software / hardware verification and validation
- Bioinformatics / cancer research

As quantum annealers are easier to design and build, there is already commercial availability of a quantum annealing system. Such availability can only help in the development of new algorithms and related software tools for this segment of the quantum computing space.

- Finally, there is some recent research to suggest that quantum annealers may provide their own path to universal quantum capability through the inclusions of additional coupling capabilities.

Analog Quantum Systems

Analog quantum systems represent a step up in generality, computational powers and difficulty in building and using, over quantum annealing systems. Essentially, these systems are designed to simulate complex quantum interactions that are intractable for conventional computing systems.

- An analog quantum system serves as a controllable physical system that can simulate other more complex and more interesting quantum systems.
- This kind of quantum computer is roughly analogous to the class of computers popular in the 1950’s and 1960‘s that used the continuously changeable aspects of physical phenomena such as electrical, mechanical, or hydraulic quantities to model the problem being solved.

Typical application particularly well suited for analog quantum systems include:

- Quantum chemistry

- Material science
- Optimization problems
- Sampling
- Quantum dynamics

Analog quantum simulators, functioning in the analog realm with a virtually infinite number of states, do not rely on logic-based operations of qubits and thus avoid the problems connected with coherence and entanglement in digital quantum information processing. However, this comes at a price: the analog interactions among qubits are relatively inflexible, allowing the analog simulator to solve only a specific class of problems. Because of this, it may be necessary to design different processor architectures and qubit interactions to solve different problems. Quantum analog systems have more stringent technical requirements than quantum annealers because of the desire to preserve the quantum state and interactions throughout the simulation. A workable quantum analog system will likely not be available for at least five to ten years.

- One onerous issue going forward is that because the process is analog, there is no real option for correcting errors that accumulate during a calculation. This approach will work well as long as the noise in the simulation is similar to that in the system being simulated; otherwise the simulation may be in error.
- As a result, an analog device must keep a quantum information intact long enough for the simulation to run its course without resorting to full error correction.

Universal Fault-Tolerant Quantum Systems

The universal fault-tolerant quantum computer is the holy grail of quantum computing. A universal fault-tolerant quantum computer is the most powerful, the most general, and the hardest to build flavor of quantum computers. Many experts indicate that it may take more than a decade to develop a fully functioning universal fault tolerant quantum computer of the scale required to tackle broad classes of problems.

- As such, a universal fault-tolerant quantum computer offers the potential to provide a speed up speed up over a number of existing algorithms and related applications in the conventional computing world, but it also promises to open up an entire class of new algorithms that are not possible on a conventional system regardless of its ultimate computational capability.

The power and flexibility behind a universal fault-tolerant quantum computer stems from its ability to tap into a wide variety of quantum logic gates that are analogous to the binary logic ecosystem used in conventional computational algorithms and related software implementations. Simply put, a universal fault-tolerant quantum computer allows long, error-free calculations that incorporate the full range of fundamental logic building blocks (comparable to the collection of NOT, AND, OR, etc., gates in conventional computing) but with the unique characteristics of the quantum environment.

- One such example in the universal fault-tolerant quantum computing space is the controlled-controlled NOT gate that switches an input bit if and only if two input control lines are set. This gate – similar to the Exclusive OR gate in digital computing – has been proven to be a key two-qubit logic gate that is often used to entangle qubits.
- In addition to a universal set of logic gates, quantum computers also must have functions which initialize and measure quantum states of the qubits.
- Due to the sensitive nature of maintaining an environment for quantum effects to operate properly, universal fault-tolerant quantum computers need to have the ability to do wide-scale

error correction. As such, the architecture of such a system may have to expend numerous physical qubits to construct a properly functioning error-corrected logical qubit.

- Finally, not all quantum technologies are equal. For universal fault-tolerant quantum computing, the gate time, or speed to perform gates, can differ by factors of thousands to millions. This means that the slower technologies will not show quantum superiority over conventional computers until larger, sometimes much larger problems are tackled.

Because of its ability to implement long calculations using all of the needed logic functions, a universal fault-tolerant quantum computer, as its name suggests, promises to address a wide range of applications:

- All of the applications of any other type of quantum computer plus:
- Secure computing
- Machine learning
- Cryptography
- Quantum chemistry
- Material science
- Optimization problems
- Sampling
- Quantum dynamics
- Searching

Currently, there may be as many as many 20 different universal quantum computing efforts under way in the world, but the most advanced systems are of order a few physical qubits. Scaling up universal fault-tolerant quantum computers to larger number of qubit is one of the most daunting challenges facing universal fault tolerant quantum computer developers today.

- Keeping a qubit or indeed a set of connected qubits in a superimposed state, a configuration where the qubit exhibits the characteristics of an amplitude profile for even fraction of a second, is a complex engineering task.
- The ability to keep qubits from falling out of this superposition state — called decoherence, is a key enabler for the future scaling of quantum systems.
- It is this issue of decoherence that requires the significant overhead in universal quantum computing architectures to support considerable error correction requirements.

Concomitant with universal quantum computing hardware is the development of new algorithms, many of which promise exponential speed up, a goal that is essentially unattainable in the conventional computing space.

- The time it takes for solvable computational tasks of size N in the conventional computing world is capped essentially by polynomial growth of solution time, N^x, where x is a positive number > 1. Some of these tasks are easy to parallelize, allowing at most a linear reduction in time with the growth of machine size. There are problems where the solution grows exponentially in time with a conventional computer (as 2^N) and no parallelism can overcome this difficulty.
- However, quantum computers promise exponential speed-up for some of these problems, allowing a problem solution time that grows as N^x. Quantum computing essentially transforms

these intractable, exponentially difficult problems into problems that scale like familiar solvable problems.

- It is important to note that currently there is only a limited number of known quantum algorithms with exponential speed up. The vast majority of known good quantum algorithms attain only polynomial speed up over conventional computing, reducing the time required from N^x to $N^{x/2}$. However, because quantum computing gate times are slower than conventional computers, this means that difficult problems must be addressed before quantum superiority is realized across all the named potential applications.

Universal Quantum Systems without Fault-Tolerance

Because the overhead of fault-tolerance is so large, many are exploring what quantum algorithms can be performed using little or no error mitigation. Such systems have qubit technologies like those required for a fault-tolerant system, but not enough qubits to implement fault-tolerant computations. Because faults accumulate with the number of qubit gates or with time, this type of system is limited to short-depth computations which give approximate answers to challenging problems.

- Some experts indicate that it will require at least 50 to 100 physical qubits to reach quantum superiority on a universal quantum system without fault-tolerance.

Typical applications that may include:

- Machine learning
- Sampling / Monte Carlo
- Pattern recognition and anomaly detection
- Cyber security
- Image analysis
- Financial analysis
- Software / hardware verification and validation
- Bioinformatics / cancer research
- Quantum chemistry
- Quantum dynamics

In addition, we believe that these machines may be applied to combinatorically-hard optimization where entanglement can improve the speed or accuracy of the answer, for example:

- Scheduling problems,
- map coloring problems,
- knapsack problems,
- maxcut problems

Again, these systems look in many respects like the fault-tolerant counterparts but without full error correction, and the same caveats for building more capable systems apply. These may be the first universal systems to demonstrate unequivocal quantum superiority.

THE QUANTUM APPLICATIONS SPACE

The application space for quantum computing theoretically includes all of the algorithms that are possible on conventional computers in addition to an as yet undetermined set of algorithms that can only be run efficiently on a quantum system. Examples of such algorithms include factoring, linear systems, and searching unstructured data.

- It is important to note that there are a vast number of conventional computing applications that may be ill-suited to a quantum computer.
- As such quantum computers, of any flavor, are not seen as wide-scale replacements for conventional computers in the majority of typical computer uses cases today and going forward.
- There likely will be no technical or financial basis for using quantum systems for the array of typical computing applications that include word processing software, database software, spreadsheet software, presentation software, multimedia software, enterprise software, information worker software, and content access software to name just a few.

There are a number of important algorithms that exist entirely in the quantum computing realm:

1. Quantum factoring

   Making use of the quantum Fourier transform. The quantum analogue of the discrete Fourier transform in conventional computing, called Shor's factoring algorithm, stated simply, takes a given integer N and finds its prime factors. On a quantum computer, Shor's algorithm runs in polynomial time, substantially faster than the most efficient known classical factoring algorithm, the general number field sieve, which works in sub-exponential time. Formulated in 1994, Shor's algorithm is one of the best known quantum algorithms. Breaking down integers into their prime constituents in polynomial time creates considerable vulnerabilities in a number of widely used and heretofore considered virtually secure cryptographic schemes.

   - It is important to note that the quantum Fourier transform, critical to Shor's algorithm, is a fundamental quantum process for many other quantum algorithms such as computing the discrete logarithm (finding the integer k exponent solving the equation $b^k = g$, where b and g are elements of a finite group) and algorithms for the hidden subgroup problem (given a black box function, determining the properties of that function using as few queries to the black box as possible).
   - However, to demonstrate quantum superiority when factoring numbers requires an extremely large universal fault-tolerant quantum computer, likely one with hundreds of millions of physical qubits. A quantum system of such size is more than a decade away.

2. Quantum Search

   For search algorithms, quantum computers take advantage of manipulating quantum states so that incorrect search answers interfere with each other, essentially removing them from the search space, while reinforcing the sought after search term.

   - One of the best examples of such a search algorithm is Grover's algorithm, which scales with problem size as $N^{x/2}$ rather than as N^x (where x is a positive number > 1), giving a square-root speed-up over any equivalent classical algorithm.

- Although a square-root speed-up may not at first sound impressive, with a budget of a million operations, a classical algorithm is limited to searching through about a million (unsorted, unstructured) possibilities. Grover's algorithm, on the other hand, can use those million operations to search through trillions of possibilities- a million times greater.
- It is interesting to note that despite the relatively slow advantage of Grover's algorithm versus conventional counterparts, it has been proven that Grover's algorithm is optimal and that any alternative algorithm can only be as efficient as Grover's. Such an insight is important in understanding the limits of quantum computation.

3. Quantum Walks

   Quantum walks are motivated by the widespread use of classical random walks in the design of randomized algorithms, and they are part of several quantum algorithms. For some oracular or so-called black box problems, quantum walks provide an exponential speedup over any classical algorithms. Quantum walks also give polynomial speedups over classical algorithms for many practical problems, such as the element distinctness problems that determine if all the elements in a given list are distinct.

   In a related field, the ability of a quantum system to produce true random numbers offers some significant improvements to a spate of algorithms that require true random number input to produce statistically valid results.

   - Monte Carlo methods are a broad class of computational algorithms that rely on repeated random sampling to obtain valid numerical results. Monte Carlo methods are mainly used in three distinct problem classes: optimization, numerical integration, and generating draws from a probability distribution.
   - It is important note that here the ability to produce true random numbers is not about creating a new algorithm or running an existing one faster, but instead as a way to improve the overall quality and validity of an existing algorithm.

IN SEARCH OF A MEANINGFUL QUANTUM PERFORMANCE METRIC

With all of the different schemes for designing and then implementing some form of a quantum computer, properly characterizing their various performance capabilities serves a number of important roles. It can help developers and users alike to understand and assess the various performance features and unique characteristics across different quantum computing implementations, be used to compare the impact of new algorithms or applications on different quantum platforms, gauge the pace of progress within the field, and perhaps most important, set a path forward for the most meaningful and critical performance attributes of any new quantum system. It is challenging to compare devices with widely different performance characteristics, especially in the rapidly evolving and relatively open field of quantum computing.

In defining a metric for quantum computing it is important that the metric does not simply focus on the number of qubits. Such a simplistic measurement would, in essence, be the quantum equivalent of the HPCs world's use of the peak flop/s rating as a way to compare system capability and progress. Although peak or even benchmarked flop/s is an easily determined metric for a conventional system, it does not fully capture the overall performance of the array of system components that include compute, memory, storage, and interconnect schemes. In addition, metrics such as flop/s do little to help users assess the performance a system will have on their base of existing or expected applications or help to measure and improve overall workflow efficiency

One proposal that spans a number of important quantum computing performance considerations is a quantum volume metric that embraces a number of different quantum computing characteristics, such as number of qubits, effective error rates, connectivity, and if gates can be run in parallel. In this case, the metric could serve to indicate if such a particular system could even run a given algorithm with any meaningful fidelity.

As such, a suggested quantum volume metric could encompass four (or more) elements:

1. The physical number of qubits
2. The number of possible instructions (gates that can be used) within the coherence of the device.
3. The connectivity of the device, which would capture the ability of a network to connect the qubit pairs within a quantum processor, understanding and perhaps highlighting that in practice, all quantum devices have a limited connectivity such as a line or a grid. This is a critical consideration, as compiling a given quantum circuit into a product of nearest-neighbor gates respecting the device connectivity introduces an additional overhead and effectively reduces the available space-time.
4. The number of instructions that can be done in parallel, although the metric would not give any credit for trivial parallelism by complete duplication of the quantum processor.

HIGHLIGHTS OF IBM'S EFFORTS

IBM is in the midst of a long-term effort to develop the complete ecosystem needed to support the wide-scale use of a universal fault tolerant quantum computer

- In May of 2016, IBM announced that it was making a prototype universal quantum computer available to the general public to encourage a broad range of potential innovators and perhaps in the long run, users to explore and possibly even develop, new applications for this system.
- Access to this prototype quantum system is accomplished through the IBM Quantum Experience, which enables anyone to easily connect to IBM's quantum processor via the IBM Cloud, to run algorithms and experiments, work with the individual quantum bits, and explore tutorials and simulations around what might be possible with quantum computing.
- The Quantum Experience provides access to quantum computing tutorials, a graphic quantum software development environment, access to a quantum assembly language infrastructure, and the ability to submit jobs directly to the IBM prototype quantum processor
- The current quantum processor is composed of five superconducting qubits, housed at the IBM T.J. Watson Research Center in New York, and it represents the latest advancement in IBM's quantum architecture development program that's considered one of the leading approaches towards building a universal quantum computer

Since its launch less than a year ago, more than 38,000 users have run over 275,000 experiments on the IBM Quantum Experience. It has become an enablement tool for scientists in over 100 countries and, to date, 15 third-party research papers have been posted to arXiv - an on-line scientific paper repository - with five published in leading journals based on experiments run on the Quantum Experience.

In addition to working with developers and universities, IBM has been engaging with industrial partners to explore the applications of quantum computers. Any organization interested in collaborating to explore quantum applications can apply for membership to the IBM Research Frontiers Institute, a consortium that develops and shares a portfolio of advanced computing technologies and evaluates their business implications. Founding members of the Frontiers Institute include Samsung, JSR, Honda, Canon, Hitachi Metals and Nagase.

In March of 2017, IBM continued to demonstrate its commitment to developing a universal quantum computer with the release of two additional upgrades to its Quantum Experience:

- A new application program interface that enables developers and programmers to begin building interfaces between its existing five quantum bit (qubit) cloud-based quantum computer and classical computers, without needing a deep background in quantum physics.
- An upgraded simulator on the IBM Quantum Experience that can model circuits with up to 20 qubits. In the first half of 2017, IBM plans to release a full software development kit on the IBM Quantum Experience for users to build simple quantum applications and software programs.

FUTURE OUTLOOK FOR IBM AND QUANTUM COMPUTING WRIT LARGE

Even the most optimistic quantum computing supporters admit that constructing a working universal fault-tolerant quantum computer is a technically demanding task, and that a full scale universal system is not expected for at least another decade.

However, the potential performance of quantum computers on specific applications can be quite dramatic compared with traditional binary computers used today as well as those envisioned for the next decade and beyond. This promise of unprecedented performance, in some cases well beyond the capability of any binary computer, will continue to generate interest and drive funding for all forms of quantum computing research for the foreseeable future.

Building a working quantum computer, however, represents only a portion of the challenges facing the field in the coming years. To date, quantum computers have suffered from a lack of algorithms that can take advantage of their unique architectures, and indeed, there are only a few notable quantum algorithms today, like factoring numbers and search, but there is growing research on chemistry and materials problems and machine learning. However, most of this work proceeds theoretically with little or no access to actual quantum hardware.

In order to address these concerns, IBM has taken a bold step forward by working to make quantum computing research more accessible to a wider range of developers in hopes of expanding the scope of new quantum-based algorithms and related applications. To that end, a free, readily accessible, and perhaps most important, easy to use quantum computer interface may be the most important element of this recent announcement.

- Ultimately the success of this IBM initiative will be judged by its ability to garner a broad base of scientific interest that leads to the creation of a portfolio of quantum computing use cases and a robust quantum computing research community that not only drives individual innovation, but that builds a much needed technical foundation for developing new quantum computing algorithms and applications.

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