

Quantum Computing Basics

A classical computer has a binary digit or bit as its basic computational unit. The bit can have a value of 0 or 1. Classical computer use a large number of these bits (typically 64 or 128) to process data and compute results. A quantum computer by contrast has quantum bit or qubit as its basic computational unit. A qubit can be in a state of 0 or 1 or it can be simultaneously 0 and 1. This simultaneous state of 0 and 1 is called superposition.

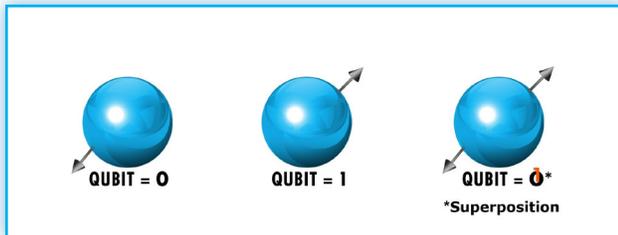


Figure 1 Qubit states

However, when a measurement is made to observe the value of the qubits, the superposition breaks down and the qubits “collapse” to a definite state of 0 or 1. This means that though parallel computations are possible in a quantum computer, only one result is available for observation at the end of a computation. The final state of 0 or 1 for a qubit is probabilistic unlike in a classical computer where the values of the bits are deterministic. Qubits are set into a state of superposition during the initialization of a quantum computer. As long it maintains its expected state it is coherent. If a qubit loses its state, then it is said to be decoherent.

Superposition implies that a quantum computer can simultaneously store a huge amount of information as compared to a classical computer. **An 8-bit classical computer can store only one out of 256 possible values, whereas an 8-qubit quantum computer can store all 256 states at the same time.** This potentially gives it the ability to execute a large number of operations in parallel leading to tremendous computational power.

Entanglement is quantum phenomenon whereby the state of one qubit affects the state of another qubit with which it is entangled. This phenomenon is independent of the distance these qubits may be from each other. Entanglement means that entangled qubits “communicate” at a speed that is not limited to how fast signals can travel down a wire or trace or silicon die. Whereas superposition gives the ability to store and compute states in parallel, entanglement is used to control the operation of the quantum computer’s initialization and computation process.

Another quantum phenomenon that is exploited in the design of some quantum computers is quantum interference whereby quantum particles exhibit wave-like behavior and either enhance or cancel their amplitudes. Quantum algorithms can be designed to take advantage of quantum interference so that the computations can converge at a rapid rate by attenuating the incorrect results and amplifying the correct one so that a measurement will have a very high probability of producing

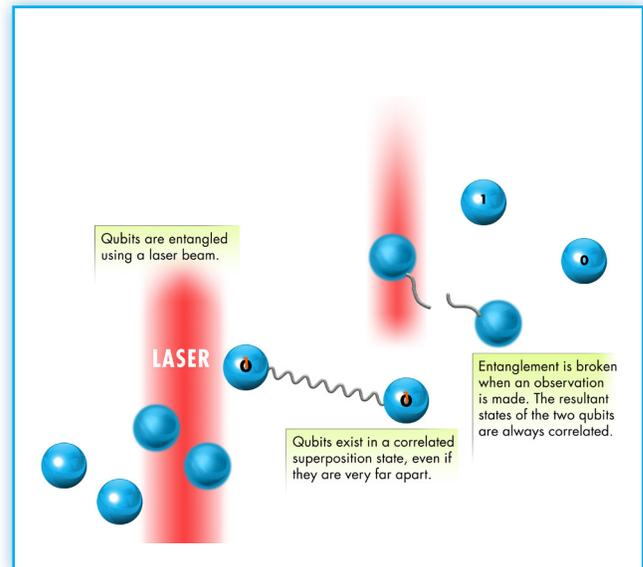


Figure 2 Entanglement

the correct answer to the computation. Hence even though the output is not deterministic, a well-designed algorithm should be able to give an accurate answer.

Several different types of qubits are possible. Trapped ions, electrons, magnetic spins, photons, superconductors are some of the qubits that are currently in use. Quantum computer hardware is very complex. Generally, to produce a stable qubit requires that the system be cooled to very close to absolute zero (0K). Hence a quantum computer will typically have an ultra-low temperature refrigerator. To place the qubits in entanglement requires strong magnetic fields or lasers and to connect the inputs and output to the quantum computer requires nanoscale electrodes.

Potential Impact of Quantum Computing

Quantum computers are useful for computations that can take advantage of the parallelism that is provided by qubit operations. Examples of these are optimization problems, factoring of numbers, simulations of molecules and materials, searching through a large amount of data and similar operations. Some areas of interest for the electric utility industry are listed below.

- **Modelling and Simulation:** There is a vast field of modelling and simulation applications that could be benefitted by quantum computers. The inherent massive parallelism that can be realized from a quantum computer with several hundred qubits could potentially enable more realistic models to be created that can have a much larger number of model parameters. Currently, for several models it is required to simplify the model so that the simulation computations can converge in a reasonable amount of time. It is however to be noted that each modelling scenario would require its own quantum modelling algorithm. A universal quantum computer that can be “programmed” to run the simulation for any model may be several years away.

- Quantum computers may not completely replace classical computer or supercomputers but will work in conjunction with them to solve larger and more complex problems in modelling and simulation. The quantum computer could be more like a math coprocessor or graphics processing unit (GPU) than a standalone computer. The simulations could possibly be run in a hybrid kind of computing environment where the quantum computer would run the simulation for which it is optimized and a conventional high performance computer would run the other computational tasks related to the simulation model.
 - o **Computational fluid dynamics (CFD)** – Turbulent fluid flows in reactors, steam generators, heat exchangers and other power plant components can lead to equipment degradation, rupture of tubes and other damages necessitating expensive repairs and/or replacements or create a hazardous situation in the plant. Modelling the turbulent flows of fluids is a significant and ongoing research effort. Empirical evaluation is costly, time-consuming and not always possible. Therefore, simulating the flows is the preferred option. For several years, many models have been developed to simulate turbulent flows. The two major models used are the Reynolds-averaged Navier-Stokes model (RANS) and the large-eddy simulation model (LES), each of these being more suitable for certain combination of flows, materials, geometries or other parameters. The simulation for these models requires computationally intensive calculations requiring the use of super-computers or other high performance computing technology. This is an area that could be positively impacted by quantum computers if quantum algorithms are developed that can run the complex simulations required for analyzing turbulent flows. As quantum computational power increases, as represented by higher qubit quantum computers, the models can also improve taking into account more parameters. The LES and RANS models can also be used together in a hybrid model, with the simulation outputs of LES feeding into the RANS model providing the latter with more accurate modelling parameters
 - o **Neutron irradiation damage** - In a nuclear plant, there are several critical components that are subjected to damaging irradiation from sub-atomic particles, especially neutron irradiation. These irradiations can cause degradation of the plant component. Again, it is not always possible to experimentally evaluate irradiation effects and so in order to evaluate the degree and type of damage that this irradiation can cause, several computational models have been developed. To research the effect of irradiation a plasticity model of irradiated metal such as Fe or Cu and other commonly used element is used to prepare the irradiation model. The results of the simulations can give an understanding of what might be happening in the actual plant component. The simulations take a very long time to run and models need to be constantly perfected after analyzing the results of the simulations against empirical or field data. Also, the current irradiation simulation models can only model fewer variable parameters because of time and complexity constraints. A quantum computer could potentially run the irradiation simulation models with larger number of variable parameters in a much shorter time as better quantum algorithms are developed for the models.
- o **Researching material properties** – There is a growing demand for new types of materials in the form of better catalysts, corrosion resistant materials, higher temperature superconducting materials, more efficient fuel cells, highly improved solar cells and many others. As new candidate materials are being researched for improved properties it is often required to model the new materials using one or more of several models available. Some of these models are based on quantum mechanics. In any case the models are complex and the simulations are lengthy and computationally intensive. Added to that is the fact that very often the experimental validation of the models is not easily done. Quantum computing offers the ability to model material properties specially for quantum mechanics based models. Modelling any quantum mechanical model on classical computers is extremely difficult but for a quantum computer it is expected to be a more natural fit. New quantum algorithms will need to be developed that can work on these models. The challenge in modelling materials properties and behavior is that the models are often multi-scale and so the quantum computer may be working in tandem with classical supercomputers to simulate more realistic material properties models.
- Highly secure, real time monitoring and control of multiple power plants like in a SMART grid. Enhanced security can be provided to power grids by using quantum communication techniques based on quantum entanglement. The entanglement phenomenon can be used to design a super-secure communication system whereby a pair of entangled photons can be residing at two distant locations and can be used to encrypt and decrypt data remotely. If anyone tries to eavesdrop on the communication it will destroy the entanglement and the intruder would be detected. Even though quantum cryptographic systems are currently available, those based on quantum computers are expected to be much more efficient and economical. They will also be better integrated into a quantum computing system. In addition, working in conjunction with SMART grid computing systems, data from multiple power plants could potentially be almost instantly analyzed to detect any malfunctions in any one or more plants. The variant plant or plant component could be notified and if needed isolated from the power grid to prevent cascading faults.

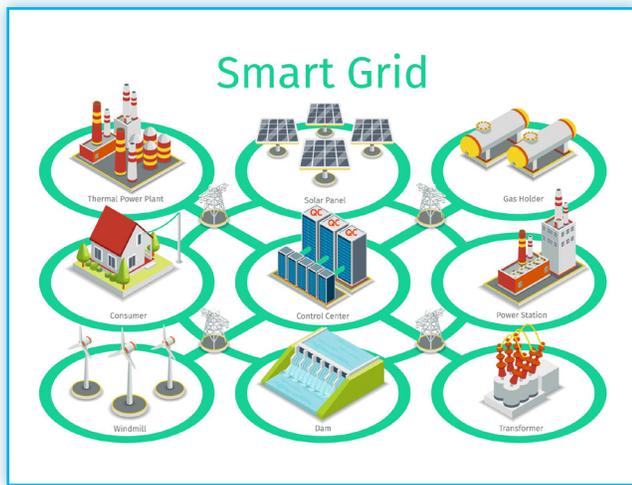


Figure 3 Smart Grid with quantum computers at the control center

VALUE OF QUANTUM COMPUTING TO THE UTILITY INDUSTRY

The value and benefits to the utility industry from quantum computing can be many fold. There is the ability to run simulations on a larger scale leading to more reliable and realistic designs. This should lead to saving time and money. Researchers could run high speed simulations that could provide valuable information for material and system design. Many new material designs could become possible with quantum simulation and design. Plant designers would be able to develop power systems based on lossless transmissions, using high temperature superconducting materials, that will enable more efficient generation & transmission and thus saving money and materials. The technology can also impact design of high temperature superconducting materials in high speed transport systems using magnetic levitation that could transform the commuting experience. There is also potential for the carbon capture technology to benefit through research into the design of catalysts to extract CO₂ from the air with less energy. Quantum communication based techniques promise super-secure communication systems that are practically immune to hacking, since any eves-dropper can be quickly detected leading to super secure systems.

The timeframe for deployment of quantum computers that can realize the above benefits is still not predictable because while new quantum computing systems and technologies are constantly being announced, one cannot see a commercially viable scalable universal quantum computer that can really deliver the promises of quantum computer, now or on the horizon. The reason is that the technology is still in its infancy. Though superposition potentially gives the quantum computer great computational power, the algorithms that are run on a quantum computer have to be developed to take advantage of this parallelism.

Otherwise its performance may be not better than an equivalent classical computer. Also, a major challenge to building a large quantum computer with several operational qubits is that the qubits themselves are very fragile and they are usually able to maintain their states of superposition and entanglement for only a fraction of a millisecond or less.

STATE OF THE TECHNOLOGY

Quantum computing technologies are in various states of readiness ranging from proof of concept systems to early demonstration models. There are less than a handful of companies designing and developing quantum computers. D-Wave and IBM are the main vendors in this area currently, out of which only D-Wave has actually sold quantum computers to large companies like Google, NASA, and Lockheed. IBM has started offering quantum computing available as a service on the IBM Cloud for experimental and research purposes. In addition to working with D-Wave, Google has also been developing its own quantum computer. Some companies like QxBranch and Rigetti Computing are working on developing quantum computer chips while others such as Microsoft are working on developing the software, mainly in the form of quantum algorithms and software design tools.

The present commercially available systems are even now being validated for some useful results. There are several proponents who have claimed that quantum computer systems have indeed verifiable results validating the claim that an order of magnitude improvement in performance over classical systems was seen. However, many opponents have argued that the test cases were geared towards producing favorable results. It will take some time to settle the question as to what kinds of computation problems really run faster on a quantum computer. Meanwhile, there is a steady stream of regular announcements of some new quantum computer or quantum computing chip that is being developed or tested or some new quantum information processing technique that is being tested, such as quantum teleportation.

The major technological hurdle in developing a quantum computer is the phenomenon of decoherence. Qubits tend to be highly unstable and most qubits tend to stay coherent for extremely short durations. The hardware as well as the algorithms have to be designed with a high degree of error corrections built into them. Entanglement, which is necessary to control the qubits during a computation, is not easily achieved. Finally, preparing the inputs for a quantum computer is time-consuming and costly. Since the output of a quantum computer is always probabilistic the algorithms have to be designed in a way that the correct output has the highest probability of being read when the outputs are measured for a computation.

Quantum computing technology will affect many industries. Organizations dealing with drug discovery, weather forecasting, genetics research, traffic control, image processing, security, machine learning and automation are some of the many that stand to benefit from real scalable commercially available quantum computing technology.

Research is going on at a fast pace all over the world and not only large commercial organization like Google, Microsoft and IBM are involved in this but also several universities and governmental organizations. China has recently launched a satellite that will test quantum encryption technology using quantum teleportation on a pair of photon qubits generated on board the space-craft. Eventually they want to create a super-secure communication network. Canada, Japan, Italy, and Singapore also have plans for quantum computing based space experiments.

Public Literature

The principles of quantum mechanics have been developed for almost a century so the basic science behind the phenomenon is well documented and available in literature at basic and advanced levels. However, the subject as such is hard to really understand since it is very non-intuitive. There is a good amount of technical and general literature on the quantum algorithms and other quantum techniques and many discussions on [youtube.com](https://www.youtube.com) explaining the basic concepts on quantum computing. However, the technology details for designing a real quantum computer are well-guarded and patented secrets.

Next Milestone

The quantum computing industry is still in its infancy and the field is constantly evolving. Google, IBM, Microsoft, and others have announced a lot of funds for research and development. Vendors offering quantum computers will have to prove the commercial viability of their systems. The next milestone would likely be a quantum computer that can be programmed to consistently solve at least a few computing problems faster than most classical computers.

Currently except D-Wave no one other company has generated any revenue from quantum computers. Each D-Wave system costs about \$10M and is currently used mainly for research. D-Wave systems have been evaluated mainly by the manufacturer and buyers like Google and NASA. The results of some of these tests have also been evaluated by several third parties. Google and NASA have been working with D-Wave not just in evaluating the D-Wave systems but also in developing newer tests, algorithm and designs. Google is also said to be developing its own quantum computer.

There are different paths that quantum computer manufacturers/vendors could possibly take. There may be hardware manufacturers that would supply large quantum computer systems while some may

opt for developing smaller quantum computers with lower qubit count but those could be networked using quantum teleportation or other quantum communication technique to give higher performance. Several companies are only engaged in developing quantum algorithms and some in developing software tools.

The most likely usage of a quantum computer in the near future is likely to be in the form of a coprocessor unit that works in conjunction with a classical computer. In addition to its regular usage, the classical computer would provide the user interface, prepare the inputs for the quantum computer, read the outputs of the quantum computer and then integrate the outputs into its own process.

NEXT STEPS

Building a quantum computer is a very complex task for several reasons. Qubits can easily lose their entangled and superposition states due to external mechanical, thermal, electrical, magnetic or other disturbances. Hence it has been hard to scale a quantum computer that uses entanglement, beyond about a dozen qubits or so. Another challenge is that the intermediate or final states of qubits in a computation cannot be copied (no cloning). This makes it challenging to debug quantum computer based systems and the software code compilers and other tools need to be designed around that.

A universal quantum computer that can be programmed to run any type of quantum algorithm is still in the realms of experimental development. Adiabatic quantum computers using the quantum annealing process of computation have been built with about 1000 qubits. However, they do not provide much control on the computation process and rely on a natural progression of the computation to eventually reveal the required result. They are also useful for only certain kinds of computations.

At present there are just a handful of useful algorithms available today that can be tested on current quantum computers. However, a side benefit of researching these quantum algorithms has been the continuous improvements of classical algorithms as well.

Currently EPRI's engagement is limited to studying the market for potential usages. In the near future EPRI could also participate in technology evaluations to study the kinds of computing problems that can be solved with the existing or evolving quantum computing technologies.

In the future, quantum computer technology promises a revolutionary change to the way we do things and there is probably no field of technology or research that will not be affected by it.

REFERENCES

1. University of Waterloo, “Quantum computing 101” Institute of Quantum Computing, Available at <https://uwaterloo.ca/institute-for-quantum-computing/quantum-computing-101#Build-a-quantum-computer>
2. “Quantum computing,” Wikipedia. Available at https://en.wikipedia.org/wiki/Quantum_computing
3. UNSWTV, “Quantum Computing Concepts,” YouTube video, Available at https://www.youtube.com/watch?v=tqN6I-WCXTY&index=1&list=PL50XnIfjxPDWDyca8EbbLe8GHfXkWU7W_
4. “A little bit, better”, The Economist, June 20 2015. Available at <http://www.economist.com/news/science-and-technology/21654566-after-decades-languishing-laboratory-quantum-computers-are-attracting>
5. Adam Mann, “Laws of Physics Say Quantum Cryptography Is Unhackable. It’s Not”, Wired, June 7 2013. Available at <https://www.wired.com/2013/06/quantum-cryptography-hack/>
6. Rodney Van Meter and Clare Horsman, “A Blueprint for Building a Quantum Computer,” Communications of the ACM, October 2013.
7. Rodney Van Meter, “Quantum Computing’s Classical Problem, Classical Computing’s Quantum Problem,” Foundations of Physics, Jan 7 2014.
8. Tom Simonite, “IBM Shows Off a Quantum Computing Chip,” MIT Technology Review, Computing, April 29, 2015. Available at <https://www.technologyreview.com/s/537041/ibm-shows-off-a-quantum-computing-chip/>
9. Institute for Quantum Computing, “Quantum Computing: Transforming the Digital Age- Krysta Svore – June 9 2015” YouTube video, Available at https://www.youtube.com/watch?v=eUp_B7ZpiXk
10. IAndris Ambainis, “What Can We Do with a Quantum Computer?” Published 2015. Available at <https://www.ias.edu/ideas/2014/ambainis-quantum-computing>
11. John M. Pruitt, Yassin A. Hassan, David A. Steininger, “Large Eddy Simulation of Turbulent Flow in a Tube Bundle,” Thermal Hydraulics of Advanced Heat Exchanger Proceedings, ASME, NE-Vol. 5, Nov 1990.
12. James C. Tyacke, Paul G. Tucker, “Future Use of Large Eddy Simulation in Aero-engines”, Journal of Turbomachinery, Aug. 2015, Vol. 137.
13. Chaitanya Deo, Carlos Tomé, Ricardo Lebensohn, Stuart Maloy, “Modeling and simulation of irradiation hardening in structural ferritic steels for advanced nuclear reactors”, Journal of Nuclear Materials 337, 2008.
14. Emily A. Carter, “Challenges in Modeling Materials Properties Without Experimental Input”, Science 321, 80 (2008).
15. Nathan R. Barton, Athanasios Arsenlis, Jaime Marian, “A polycrystal plasticity model of strain localization in irradiated iron”, Journal of the Mechanics and Physics of Solids, Oct. 2012.
16. “The Golden Age Of Quantum Computing Is Upon Us (Once We Solve These Tiny Problems)” Fast Company, May 13, 2015. Available at <http://www.fastcompany.com/3045708/big-tiny-problems-for-quantum-computing>
17. Timothy Prickett Morgan, “Google Sees Long, Expensive Road Ahead For Quantum Computing” Fast Company, July 22, 2015. Available at <http://www.nextplatform.com/2015/07/22/google-sees-long-expensive-road-ahead-for-quantum-computing/>
18. “Quantum computers could offer a giant leap in speed—but only for certain applications”, Economist, March 12, 2016. Available at <http://www.economist.com/technology-quarterly/2016-03-12/after-moores-law?fsrc=scn/tw/te/pe/ed/aftermooreslawtechnologyquarterly&#section-4>

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