18NTO301T - APPLICATIONS OF NANOTECHNOLOGY

Module-III

QUANTUM COMPUTERS

DEPARTMENT OF PHYSICS AND NANOTECHNOLOGY
SRM INSTITUTE OF SCIENCE AND TECHNOLOGY

Quantum Computers

"Instead of using binary logic of just 0s and 1s, a quantum computer can also account for superpositions between 0s and 1s. These states are called quantum bits, or qbits. Since qbits allow us to have infinitely more states available, this uncaps the potential to explore many different pathways of a computer algorithm all at once—making more difficult problems easier to solve at an entirely new speed and scale.

Second, the intricate correlation, or entanglement, between many of the qbits takes this power one step further. While in classical physics, one would have to run each and every step separately, because of the great strength of entanglement amongst particles, with one collective action, all particles can be affected at once. In short, this principle allows us to explore resources of the same system, at the same time, significantly increasing the efficiency from a classical computer for many potentially useful tasks."

Built using a quantum processor, a quantum computer (QC) can potentially reduce execution time to hours and days for problems that would previously have taken hundreds of years to solve on our best supercomputers, also known as classical computers. The basic element of a QC is the quantum bit (known as a qubit). Quantum bits are the quantum analog of the classical bits and thus the basic unit of quantum information. Whereas in the classical domain, they function as a two-level system, in this case, the qubits must obey the laws of quantum mechanics.

Quantum Computers

- In a in a physical point of view, basic chunk of information, one bit, is a physical system which can be prepared in one of the two different states representing two logical values such as No/Yes or False/True or 0/1 or Off/On, etc

- Today’s computer charge diff./voltage between the plates in the capacitor denotes bit value one. If there is no charge then bit is 0.

  or

- One bit of info. can also be encoded in 2 different polarization of light.

  or

- Different electronic states of an atom.

- If we choose an atom position, then Quantum mechanics tells us that apart from two electronic states the atom can also be prepared in a coherent super position of 2 different states.
- This means atom is both in state 0 and state 1.
- There no equivalent of this superposition in classical mechanics world; it is purely quantum mechanical phenomenon.

- Now we push the idea of superposition of numbers a bit further.
- In a register composed of 3 physical bit, in classical we can store one out of 8 different possible configurations of 0s and 1s. (000, 001,010…… &111)

- A quantum register composed of 3 qubits can store in a given moment of time all the 8 numbers in a quantum superposition.

(Qubit can be store in various things such as single photon, nucleus & electron)

- All 8 numbers are physically present in the register but it should be no more surprising than a qubit being in both state 0 and 1 at the same time

- If we keep adding qubits to the register we increase its storage capacity exponentially.

3 qubits can store 8 different numbers at once. 4 qubits can store 16 different numbers at once, and so on.

In general L qubits can store 2^L numbers at once.

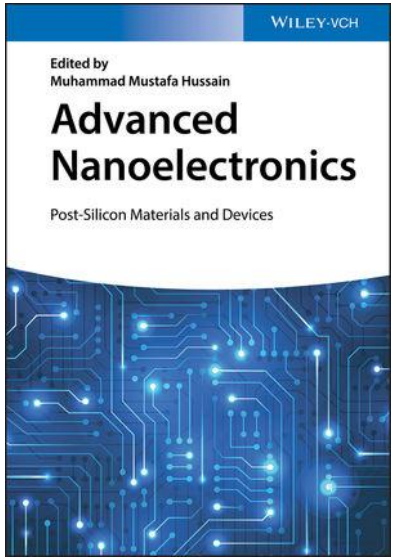
- Once the register is prepared in a super position of different numbers we can perform of all of them.

Example: If qubits are atoms, then suitably tuned laser pulses affect the atomic electronic states and evolve initial super positions of encoded numbers into different positions.

- In previous example:
  - We can generate massive parallel computation, albeit in one piece quantum computer
  - Only in one computational step, perform the same mathematical operation on 2^L input numbers encoded in coherent superpositions of L qubits.
  - For the Same task classical computer may need 2^L steps of 2^L different processor to do it in a single step.

Quantum computers offers an enormous gain in the use of computational resources such as time and memory.

Nanocomputing Technologies



- Limitations in Photolithography (micro to nano)

  Half of the wavelength

  Considering molecular level
- Problems: Doping below 50 nm of Si
- Alternative to bulk Si. (1980's)
- Nanotubes, nanowires, logical gates & memory using an assorted materials including gold, organics, DNA, & neurons etc.

- Nanocomputers have to be built self assembled bottom up, where as exiting works with photolithography top down.

From microelectronics to Nanoelectronics

- Rapid growth in electronic components. (ICs with tens of components, VLSI with hundreds of millions of components)
- Moore’s law.
- VLSI circuits in 2008 based on the CMOS FET, and the state of art fabrication reached 90 nm.
- In the Nano realm, where devices are meeting technological challenges for further scaling, quantum mechanics prevailing.
- Scaling down is finding problems with thermal fluctuations, power dissipations, and quantum effects, and the technological limitations in manufacturing methods(lithography), etc

From nanoelectronics to nanoelectronic computers

- Design issues are raised for computer architectures based on nanoelectronic, and quantum devices.

- The developments of nanoelectronics could eventually lead to extremely large scale of integration (Trillion/10^{12} devices cm^{-1}).

- The architectures of the ICs must be suitable for implementation of nanoelectronic devices.

- Many features in nanoscale devices that impose limitations on nanoelectronic architectures, while the most prominent have been recognized as the devices' poor reliability, the difficulties in realizing the interconnections, and the problem of power dissipation.

The building blocks of quantum mechanics

The birth of quantum mechanics took place the first 27 years of the twentieth century to overcome the severe limitations in the validity of classical physics, with the first inconsistency being the Plank’s radiation law. Einstein, Debye, Bohr, de Broglie, Compton, Heisenberg, Schrödinger, Dirac amongst others were the pioneers in developing the theory of quantum mechanics as we know it today.

The fundamental building blocks of quantum mechanics are:

1. **Quantisation**: energy, momentum, angular momentum and other physical quantities of a bound system are restricted to discrete values (quantised)
2. **Wave-particle duality**: objects are both waves and particles
3. **Heisenberg principle**: the more precise the position of some particle is determined, the less precise its momentum can be known, and vice versa. Thus there is a fundamental limit to the measurement precision of physical quantities of a particle
4. **Superposition**: two quantum states can be added together, and the result is another valid quantum state
5. **Entanglement**: when the quantum state of any particle belonging to a system cannot be described independently of the state of the other particles, even when separated by a large distance, the particles are entangled

Since the first idea of a quantum computer was proposed by Benioff, Manin, Feynman and Deutsch back in the 1980s [benioff- Deutsch], many technological advances have taken place. We can now count on 10+ technologies that industry and academia are looking into with the goal of building a quantum computer. Some of them are targeting a 'universal' quantum computer, others a specialised quantum machine that will speed up specific problems.

This is made possible through qubits. Qubits can be realised with multiple technologies, for example, quantum dots are structures that can confine and manipulate a single electron to be acted as a qubit.

Another way of manipulating the spin of an electron is done via nitrogen-vacancy centers in diamond. Transmon qubits are one type of superconducting qubits that use Josephson junctions to create a single magnetic flux for use as a qubit [koch].

Qubits can also be achieved by controlling the polarisation of photons, or the number of photons. Unlike classical computing, qubits can be in 1, 0 or in a superposition of 1 or 0 quantum states until we measure them. Following this logic, a pair of qubits can be in any quantum superposition of four states and three qubits will be in any superposition of 8 states.

By extrapolation, we can generalise that n qubits will be in a superposition of up to n different quantum states simultaneously.

It is this simultaneity property that leads us to a potential quantum advantage.

If we can use this massive parallelism, we can compute many operations at the same time, thus inferring a time advantage. Besides qubits, and in order to operate a quantum computer, we need the full quantum hardware and software layer stack.

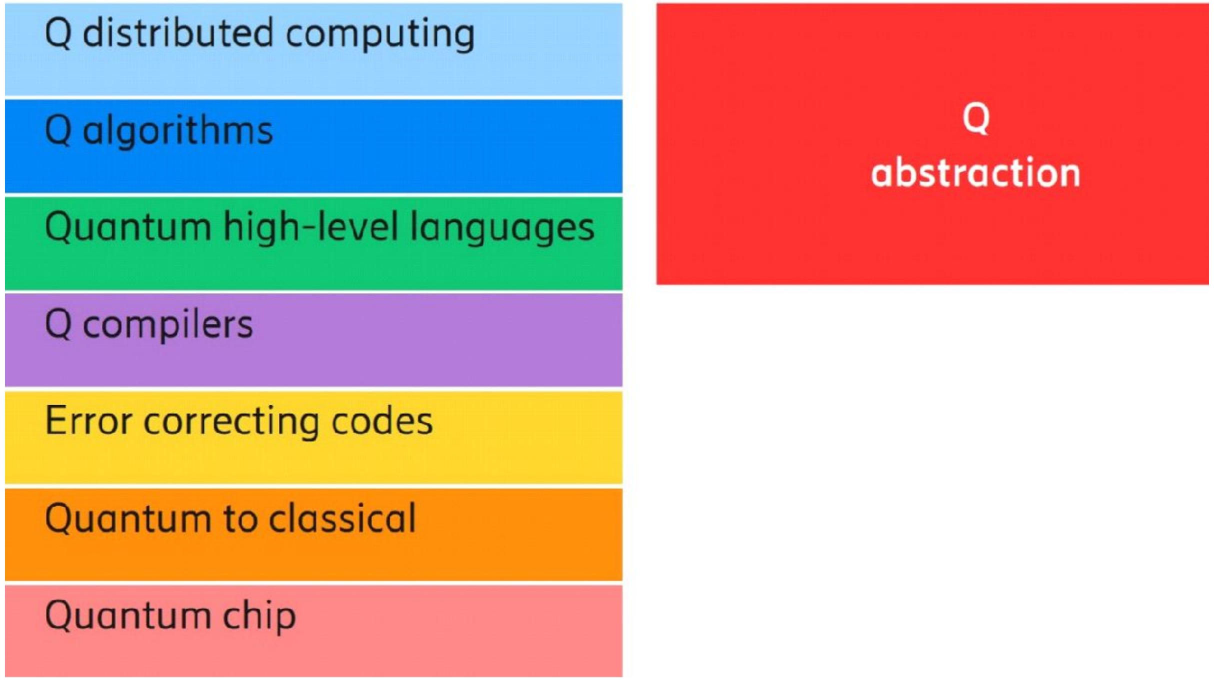
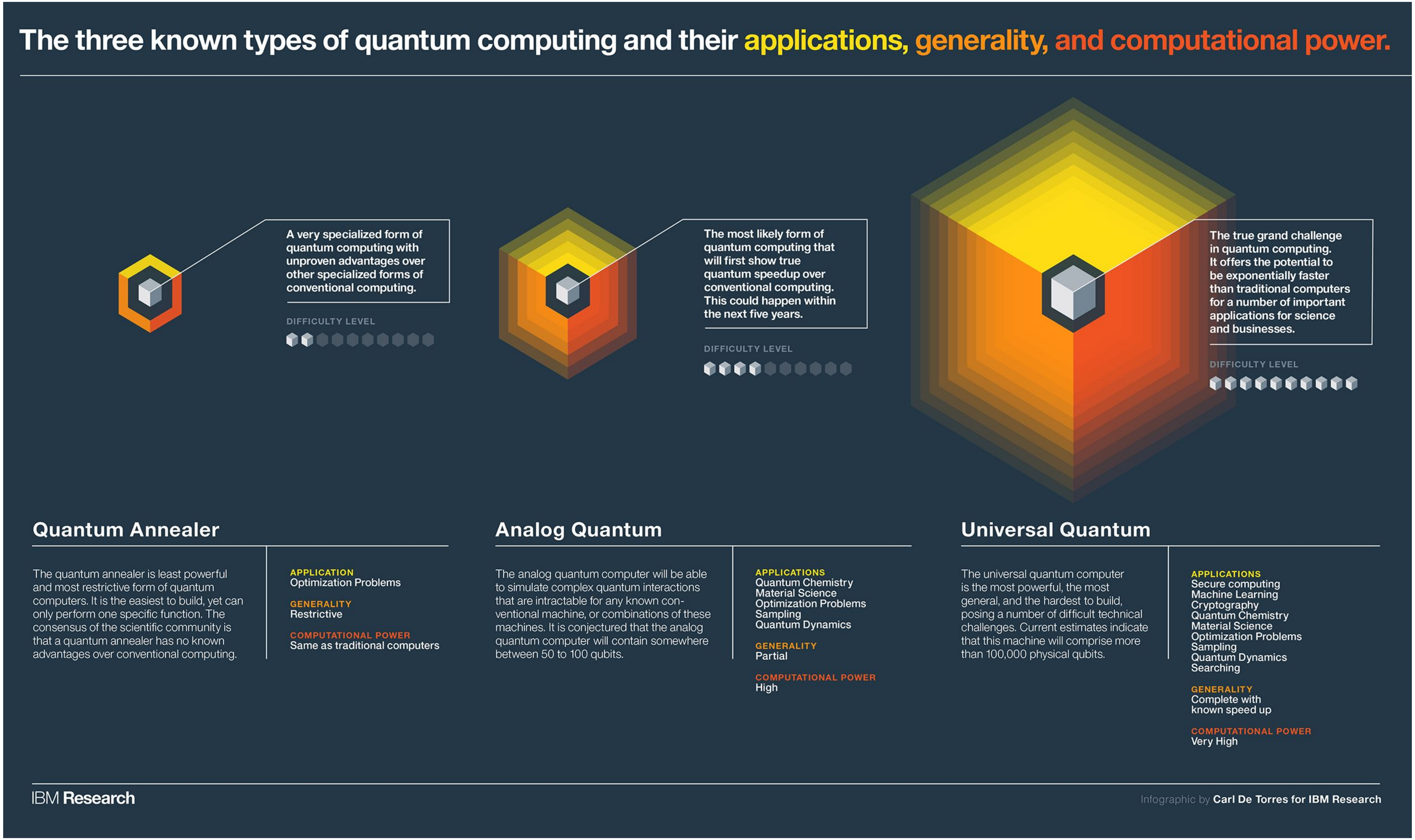


Figure 1. Quantum computer hardware and software stack

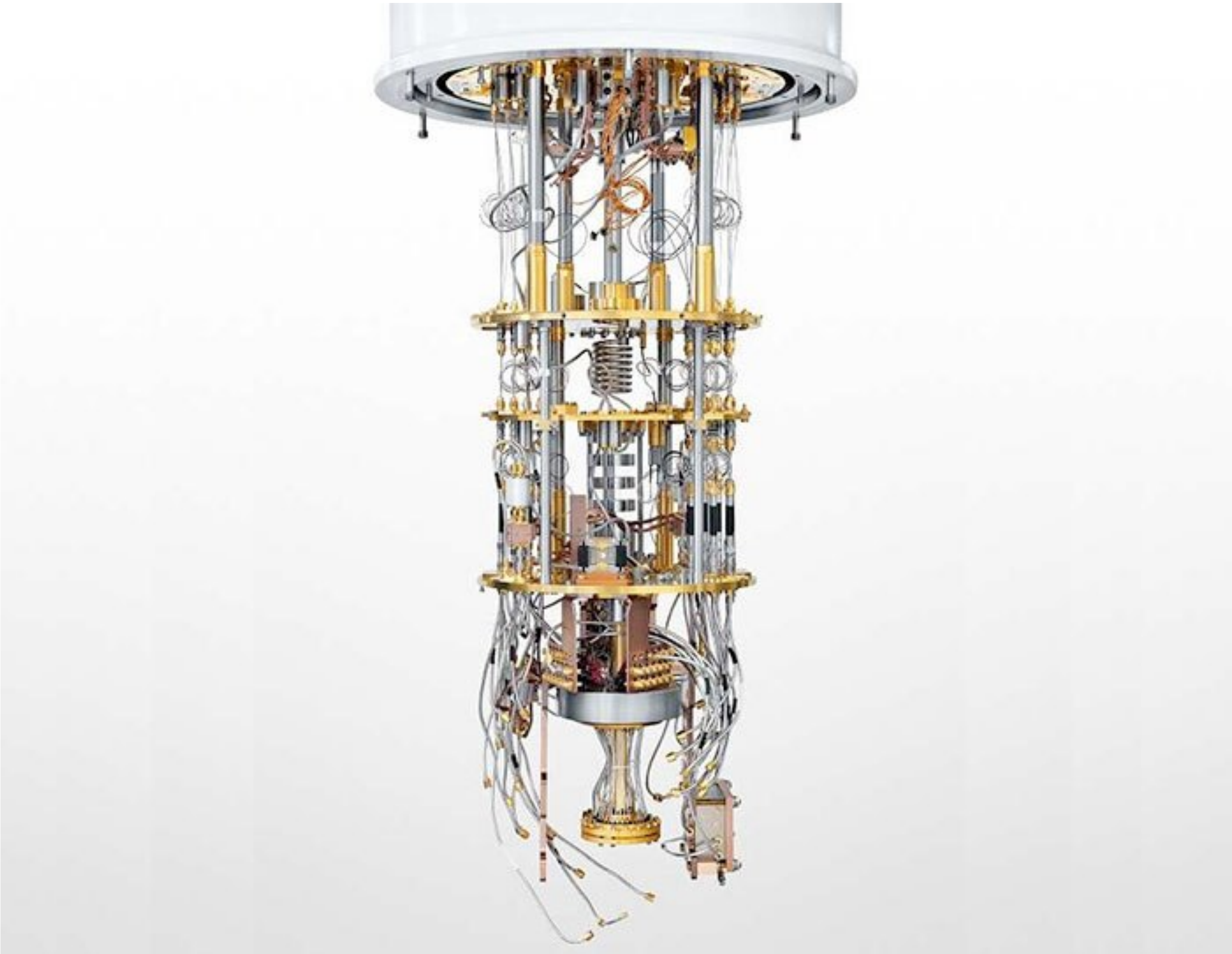
https://www.ericsson.com/en/blog/2019/7/introduction-to-quantum-computer-technology

Applications
As the technology develops, quantum computing could lead to significant advances in numerous fields, from chemistry and materials science to nuclear physics and machine learning. Top applications include:

- Machine learning
- Super-catalyst design
- Medicine
- Chemistry
- Climate change/Earth science
- Battery chemistry
- Material science
- Engineering
- Artificial intelligence
- Information security
- Biomimetics
- Energy
- Photovoltaics
- Financial services
- Supply chain and logistics



The three known types of quantum computing and their applications, generality and computational power. Source: Carl Torres for IBM Research



Quantum computer chips within a cryogenic environment. Image courtesy Rigetti Computing. Photo by Justin Fantl.

The IBM Q System One. Source: IBM

https://www.edn.com/the-basics-of-quantum-computing-atutorial/#:~:text=The%20basic%20properties%20of%20quantum,tails%E2%80%94a%20very%20binary%20concept