
Quantum
Mechanics
A Non-Technical
Brief
by
Gerald F Pillay
31 Oct 2020

QUANTUM MECHANICS

A NON-TECHNICAL BRIEF

As of 31 Oct 2020

By

Gerald F Pillay

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ABOUT THIS BOOK

A comprehensive non-technical summary and up-to-date review of Quantum Mechanics, and how it has changed the world; with a look into the impossible future it promises:

.(a) **First Quantum Revolution** - the primary discoveries, enabling the Information Age

(.b) **Second Quantum Revolution** –gestating the Quantum Computer's computational core (up to the present)

.(c) **Third Quantum Generation** – roadmaps and breakthroughs to the hybrid and intermediate generations of Quantum Computers (by 2040), and

.(d) **Fourth Quantum Generation** – When the Quantum Computers and their associated inventions run the place, map the stars and take us beyond Absolute Zero (beyond 2070).

Publisher
Gerald F Pillay
139A Lor 1A Toa Payoh, #01-48
Singapore 311139
gfpillay@singnet.com.sg

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Dedication

To the late Dr. Sam Kong San, my esteemed career-long (IT) technical counterpart, who was invariably to be found ensconced at the horizons of technology. He was the constant challenge that got me to thinking across technical boundaries, which in the end became my trademark as an administrator and policy consultant in technical education. Together we pioneered the comprehensive computerization of the latter domain on an IBM mainframe. He would have loved this review and probably have taken it many more steps than I have dared into the future of QM.

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Quantum Mechanics

Preface

While Einstein defined the principles that applied in space-time, including the nature of energy and the speed of light, Quantum Mechanics (QM) started from the sub-atomic universe, to establish the common principles from there. Because Einstein proved so fundamentally right, I think of QM as the tail of the dragon looking for its head, swallowing it, and rising as the phoenix.

Quantum Mechanics was not just an add-on. It said everything had to be understood anew. Its science and language were new. I soon lost track, and it got worse. So, I decided I would knuckle down and find out.

Scientists are still working at the frontiers, but I am happy to say (for myself) that there is a new Quantum Science, with fantastic possibilities for mankind. Here are some steps I have gone through:

First Quantum Revolution (Q1) – The Sub-Atomic World, and the technological applications that have already transformed our lives

Second Quantum Revolution (Q2) - The quest to build the Quantum Computer,

Third Quantum Generation (Q3) – The Road to the impossible Future, and

Fourth Quantum Generation (Q4) - There Be Titans

After over a century, scientists are just at the beginnings of Q2.

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FIRST QUANTUM REVOLUTION (Q1)

MATTER

It helps to appreciate that the entire visible universe is made up of the same matter, which in turn is made up of the same fundamental particles. The latter originate as pure energy in the first instance, at cosmic events such as the big bang. In appropriate conditions, the energy transforms into matter in its many composite features. The overall formula for this is E=mc2, where E is energy, m is mass and c the speed of the mass. This is in essence Einstein’s Theory of Special Relativity.

It may be said that energy resides in and acts on matter in a wide range of forms. When energy radiates, it does so as particles in a wave.

Overview of Q1

There were parallel and complementary branches of science that explained the material world. Quantum Mechanics (QM) came into being early in the last century to study the workings of matter at the sub-atomic level, the details of which were not known. The concepts and tools were not yet there. Scientists sensed that if they knew what the atom was made of and how it worked, they would make a “quantum leap” (no pun intended) into vastly expanded realms of possibility. They also understood, but needed to prove, that the sub-atomic universe was a microcosm of the larger universe and that both constituted a continuous unity.

On 14 Dec 1900, Max Planck, a German physicist, published his groundbreaking study of the effect of radiation on a “blackbody” substance, and the quantum theory of modern physics was born. He made the breakthrough when he confirmed that all matter moved as discrete individual packets or quanta, later named a photon.

Hence the operations of elementary particles became known as *quantum mechanics*. Quanta could be a single quark; or they could comprise more than one, in which case they were known as *hadrons.* The same applied to leptons. Where there were more than one lepton, the quantum was a *baryon*.

Energy is matter in movement**.** Energy therefore was *quantized.* This meant its operations were measurable*.* As energy pervaded all levels of the universe this was Aladdin’s “open o sesame” to studying the subatomic world. It also introduced the probabilistic basis into science, as measurement went down the scale into the miniscule in both size and time – and indeed in temperature as well. This was the beginning of the Quantum Revolution.

One of QM’s first achievements was to define explicitly and in all round measurable detail the structure and behavior of the **atom.** It was Niels Bohr (1913) who was responsible for this. On the one hand, QM defined the elements that made up the atom, namely the electron, the proton and the neutron, and the forces that bound them together. At the same time, QM re-defined the **Periodic Table of Elements** to delineate the chemicals in exact compositional and behavioral terms, right down to the location of the last valence electron.

Today, the broader sciences have confirmed that the world from the sub-atomic level up is made of the same elementary particles. The second achievement of QM was that they established what these were, in a **Standard Model of Particle Physics.** An electron is a *quark*. A proton is most likely a *hadron*, and a photon is a *boson*. It is quite possible that they may find further sub-layers or refinements of elementary particles, judging from some fuzziness still in particle theory, but the architecture and primary constituents have now been proved and accepted by virtue of their widest applications.

Thirdly, QM also identified that there were **Four Fundamental Forces** that applied across nature, big and small - fundamental meaning forces than could not be further broken down. It was known earlier that gravity and electromagnetism operated in space (as well as on earth). QM now found that they also functioned at the sub-atomic level. The other two fundamental forces, the strong and the weak, are sub-atomic. Although, these four forces are related, QM scientists have so far not been able to integrate them into a single relationship. The role of gravity is still hanging loose. If and when they do, QM will have successfully subsumed Einstein's Theory of General Relativity. At the moment, QM is still a bit like the tail trying to swallow the dragon. This reflects the scale of what has been achieved, and points to the triumph that lies ahead.

Fourthly, QM unboxed the constituents of **energy,** that most fundamental feature of nature besides matter, and **Electromagnetism (EM)** as its central process and manifestation. One output of electromagnetism is electromagnetic radiation (ER), which is energy moving as a flow of photons. ER is the pervasive working tool that keeps both nature and our world ticking. At the cosmic level, ER transmits to us the replenishing energy of the sun (for photosynthesis), new-born elementary particles, and heat. At the sub-atomic level, it is one of the fundamental forces that mediates the responses of elementary and atomic sub-particles arising from changes of energy. But QM's most significant and detailed findings have been at the atomic level.

At atomic level, when new energy excites a conducting metal, the atoms therein will lose one or more electrons with weaker "ionizing energy". These will flow away in whatever electric circuit is created. Every such electrically charged current instantly triggers a magnetic field and every such magnetic field instantly triggers an electric field. The two unite and propagate a composite oscillating field known as the Electromagnetic (EM) field, which radiates ER as particles of **photons**.

The one of the better explanations of ER is given in this quotation:

> The prototype of quantum field theories is Quantum Electrodynamics (QED), which provides a comprehensive mathematical framework for predicting and understanding the effects of electromagnetism (EM) on electrically charged matter at all energy levels. Electric and magnetic forces are regarded as arising from the emission and absorption of exchange particles called photons. These can be represented as disturbances of electromagnetic fields, much as ripples on a lake are disturbances of the water. Under suitable conditions, photons may become entirely free of charged particles; they are then detectable as light and as other forms of electromagnetic radiation (ER). Similarly, particles such as electrons are themselves regarded as disturbances of their own quantized fields. Numerical predictions based on QED agree with experimental data to within one part in 10 million in some cases.”[1]

Next, QM’s identification of **light as a stream of photons** was a breakthrough of cardinal importance. It was first propounded by Einstein and confirmed by Planck. As a boson, the photon is designed to carry energy. it is smaller than an electron, has no mass, and blasts out into space at the speed of light. ER radiation is a composite of streams of photons in a wide spread of differentiated frequencies, known as the *electromagnetic spectrum.* This encompasses all the frequencies from low-end radio waves to high-end gamma-rays and includes the entire range of visible light. Light is therefore a beam of photons radiating at the frequency of visible light. The different component photons of ER can be detected, deflected, refracted or absorbed depending upon the medium at the far end. If not interfered with, a photon

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1 https://www.britannica.com/science/quantum-field-theory

travels into space forever. That is how star light gets to us. The discovery that energy travels as photons over a range of frequencies, which can be differentiated and directionally propagated, has enabled application in a wide range of inventions

And lastly, it was established that energy is both a wave and a particle, conforming to the **wave-particle duality theory.** The latter is one of the central tenets of QM: energy is matter and flows in waves. This was the work of the mathematician Erwin Schrodinger. ER waves can be isotopic (omni-directional) but generally travel along the direction of propagation of the energy. Of QM's many features, ER has been most widely applied, from the transistor to the qubit.

It is now an established working theory that the universe originated at the big bang, and that matter originated as elementary particles therefrom and thence. To study it at sub-atomic level, it has been necessary to near replicate conditions at the big bang. It has been only through the acceleration to near light speeds and the collision of particles at CERN's Large Hadron Collider that scientists have been able to confirm the existence of some of the sub-atomic particles, QM has been going step by step, and taken a century to get where we are, with several intermediate formulations until the present.

QM has redefined matter and established the framework for understanding the physical universe as a unity. It is interesting that it was Einstein who first identified the existence of the photon as a packet. QM has confirmed this, and created a new scientific fabric of thought to understand and master the physical world

In the process QM has successfully subsumed the principles of classical physics, including those of Newton and Maxwell, much of which are still applicable at the earth's surface. In other areas, it has basically overwritten the old with its new mathematics.

There is no going back. QM has already changed the world. Imagine us a century ago. There was no IC chip. We were without television, smartphones, and computer games. There were no laptops, word processors and printers in the office, no internet, and no microwave oven. There were no FM broadcasts, or lasers, and no MRI or endoscopy in the hospital; not to mention the man on the moon. **In fact, without QM, we would not be in the Information Age**.

What's amazing is that today, within one silicon chip there are about 3 billion transistors, enabled by the progress of this first quantum revolution. And they work reliably.

It is in fact said that the First Quantum Revolution is complete. Quantum Physics has replaced Physical Science. The Second Quantum Revolution is on.

At the sub-atomic level, the atomic nucleus has still to be fully unravelled. There is still not yet a unified theory of the fundamental forces, nor complete application of the wave-particle theory. And there is the whole subject of anti-matter to be fleshed out.

At the macro level, there is the subject of dark matter. I was intrigued that it was the abundance of neutrinos at the big bang which tipped the balance between us being matter or dark matter. The new Quantum Science may also ultimately throw light on whether the black hole is the all-consuming head of another dragon or nature's re-cycling bin. In all probably it will have at some future date have contributed to us discovering a new earth.

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Sub-Atomic World

Structure of the Atom

The first step down into the sub-atomic is the *atom*. It was Niels Bohr (1913) who was responsible for substantially defining the currently understood picture of a single atom, viz:

Particle	**Charge**	**Mass (gm)**
1 Electron (circulating)	Negative^{-}	$9.1x10^{-31}$
1 Proton (Nucleus)	Positive^{+}	$1,672x10^{-27}$
1 Neutron (Nucleus)	Neutral^{0}	$1.674.10^{-27}$

Following other refinements, the current Quantum understanding of the structure of the atom may be summarised as follows (simplified):

The atom

The smallest *atom* is about 0.1 (or one-tenth) of a nanometer ($1x10^{-10}$ nm)[2]. It comprises one *proton* and one *neutron* forming the *nucleus*, and one *electron* circling in orbit around the nucleus. If its proto*n* were a grain of rice, an electron would be half a grain, and the distance (radius) between them would be half a football field. The electron's orbit would be over six times (2πr) this distance. An atom is therefore almost

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[2] 1 Angstrom

entirely empty space. The neutron is usually slightly bigger than the proton.

The above is the Hydrogen atom. Because it has one proton, it has the *atomic number* (1). There are 118 elements in the Periodic Table of Elements. The last element Oganesson (Og) has 118 protons and the atomic number 118. All protons are charged[3] positive.

Every proton is paired with an electron, which is half its mass and is of equal but negative charge. It circles the nucleus. Every proton is also paired with a neutron, which has no charge and also sits in the nucleus. Thus, Oganesson has 118 protons, 118 electrons and 118 neutrons, as against Hydrogen which has one of each.

The electron

The sums of the positive and negative charges of the protons and electrons balance each other out at the point in orbit. The force required to remove an electron is called its ionization energy. Each electron has its own "orbital". They tend to circle in a cloud, each as a variable wave, at well-defined relative heights from the nucleus.

The electrons do not take a fixed path. Instead, their individual orbitals respond to the varying energies along the way, but following a broad route round, at the distances or heights according to their quantization. Collectively, each set of electrons and their orbitals envelop the entire sphere of the atom like a shell.

QM has established that there can be up to seven concentric layers of shells, and four sub-shells. It has also been found that electrons are seated in pairs due to the "spin"

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[3] A charge is an intrinsic feature of an elementary particle and it is positive or negative. A particle without a charge cannot respond to an electrical field. Charges are quantisized.

characteristics of elementary particles. The first layer seats only two and the largest up to 32. From time to time, there can be a hole or missing electron. When the net result of energy changes leaves the outmost shell with unoccupied positions or an extra electron, it is said to be in valence. With enough outside force, a valence electron can escape and become free. Atoms with extra or missing electrons are called ions.

Electrons in the lowest shell have the lowest ionization energy, and those in the outer the strongest. Electrons that lose energy will drop to a lower shell. One that absorbs new energy will move outward. Electrons cannot in themselves radiate energy but can absorb energy from or lose energy to sources external to themselves

Because, electrons move around in waves, it is impossible to know the exact location of an electron. Thus, they move around in “clouds of probability” - called orbitals.

The atomic nucleus

The atomic nucleus is made up of protons and neutrons. Collectively, these are known as *nucleons*.

The atomic nucleus is very dense and extremely small. It contains more than 99.9% of the mass of an atom and scales around ten thousand times smaller than an atom ($1x10^{-15}$) nm.

There is one proton for every electron. The protons attract the negatively charged electrons and keep them in orbit around the nucleus. The number of protons in an atom's nucleus determines which chemical element it is.

Neutrons are uncharged particles found within all atomic nuclei (except for Hydrogen). A neutron's mass is slightly larger than that of a proton. The extra attraction from the neutrons keeps the protons' positive electrical charges from tearing an atomic nucleus apart. Thus, the reason for neutrons is to allow more than one proton to coexist in an atomic nucleus. When the number of neutrons is not the same as protons, the atom is said to be *an isotope*. Where atoms have too many neutrons, the isotope is said to be *radioactive.*

The study of the atomic nucleus is a separate branch called *nuclear physics*. Scientists have still not settled the architecture of the atomic nucleus. The number of neutrons vary via-a-vis the proton, and they can become unstable in larger numbers. All protons and neutrons are bound by the strong fundamental force, which additionally binds these nucleons within the nucleus. Knocking off a neutron releases enormous energy, the basis of the atom bomb.

Fundamental Particles
(@ *Elementary Particles*)

Following the invention of accelerators, colliders, and other instruments of measurement, together with various theoretical models to explain their workings, today we have a framework of fundamental particles, generally accepted as the **Standard Model of Particle Physics:**

FUNDAMENTAL PARTICLES****			
Fermions		**Bosons**	
Quarks Spin – ½ Colour change* Strong Interactions	**Leptons** Spin – 1/2 No Colour change* Electroweak Interactions	**Gauge bosons** Spin – 1 Force carriers	**Scalar bosons**
Three Generations** **1 Up** *(Down)* **2.Charm** *(Strange)* **3.Top** *(Bottom)*	**Three Generations**** **1 Electron** ***(****Electron Neutrino)* **2 Muon** *(Muon Neutrino* **3.Tau** ***(***Tau Neutrino)*	**Four Kinds** (The four fundamental interactions) **1 Photons** ***(****Electro magnetic interaction)* **2.W & Z Bosuns** **(***Weak Interactions)* **3 Gluons (8 types)** *(Strong Interactions)* **4 Graviton** *(gravity, hypothetical)*	**Unique** **1.Higgs boson**

*Quarks have colour - red, green or blue. They are identification signals in strong force interactions
** Also known as “Flavours”
***An excellent explanation of the Standard Model may be found at https://en.wikipedia.org/wiki/Elementary_particle

On 4 July 2012, the late Choo Eng Khoon and I celebrated when the Higgs boson was announced to have been observed at CERN's Large Hadron Collider after many years of experimentally searching for evidence of its existence. It marked a final step in the building the Standard Model. As of this moment, the graviton has not yet been observed in reality.

At a simplistic level, fundamental or elementary particles are either ***fermions*** or ***bosons***. It might be said that the *fermions* are the building blocks, while the *bosons* handle the fundamental forces.

All elementary particles possess a number of intrinsic characteristics. These correspond with one another according to the functions they perform, the forces they deal with, or their need to complement one another. These characteristics include mass, an electric charge, spin and a colour charge. Fermions divide into quarks and leptons. Each quark and lepton has its opposite of an *anti-quark* and *anti-lepton*, corresponding to the same situation in the bigger world.

The most important fact in all QM is that, at any one time, each of these intrinsic characteristics of an elementary particle exists in different states, naturally or induced. The set of characteristics of a particle at any one time is said to be its **quantum state.** Where linked together, the whole constitutes the **quantum state of a system.**

Quarks

The quark emerges as the major building block of matter. Its signal property is that it interacts with the strong force. Put it the other way, you need a strong force to work with a quark. It also interacts with other quarks and elementary particles. The quark comes in three generations. Each generation in turn has a set of opposites, making six postures or “flavours” of quarks, in all.

Quarks have mass[4], a positive or negative electric charge, a "spin" feature (best thought of as a magnetic reactivity) and a colour charge. These are like built-on "handles" so to speak for the strong force to identify and grapple a quark and deploy or combine it variously. They are each of differing values for the different flavours of the quark.

While quarks have colour, the particles that they make up are colourless. When combined, the red, blue, and green come together to make a colourless particle, much as red, blue, and green light form white light when combined.

Electrons are quarks. Where quarks combine with others, they are called *hadrons.* Heavy subatomic particles that are made up of three quarks are called *baryons*. Protons[5] and neutrons are baryons

Leptons

Leptons are best thought of as supplementary building material, Again, there are six flavours, electrons, muons and taus and their neutrino counterparts. They do not interact with the strong force. They only respond to the weak force and (it is thought with) the gravitational force. They also react under the electromagnetic force, except the electrically neutral neutrinos

Leptons have a distinct mass and a negative electric charge, while their neutrinos have a neutral charge. The charged leptons[6] are electron-like and one is classified as

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4 The smallest or basic quark is thought to have none, but the others have a varying range.

5 A proton is made of two Up quarks, with 2/3 positive charge each and one Down Quark with a negative 1/3 charge (2/3 + 2/3 + -1/3 = 1).

6 Charged leptons can combine with other particles to form various composite particles such as atoms, while neutrinos rarely interact with anything, and are consequently rarely observed. The best known of all leptons is its electron.

such. Leptons are thought to have colour, but I gather this still being worked out. The other flavours are called *neutrinos.* All leptons have mass, varying widely according to the flavours. Electrons, the lightest lepton, have a mass only 1/1,840 that of a proton.

Neutrinos previously thought to be massless are now believed to have a small "nonzero" mass, smaller than any other known elementary particles. Neutrinos have a half spin, no electrical charge, and it seems no colour.

Electrons have the least mass of all the charged leptons. The heavier muons and taus will rapidly change into electrons and neutrinos through a process of particle decay, **Thus electrons are stable and the most common charged lepton in the universe**, whereas muons and taus can only be produced in high energy collisions (such as those involving cosmic rays and those carried out in particle accelerators).

For every lepton flavour, there is a corresponding type of antiparticle, known as an *antilepton*, that differs from the lepton only in that some of its properties have equal magnitude but opposite sign. According to certain theories, neutrinos may be their own antiparticle. It is not currently known whether this is the case.

Neutrinos

I am most intrigued by neutrinos. Neutrinos are one of the most abundant and intriguing particles in the universe. Because they have very little interaction with other matter, they are incredibly difficult to detect, see inset following:

> "Neutrinos are teeny, tiny, nearly massless particles that travel at near lightspeeds. Born from violent astrophysical events like exploding stars and gamma ray bursts, they are fantastically abundant in the universe, and can move as easily through lead as we move through air. But they are notoriously difficult to pin

> down.
> Neutrinos are really pretty strange particles when you get down to it," says John Conway, a professor of physics at University of California, Davis. "They're almost nothing at all, because they have almost no mass and no electric charge…They're just little whisps of almost nothing." Ghost particles, they're often called.
>
> But they are one of the universe's essential ingredients, and they've played a role in helping scientists understand some of the most fundamental questions in physics.
>
> For example, if you hold your hand toward the sunlight for one second, about a billion neutrinos from the sun will pass through it, says Dan Hooper, a scientist at Fermi National Accelerator Laboratory and an associate professor of astronomy and astrophysics at the University of Chicago. This is because they're shot out as a byproduct of nuclear fusion from the sun – that's the same process that produces sunlight.
> "They're important to our understanding of the kind of processes that go on in the sun, and also an important building block for the blueprint of nature," Hooper said.
>
> Particle physicists originally believed that neutrinos were massless. But in the 1990s, a team of Japanese scientists discovered that they actually have a smidgen of mass. This tiny bit of mass may explain why the universe is made up of matter, not antimatter. Early in the process of the Big Bang, there were equal amounts of matter and antimatter, according to Conway. "But as the universe expanded and cooled, matter and antimatter were mostly annihilated. And a slight asymmetry favored matter over antimatter. We think neutrinos may have something to do with that process…. And it's a puzzle, why we're made out of matter and not antimatter."[7]

It seems one can think of them as the original or primeval substance from which elementary particles are made.

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[7] https://www.pbs.org/newshour/science/what-is-a-neutrino-and-why-should-anyone-but-a-particle-physicist-care

As with all models of reality, anomalies keep emerging. There is talk of perhaps another level of particle, tentatively named the *preon,* but we can leave it to the next revision of these memoirs. (Further on, it will be found that technologists are trying to split the electron, to find anyons and majoramas to use in computers,)

Bosons

Whereas the elementary particles that make up matter are fermions, bosons are force carriers. These function as the 'glue' holding matter together. Elementary particles interact with each other by the exchange of gauge bosons—usually as virtual particles, see next paragraph.

Bosons divide into (a) gauge bosons or (b) scalar bosons. A gauge boson carries any of the fundamental forces or interactions of nature. The scalar bosom is somewhat of a virtual figure, a mathematical resultant or checksum figure.

Gauge bosons

There are four kinds of gauge bosons: (1) *Photons*, which deal with the electromagnetic force, (2) *Gluons*, which deal with the strong forces, (3) *W & X bosons* which deal with the weak forces, and (4) *Graviton*, which deals with gravity (hypothetical still).

Except for the W & X boson, carrier bosons have no mass. Under Einstein's Special Theory ($e=mc^{2)}$, they would have no energy. Nevertheless, all carrier bosons do have and carry energy. This is factually so and established mathematically so by their having momentum. Thus, photons and gluons have and carry energy, the former of course light. Bosons were named for having zero electric charge. This gives them the unique ability for more than one boson to occupy the same state. All known gauge bosons have a spin of 1, as might be

Scalar Bosons

The *scalar boson* is a boson entity with a spin integer of zero. Under the Quantisized Gauge Theory (of physics) on which the Standard Model has been built and (so far) successfully confirmed by experimentation, actual evidence of the scalar boson was the last, if not among the last, requirements to confirm the Standard Model. The candidate for this position has been the **Higgs boson**, which was finally sighted at CERN in 2111. It was the last unverified part of the Standard Model.

In the Standard Model, the Higgs particle is a massive scalar boson, with zero spin and no electrical charge It is very unstable, decaying into other particles almost immediately.

Multiple Generations of Bosons

Gauge bosons are quanta of gauge fields. Consequently, there are as many gauge bosons as there are generations of the gauge field. In the simple case, there is only a one-gauge boson, the photon. A more complicated group has eight generators and corresponding to the eight gluons. The three W and Z bosons correspond (roughly) to the three generators of its group.

Higgs Boson – God's Particle

Until the Higgs boson was confirmed to exist, incredible as it seems, the whole superstructure of the Standard Model, while verified by experiment and measurements in umpteen particulars, could not be signed off as verified. The reason: in the then accepted theoretical construct of the universe, it was necessary that the boson existed, to confirm that mass existed, and we exist. Hence the journalistic hyperbole that it was “God’s particle”.

Higgs Field

Confirmation of the Higgs boson is thought to point to the way to the “Higgs field “, which lies behind the boson discovery, and which is thought might extend as a or the common continuum of matter in the universe. It could lead, inter alia, to some grand unified theories.

Fundamental Forces

There are four fundamental forces known to QM. The (1) gravitational forces and (2) electromagnetic forces produce long-range interactions whose effects can be seen directly in everyday life. The (3) strong and (4) weak force produce operate at sub-atomic distances and govern sub-atomic interactions.

The **(1) gravitational force** in space is attributed to the curvature of space-time under Einstein’s Theory of General Relativity. The earth itself has a gravitational field centered on its core, which interacts at the sub-atomic level as well, and decreases skywards.

The (**2) electromagnetic force** is that which occurs between charged particles. It is carried by the boson photon. At the sub-atomic level, its energy or force mediates in the re-arrangement and movement of sub-atomic particles in response to external energy. Above ground, so to speak, this force manifests itself as radiant energy (ER) carried by photons in the Electromagnetic Field (EM). The former travels out into space unimpeded at the speed of light. I have not gone into what it does there – where it certainly meets forces of gravity in space. On earth, while it occurs naturally, as in lightning, man has learnt to generate and use it for wide range of purposes.

The (**3) strong force** is wholly subatomic. The strong interaction is carried by the boson *gluon* and is responsible for quarks and leptons binding together to form hadrons such as protons and neutrons. It is also the force that that binds nucleons to form the atomic nucleus.

The **(4) weak force** again is sub-atomic. It is carried by *W and Z bosons* and acts on the nucleus of atoms mediating radioactive decay. The electromagnetic and the weak forces have been unified in recent sub-atomic quantum thinking as the “electroweak force”.

At the sub-atomic level, if we consider the strong force to have a magnitude of 1, then the electromagnetic force has a relative magnitude of 1/137, the weak force has a relative magnitude of 10^{-6}, and the gravitational force has a relative magnitude of 6×10^{-39}.

The fundamental forces are at present not linked. It is said the theories supporting them at present lack a symmetry normally associated with science. Some physicists believe the fundamental forces can become unified into a single force at very high energies. But particle accelerators cannot at present produce the enormous energies required to experimentally probe this. Gravity remains the main problem.

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Quantum Electrodynamics

The following quotation captures the essence of the above:

> “The prototype of quantum field theories is Quantum Electrodynamics, which provides a comprehensive mathematical framework for predicting and understanding the effects of electromagnetism on electrically charged matter at all energy levels.

> Electric and magnetic forces are regarded as arising from the emission and absorption of exchange particles called photons. These can be represented as disturbances of electromagnetic fields, much as ripples on a lake are disturbances of the water.
>
> Under suitable conditions, photons may become entirely free of charged particles; they are then detectable as light and as other forms of electromagnetic radiation. Similarly, particles such as electrons are themselves regarded as disturbances of their own quantized fields." [8]

Electricity

Every fermion has an electric charge as an intrinsic characteristic, either positive or negative. Every electron therefore carries a negative charge. If we use enough electrostatic force (external energy) on a valence electron--either pushing it with another negative charge or attracting it with a positive charge--we can eject the electron from its atom, taking with it its negative charge, and creating a free electron. The free electron eventually finds a new atom to latch on to. In doing so, it ejects another valence electron. Now a new electron is drifting through free space looking to do the same thing. This chain effect can continue on and on to create a flow of negatively charged electrons called an electric current. **Electricity is defined as the flow of electric charges through an electric circuit.** Materials with high conductivity are called *conductors* and those with low conductivity are called *insulators*.

A "live" electric current generates an electric field around it[9], separate from the electric current itself. The **electric circuit** is an actual flow of charged particles in a conducting medium.

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8 https://www.britannica.com/science/quantum-field-theory

9 The electric field is defined mathematically as a vector field that associates to each point in space the (electrostatic or Coulomb) force per unit of charge exerted on an infinitesimal positive test charge at rest at that point. See also magnetic field, in next section.

An **electric field** radiates energy in the form of photons outside and away from the electric circuit that produces it.

Magnetism

Every fermion also has “spin” as an intrinsic characteristic, either positive or negative. It therefore has a minute element of magnetism produced by its spin moments, which produces its own magnetic field.[10] All matter is “magnetic“ to some degree. Electrons orbiting an atomic nucleus produce a magnetic field.

Magnetism is the sympathetic response of (i.e., the alignment of) particles, atoms, and molecules within magnetisable matter, in response to a magnetic field. A magnet is matter in which such particles are aligned and in turn produces a magnetic field.

Wherever there is electric current flowing, this expresses itself in the production of a magnetic field, alongside its electric field. These two fields combine to produce the condition called “electromagnetism”, which in turn radiates electromagnetic energy.

The following article provides a bloody-minded no-buts explanation given in *Quora*:

> Magnetism, just like all other primary forces in physics of the macroscale, emerges from one of 3 main properties, that are specific to every subatomic particle and are directly associated with all 3 types of fields in macroscale geometry:
> Quantum spin - magnetic moment and angular momentum
> Electric charge - differential of energy, nullified by current flow
> Rest mass - gravity and momentum in relative motion
>
> Every subatomic particle has its own magnetic moment - even

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[10] The definition of a **magnetic field** is a place in space near a **magnet** or an electric current, where a physical **field** is created from a moving electric charge that creates a force on another moving electric charge. An example of a **magnetic field** is the Earth's **magnetic field**.

a neutron, which has no electric charge. Don't listen to people, who claim, that magnetism is just a side-effect of electric current. Magnetism and electricity have 2 different sources in matter - they ARE NOT only 2 sides of the same coin. There are absolutely no interactions between magnetic and electric fields in their static forms. Electromagnetism requires motion of matter. EM induction doesn't prioritize any force over other. Magnetic field in motion induces electric current in conducting medium, while motion of electrically charged particles induces magnetic field around the current - there's no egg before chicken in this case

In electric currents, magnetic moment of all moving particles, is aligned perpendicularly to the direction of current. It's because of that alignment, magnetic field is induced by the moving charge

In atoms, magnetic field comes from unpaired electrons on the outer orbitals. Magnetic moments of electrons on the same orbital, cancel each other out.

What creates magnetic field of a permanent magnet, is the alignment of magnetic moments in a group of atoms. In a ferromagnetic material, groups of atoms become aligned by their magnetic moments, making so called magnetic domains. Due to an influence of external magnetic field, magnetic moment of atoms becomes oriented in one direction. The more aligned is the magnetic orientation of magnetic domains, the stronger is the magnetic field, which magnet produces"
Quora
Bartlomiej Staszewski,
Answered July 2, 2019[11]

Electromagnetic Energy

Electromagnetic radiation occurs when an atom absorbs (or is impounded by) external energy. The absorbed energy causes one or more electrons to change their locale within the atom. Depending on the kind of atom and the amount of energy, this

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11 https://www.quora.com/profile/Bartlomiej-Staszewski

electromagnetic radiation can take the form of heat[12], light, ultraviolet light, or other forms of electromagnetic radiation.

Clarifying precisely what electromagnetic energy is and its pervasive role in nature was among the major achievements of QM. Today it is mainly generated by the induced flow of electrical charges. It also occurs naturally in lightning, in sub-atomic interactions, and reaches us as heat and light from the sun.

At the sub-atomic level, it is one of the fundamental forces, the electromagnetic force that mediates the responses of elementary and atomic sub-particles under changes in energy.

At atomic level, under certain conditions (above thermal radiation), energy escapes as radiation from an electric current, creating a magnetic field around (outside) it. Every such magnetic field (ie one generated by an electric current) creates an electric field. These two fields combine to form one electromagnetic (EM) field, which radiates electromagnetic energy. The electric field orientates itself to the direction of the propagation of the energy (ie the field), while the magnetic component radiates perpendicular to it.

The original electric current remains in its circuit, moving at the rate which applies in its conductor. EM radiation, however, is pure energy and travels at the speed of light. This energy can radiate can be directed, omni-directionally. The electromagnetic field remains "on" as long as the originating electric circuit remains "on".

This quotation elegantly sums up the matter:

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[12] Heat is thermal radiation, has no frequency, and is not electromagnetic radiation.

> "What Is the Principle Behind Electromagnetic Wave Generation?
>
> Applying AC voltage between two metal electrodes produces a changing electric field in space, and this electric field in turn creates a displacement current, causing an electric current to flow between the electrodes. At the same time, the displacement current produces a changing magnetic field around itself according to the second of Maxwell's equations (Ampere-Maxwell Law).
>
> The resulting magnetic field creates an electric field around itself according to the first of Maxwell's equations (Faraday's Law of Electromagnetic Induction).
>
> Based on the fact that a changing electric field creates a magnetic field in this manner, electromagnetic waves - in which an electric field and magnetic field alternately appear - are created in the space between the two electrodes and travel into their surroundings.
>
> Antennas that emit electromagnetic waves are created by harnessing this principle."[13]

Photon

One of the most fundamental discoveries of QM is that electromagnetic energy travels and otherwise operates as discrete packets of energy. This packet is the photon. The photon is the "unit quantum" of energy.

Photons are elementary particles. They are smaller than electrons. They are in fact bosons. The latter are the "force carriers" among the elementary particles. Bosons are special because many bosons can occupy the exact same quantum state at the same time. A laser beam is a collection of many photons all in the same quantum state. In contrast, particles that are not bosons cannot occupy the same state at the

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13 https://courses.lumenlearning.com/physics/chapter/24-2-production-of-electromagnetic-waves/

same time. This is what keeps the atom as an object from not collapsing to a single point. The principle that non-bosons cannot be in the same state is called the Pauli Exclusion Principle.

Electromagnetic energy is 'made up' of photons. In LEDs, electrons are pumped up with energy and then encouraged to release this energy in the form of photons.

Photons have no mass. Hence, they must obey the QM law governing the energy-momentum relation[14], and therefore get all their energy from their momentum. In a vacuum, it travels at the constant of the speed of light, namely 299,792,458 m/s.

Photons do not experience time. It is emitted, and might exist for hundreds of trillions of years, but for the photon there is zero time elapsed between when it is emitted and when it is absorbed again. It does not experience distance either.

A photon has an electromagnetic field associated with it. Hence, it must be made of oppositely charged particles that give rise to the electric field component, while their motion generates the magnetic field component. The photon’s wave behaviour is due to its electromagnetic field.

Frequencies

EM radiation spans an enormous range of frequencies. This range is known as the **electromagnetic spectrum.** The EM spectrum is generally divided into seven regions, in order of decreasing wavelength and increasing energy and frequency.

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14 The energy–momentum relation is a mathematical extension for objects in motion, of Einstein’s familiar mass-energy equation and read thus: E2=(pc)2 +(m0c2).,
This equations holds for a system, a particle or a macroscopic body, having an intrinsic rest mass of m0, total energy E, and a momentum of magnitude p, where the constant c is the speed of light, assuming the special relativity case of flat space-time.

The common designations are radio waves, microwaves, infrared (IR), visible light, ultraviolet (UV), X-rays and gamma rays. Typically, lower-energy radiation, such as radio waves, is expressed as frequency; microwaves, infrared, visible and UV light are usually expressed as wavelength; and higher-energy radiation, such as X-rays and gamma rays, is expressed in terms of energy per photon.

Where man-generated, the frequency emitted can be controlled and sharply defined. In other circumstances they may be broad. Light is a stream of photons travelling at the light frequency.

Wave-Particle Duality

Einstein believed light is a particle (photon) and the flow of photons is a wave. This dual nature of light has since been proved and incorporated in electromagnetic theory and quantum mechanics. This was the work of Erwin Schrodinger. It applies to all energy.

Photon energy is the energy carried by a single photon. The amount of this energy is directly proportional to the photon's frequency, and thus inversely proportional to its wavelength. The higher the photon's frequency, the higher its energy. Equivalently, the longer the photon's wavelength, the lower its energy

Therefore, it is usually stated in this form: that the energy of an EM wave is directly proportional to its frequency (and inversely proportional to its wavelength) So, x-rays consist of very high-energy photons with shorter wavelengths compared to radio waves. You could say the “size” of a photon is basically the width of its wavelength

Because they are massless, photons are transparent to and pass through one another, as do two beams of light. But a photon can also lose energy due to absorption by other matter or inelastic scattering. Photons can also be absorbed by insulators, i.e., by electrons in their sub-atomic levels (which results in an increase in the energy of the latter).

Because EM radiation can be conceptualized as a stream of photons, radiant energy can be viewed as photon energy. Alternatively, EM radiation can be viewed as an electromagnetic wave carrying energy, composed of oscillating electric and magnetic fields. These two views are completely equivalent.

Maxwell established that electromagnetic waves possess the following properties. The magnetic field oscillates in phase with the electric field. In other words, a wave "maximum of the magnetic field" always "coincides" with a "wave maximum of the electric field" in both time and space.

Visible light is usually defined as having "wavelengths in the range of 400–700 nanometers (nm), or 4.00×10^{-7} to 7.00×10^{-7} m, between the infra-red (with longer wavelengths) and the ultra-violet (with shorter wavelengths). This wavelength means a frequency range of roughly 430–750 terahertz (THz).

When EM waves are absorbed by an object, the energy of the waves is first converted to heat (or converted to electricity in case of photo-electric material). This is a very familiar effect, since sunlight warms surfaces that it irradiates. This phenomenon is also associated with infra-red radiation. In fact, any kind of electromagnetic radiation will warm an object that absorbs it. (If EM radiation warms up matter to the point that an electric current begins to flow, it would start a cycle again.)

EM waves can also be reflected or refracted or scattered, in which case their photons are re-directed or redistributed.

All electromagnetic radiation travels at the same speed as light. Nothing can move faster than the speed of light.

Electromagnetic waves are transverse waves. A transverse wave is a wave in which particles of the medium move in a direction perpendicular to the direction that the wave moves. Their vibrations or oscillations are changes in the electrical and magnetic fields at right angles to the direction of wave travel. All electromagnetic waves transfer energy as radiation from the source of the waves to their point of absorption.

Intensity

In addition, an EM wave is characterized by its intensity. For example, the blindingly intensive red light on a theater stage may consist of photons of the same frequency and wavelength as the red stoplight at a street corner. However, stage light is more powerful or intense. This is due to the difference in quantity or number of photons emitted. The higher the number of photons irradiated, the greater the intensity of the light. The frequency and the wavelength are the same, but the *amplitude* of the wave is increased, ie the peaks of the wave rises higher or falls lower because more photons are pushed through

Therefore, the energy in a wave is determined by two variables. One is amplitude, which is the distance from the rest position of a wave to the top or bottom. Large amplitude waves contain more energy. The other is frequency, which is the number of waves that pass by each second. Increasing the number of photons does not change the energy, only the intensity.

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Quantum Field Theory (QFT).

From the understandings of QED as to the nature and behavior of fields, QMers saw the symmetry of unifying all existing phenomena within the embrace of a larger field-based concept of things. This has given rise to Quantum Field theories (QFT) at which they are poised for further work in Q3. I conclude this section by including a quotation that captures the state of mind they are in at the moment:

> "In modern physics theory, one can picture all subatomic particles as beginning with a field. Then the particles we see are just localized vibrations in the field. So, according to quantum field theory, the right way to think of the subatomic world is that everywhere- and I mean everywhere- there are a myriad of fields. Up quark fields, down quark fields, electron fields, etc. And the particles are just localized vibrations of the fields that are moving around. Theoretical physics simply imagines that ordinary space is full of fields for all known subatomic particles and that localized vibrations can be found everywhere. These fields can interact with one another, like two adjacent tuning forks. These interactions explain how particles are created and destroyed – basically the energy of some vibrations move from one field and set up vibrations in another kind of field."[15]

Classical Crossovers

Momentum

In classical physics, momentum is mass x velocity, expressed in kg m/sec. Some quantum elementary particles are massless. The photon has no mass. However, despite photons having no mass, a photon interacts as a unit in

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[15] https://www.physicssayswhat.com/2019/06/05/qft-how-many-fields-are-there/

collisions or when absorbed, rather than as an extensive wave. It has momentum.

There has long been evidence that EM radiation carries momentum. Maxwell and others who studied EM waves predicted that they would carry momentum. It is now a well-established fact that photons do have momentum. In fact, photon momentum is suggested by the photoelectric effect, where photons knock electrons out of a substance.

We do not actually see a photon. When we see stars, that is because the electromagnetic radiation (light) from those stars travel a very far distance to reach us, and then excite the electrons in our eyes.

Force

In classical physics, energy is needed for a force to do work. So, the amount of force done in a given distance equals the amount of energy used, which is work. Work and energy are equal in magnitude.

In QM, the Lorentz force (or electromagnetic force) is the combination of the electric and magnetic force on a point charge in their electromagnetic field A particle of charge q moving with a velocity v in its electric and magnetic fields experiences a force.

Quantum Technology (Q1)

QM had been totally vindicated by QM Technology of the First Revolution. In other words, QM discoveries have been proved by their successful application through technology, to improve life.

Firstly, in the dimensions of research and understanding, QM has greatly expanded and influenced both science, scientific instrumentation and technology. It suffices here to include the following quote to reflect the general impact of QM:

> "Quantum mechanics has had enormous success in explaining many of the features of our universe. Quantum mechanics is often the only theory that can reveal the individual behaviors of the subatomic particles that make up all forms of matter. Quantum mechanics has strongly influenced string theories as candidates for a Theory of Everything.
>
> In many aspects modern technology operates at a scale where quantum effects are significant. Important applications of quantum theory include quantum chemistry, quantum optics, quantum computing, superconducting magnets, light-emitting diodes, the optical amplifier and the laser, the transistor and semi-conductors such as the microprocessor, medical and research imaging such as magnetic resonance imaging and electron microscopy. Explanations for many biological and physical phenomena are rooted in the nature of the chemical bond, most notably the macro-molecule DNA." [16]

It is sufficient here to consider just one impact of QM to realise its transformation of daily life, namely the transistor and semi-conductor. Nothing would seem more obvious than applying QM enabled savvy to "dope" metals to change their relative conductivity and create a junction to amplify or switch the flow of electromagnetic energy past them, whether an electric current, light or microwave. The transistor was born in 1947, and the first radio transistor was proposed in 1952.

The transistor became MOSFET (metal–oxide–semiconductor field-effect transistor) in 1959. As it became successfully and impossibly minitiarised, it became the sire of the CMOS and MOS integrated chip (IC). General Microelectronics introduced the first commercial IC in 1964 with 120-transistors. Today, the IC is the most abundant item of manufacture in the world. They are nanoscale giant computational devices. ,

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16 https://en.wikipedia.org/wiki/Quantum_mechanics

In Apr 2019, *Cerebras*, the computer company dedicated to AI, announced they built the largest IC ever, the Wafer Scale Engine (WSE). It contains 400,000 cores with 1.2 trillion transistors on a die of slightly over 46,000 square mm in area (about 8.5 sq inches). According to the company, the chip boasts 18 gigabytes of storage spread around the die.

No one would dispute that the most far-reaching impact of the IC has been through computing and microwave electronics. Together these have given us Information Technology (IT) and Telecommunications, which have in turn together given us the supercomputer. the Internet and the Information Age.

One could also go into the impact of QM's contributions on light and electromagnetic phenomena, with equally breath-taking awe. Quite simply, there would be no radio and telephone (as we know it), TV, laptops, smartphones, MRI, GPS, the laser, the Internet, not even the neon bulb. There would be no Transiting Exoplanet Survey Satellite (TESS) in the southern sky. We would of course also be without the atomic and hydrogen bombs, and intercontinental ballistic missile.

Without Q1, we would not be able to move to Q2. Period.

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SECOND QUANTUM) REVOLUTION (Q2)

In the last decade, all the branches of science and technology and all knowledge, governmental and investment institutions have grasped the overriding potential of QM and launched into research in a frenzy. There has been an air of a "gold rush". Everything has been under the microscope.

The following captures the euphoria and triumph when QM2 turned the corner of the last millennium:

> "In the second quantum revolution, we are now actively employing quantum mechanics to alter the quantum face of our physical world. We are transforming it into highly unnatural quantum states of our own design, for our own purpose. For example, in addition to explaining the periodic table, we can make new artificial atoms—quantum dots and excitons—which we can engineer to have electronic and optical properties of our own choosing. We can create states of quantum coherent or entangled matter and energy that are not likely to exist anywhere else in the Universe. These new man-made quantum states have novel properties of sensitivity and non-local correlation that have wide application to the development of computers, communications systems, sensors and compact metrological devices. Thus, although quantum mechanics as a science has matured completely, quantum engineering as a technology is now emerging on its own right. It is just a matter of being in the right place at the right time to take full advantage of these new developments.
>
> From J. P. Dowling and G. J. Milburn, Quantum Technology: the Second Quantum Revolution, Phil. Trans. R. Soc. Lond. A. (2003)[17]

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17 http://rsta.royalsocietypublishing.org/content/roypta/361/1809/1655.full.pdf . The article is also available at https://arxiv.org/pdf/quant-ph/0206091.pdf

Introducing the Quantum Computer

Perhaps the only thing wrong with QM is that it is still called "mechanics". From hereon I refer to QM as Quantum Physics.

.* Man's primary objective in Q2 has been to build a quantum computer.

.* This has derived from the simple, mesmerizing, and utterly irresistible fact that superposition and entanglement together carry promise of handing to man exponential, in fact theoretically limitless, increases in computing power that would change the world yet again.

.* It will also give us mastery of the nano world, in its own immeasurable Future.

What is Quantum Computing?

If you read nothing else but this, you will grasp what quantum computing is:

> "A regular computer tries to solve a problem the same way you might try to escape a maze – by trying every possible corridor, turning back at dead ends, until you eventually find the way out. But superposition allows the quantum computer to try all the paths at once – in essence, finding the shortcut.
>
> Two bits in your computer can be in four possible states (00, 01, 10, or 11), but only one of them at any time. This limits the computer to processing one input at a time (like trying one corridor in the maze).
>
> In a quantum computer, two qubits can also represent the exact same four states (00, 01, 10, or 11). The difference is, because of superposition, the qubits can represent all four at

the same time. That's a bit like having four regular computers running side-by-side.

If you add more bits to a regular computer, it can still only deal with one state at a time. But as you add qubits, the power of your quantum computer grows exponentially. (For the mathematically inclined, we can say that if you have "n" qubits, you can simultaneously represent 2^n states.)

It's like that old fable about an ancient Indian, called Sessa, who invented the game of chess. The king was delighted with the game and asked Sessa to name his reward. Sessa humbly requested a single chessboard with one grain of wheat on the first square, two on the second, four on the third and so on. The king agreed at once, not realising he'd promised away more wheat than existed on Earth. That's the power of exponential growth.

Just like each square doubled Sessa's wheat, each additional qubit doubles the processing power. Three qubits give you 2^3, which is eight states at the same time; four qubits give you 2^4, which is 16. And 64 qubits give you 2^{64}, which is 18,446,744,073,709,600,000 possibilities! That's about one million terabytes worth.

While 64 regular bits can also represent this huge number (264) of states, it can only represent one at a time. To cycle through all these combinations, at two billion per second (which is a typical speed for a modern PC), would take about 400 years."[18]

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[18] https://cosmosmagazine.com/physics/quantum-computing-for-the-qubit-curious/

Fundamental Concepts of Q2 Computing

It is necessary to grapple with some of the cardinal concepts and terms of Q2 technology to appreciate what quantum computing is.

Nano

Quantum computing is a feature of the nano universe, discovered by QM in the sub-atomic world. The qubit has to be programmed through an electron-microscope and its results read by a reverse process. Power supply and controls have to be miniscule. Measurements are in nanometers (10^{-9} nm) and less[19]. In due course, one million qubits may have to be packed into a chip surface of one cm^2. i

Cryogenic World

Not only is it small, but the quantum computer is a creature of the cryogenic world. Cryogenic refers to an environment where temperatures approach close to Absolute Zero (-273.15 degrees Celsius /0 degrees Kelvin).

Temperature reflects the energy in a substance. Absolute zero is the point at which there is no heat energy remaining to be extracted from the substance, and the atoms lose all motion. This point is not known to exist naturally anywhere in the universe[20]. except close to it.

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[19] An electron is 9.1x10^{-31} gm. An electron is therefore considered nearly massless in comparison with a proton or a neutron. For comparison, the smallest virus is 1x10^{-20} gm and a typical DNA is 2.5x10^{-9}

[20] The coldest known spot is -272 degrees Celsius in the Boomerang Nebula, while the Big Bang background radiation is -270 degrees Celsius. Near Absolute Zero has been created artificially in the lab. Matter again behaves differently in the sub-absolute world – the next dimension. of QM research.

QM has determined that all forms of matter achieve their quantum “ground state” in this cryogenic temperature range. All atoms retain only zero-point energy. It is in this state (and not otherwise) that matter displays the quirky characteristics of quantum mechanics, which can then be manipulated and programmed. One of the long-term problems is how to breed a quantum computer to live on the earth’s surface.

Qubit

Like the “bit” in classical computing. A “qubit” (a quantum bit) is a unit of quantum measurement.

As a component of the computer, the qubit is physically a **device,** capable of being in one of two electronic states at any one time (0 or 1), exactly like a classical semi-conductor chip. The technical definition of a qubit is that it is a two-state (or two level) quantum-mechanical system. It is the basic unit displaying the peculiarities of QM.

By way of elucidation.

(i) The qubit was born when it was discovered that certain elementary particles (fermions) subsisted in one of two electronic states at any one time**.** Thus, an electron was in the state of “spin up” or spin down”, and a photon could be in vertical or horizontal polarisation. What was more, they could be made to resolve which state to be in! This meant they could be made to compute, if captured and placed as a “working particle” in a qubit suitably organised for the purpose. (The word “qubit” is used synonymously for both the device and the working particle, as the context requires.)

(ii) A qubit in "ground state"[21] would be in one or other of its basic states (e.g., 0 or 1), like a classical semi-conductor chip.

(iii) The second great discovery was that in cryogenic conditions a qubit could be placed in **superposition**. The effect was to activate **both** the basic states of the qubit simultaneously (each poised "in between" as it were in a 50% probability of 0 or 1). As there are generally more than one qubit, each one must be set to superposition individually.

(iv) Superposition is like balancing (spinning) a coin exactly on its edge. When In superposition, a qubit is most comfortably thought of as a coin spinning on its edge.

(v) At the end of a run, all the qubits would remain with their "coins" poised in "coherent" superposition in their respective final states, (the results "held" as it were in electronic potential), until triggered to "di-superpose" or collapse. Upon the latter, each qubit would fall into and display the result of the run, as 1 or 0 of its basic state. Like classical bits, all the qubits together would provide the answer, representing the result for that run.

(iv) Every run of a programme will not produce the same answer, but a range within the probabilities of the run. The results are therefore said to be probabilistic. The final answer is usually taken as the average of several runs.

(v) Where an additional qubit is added and superposed, there would be 2^{-2} = 4 sets of superpositioned states, and so on. The computing power would increase exponentially. (See definition of quantum **superposition** further on)

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21 Un-initialised.

(vi) There is one other feature which gives the qubit its power. This is treated further on but may be mentioned now to complete its profile: **entanglement.**

Coherence, Noise and Fragility

(i) The results of a computational run are retained by the qubits in electronic form, co-existently in the magnetically created superposition which hosts the calculation. For the reasons mentioned below, this whole environment is subject to rapid "de-coherence" on completion of a run. The coherence time is in fact in *nano* seconds. The results must therefore be read very quickly. Because they are also in the *nano* scale, they must be read out electromagnetically (commonly a hyper-sensitive magnetic device called the SQUID). However, any "disturbance" to read the system will immediately cause a collapse of the superposition and destroy all its data. This is a big problem.

(ii) Qubit computing runs are highly susceptible to "noise" from the electronics and other equipment, not to mention vibration, which cause errors in the results and accentuate de-coherence. Unfortunately, the longer the qubit chain and their electronic baggage, the higher the error rate. A qubit optimally needs absolute silence – and be vibration free.

(iii) Finally, the qubit, its magnetic housing, and all the electrical and electronic circuitries necessary to work it and read out the answers, must function in cryogenic conditions.

(iv) The qubit is therefore very fragile. In addition to probabilistic variations, these external factors add to the margins of error. The saving feature is that, taken to the macroscale, the results are perfectly acceptable.

(v) The growth of a quantum computer is directly dependent on controlling or eliminating noise. Let it be said here: noise grows with scale. At present, the noise-decoherence factor is the single biggest obstacle to the growth of the quantum computer to the massive levels where quantum computing can fulfil its incredible potential.

Quantum System

The internal control structure of a quantum computer usually (but not always) follows the classical model. Qubits are usually coupled. Whether single or coupled or where there are more of them strung together, they form a set or an array when they are controlled by one **quantum gate.** The quantum gate is the **unit channel of instruction.** Quantum gates in turn may stand alone or be grouped together to form a **quantum circuit** or **quantum register.** The latter may yet be further hooked up to work together as larger sets of circuits or registers. A set, a quantum circuit or a quantum register may be programmed as a **quantum system.**

Quantum State

Under classical physics, we speak of a particle or object having a mass at rest or in motion. In QM, they speak of "quantum state", which is a "mathematical construct of a quantum entity that provides a probability distribution of the outcomes for each possible measurement of each characteristic of a quantum system."

By way of elucidation:

(i) An elementary particle like a quark possesses intrinsic characteristics such as mass, electrical charge, spin and colour, and may additionally possess "situational" characteristics such position, momentum, and polarisation. These features together represent its **quantum state**. A particle is usually just one item making up the quantum state of a quantum system.

(ii) In "layman's terms", a quantum state is simply something that encodes the state of a system. The special thing about quantum states is that they allow the system to be in a few states simultaneously, that is called "quantum superposition”.

(iii) A quantum state may also be understood as a vector that contains all the information about a system.

Quantum Superposition

This is the “heart of quantum mechanics”. The fundamental principle formally expressed states that, much like waves in classical physics, any two (or more) quantum states can be added together ("superpositioned") and the result will be another valid quantum state; and conversely, that every quantum state can be represented as a sum of two or more other distinct states.

By way of elucidation:

(i) The features of “superposition” have been explained above under “Qubit”. Every additional qubit increases the number of simultaneous computational states arithmetically but increases the **computing power exponentially**.

(ii) This is the definitive explanation why there is superposition: “Quantum superposition arises because, at the quantum scale, particles behave like waves. Similar to the way in which multiple waves can overlap each other to form a single new wave, quantum particles can exist in multiple overlapping states at the same time.”[22]

(iii) For an exotic example from wave-particle theory, an electron orbiting an atom does not sit at a definite point in space like the earth does as it orbits the sun. Rather, it gets smeared out into a cloud of possibilities called an orbital. That orbital cloud is really a three-dimensional quantum wave, with

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22 https://phys.org/news/2018-12-quantum-superposition-revivals.html

peaks and valleys that fluctuate in time and represent the chance of finding an electron at a particular spot. The shape of this wave changes depending on the electron's energy. It is possible to create a superposition in which two quantum waves—representing two electron energy levels—get added together, which leads to a new pattern of peaks and valleys. This changes where the electron is most likely to be found and can affect the physical properties of an atom.

Wave Particle Duality

The wave function of a particle does not have a single, well-defined frequency. It is composed of a **superposition of states**, each with its own frequency. These are called "stationary states" or "energy eigenstates", and they are the states of definite energy.

If the wave function is taken as a superposition of energy states (eigenstates), the expected values of the quantities associated with the particle will oscillate back and forth. The details of these oscillations are determined by the relative frequencies of the states of which the wavefunction is composed.

By way of elucidation, the following may be helpful:

(i) In quantum physics**, wave and particle are two properties of the same physical identity.** For example, light is a wave and a particle, but the physical phenomenon it is subjected to determines which property will appear . In the photoelectric effect, the photon, as a particle-like property of light (quantum) will collide with the metal electron ejecting it with certain kinetic energy, while its wave component flows through the slits in the metal.

Quantum Entanglement

This is the “power” of the quantum mechanics. It is a physical phenomenon that occurs when a pair or group of particles is generated, interact, or share spatial proximity in a way such that the quantum state of each particle of the pair or group cannot be described independently of the state of the others, including when the particles are separated by a large distance.

Groups of independent qubits, by themselves, are not enough to create the massive breakthroughs that are promised by quantum computing. The magic starts when the quantum physics concept of entanglement is implemented. **One industry expert likened qubits without entanglement as being a “very expensive classical computer.”**

Entangled qubits affect each other instantly, no matter far apart they are, based on what Einstein euphemistically called “spooky action at a distance.” In terms of classic computing, this is a bit like having a logic gate connecting every bit in memory to every other bit.

As a result, there are multiple large potential gains from entanglement. The first is a huge increase in the complexity of programming that can be executed, at least for certain types of problems. One that’s creating a lot of excitement is the modeling of complex molecules and materials that are very difficult to simulate with classical computers. Another might be innovations in long-distance secure communications — if and when it becomes possible to preserve quantum state over large distances.

Programming using entanglement typically starts with the C-NOT gate, which flips the state of an entangled particle if its partner is read out as a 1. This is sort of like a traditional XOR gate, except that it only operates when a measurement is made."[23]

By way of elucidation:

.(i) Any time one can bring two systems together in such a way that the final state of one particle depends on the input state of the other, one can make an entangled state, by making that input state a quantum superposition.

(ii) If two qubits are linked through entanglement, they can be placed in superposition together, similarly three qubits, eight calculations; and so on.

.(iii) A change in one quantum system affects its entangled partner instantly, however distant. There is no physical transmission of matter, only information – of and within the internal quantum state. No external information is involved. There is no way to use quantum entanglement to send messages faster than the speed of light. There have been some experiments of "teleportation" of information. So far, physicists have only managed to distribute entangled particles over a distance of up to 100 kilometers.

.(iv) There is really no physical connection between two entangled particles. When you collapse one particle, the entanglement is destroyed. It doesn't collapse the other particle. You can only demonstrate their correlations by collapsing the two particles simultaneously. Only by joint measurement can entanglement become evident. So, no info or influence is transferred. They are just correlated.

Given above, the cause of correlations could be the "parent" wavefunction of the entangled particles. There are two possible states. up and down. With the absence of a physical connection, the only viable "variable" to correlate two spins is

[23] https://www.extremetech.com/extreme/284306-how-quantum-computing-works

their phase relation. The wavefunctions of two entangled particles must have retained some coherence with their phases so that they rotate in perfect phase.

> "To make an intuitive illustration, consider two coins endlessly spinning on the table. We know each has two possible outcomes if we stop the coin from spinning, a head or a tail. But while spinning, each has no definitive state; i it is not head nor tail yet. If we stop the two coins from spinning by laying the left and right hand simultaneously on top of the coins, we always get a correlated result. one coin is head and the other is tail regardless how many times we do it. In this case, there is no physical connection between the coins to cause correlation. There is no need for one. The only condition is that the two coins spin in perfect phase with each other. A perfect phase means for the coins to have same mass, same rate of spin and same starting point. The only thing different is the opposite spin of one over the other. Under these conditions, when simultaneously measured, the outcome will always remain the same."
> (I'll recruit this guy. I understand it.)"
>
> Vic Alcabasa
> BS Electrical Engineering, University of Santo Tomas, Manila
> Answered 16 June 2018
> From Quora[24]

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24 https://www.quora.com/profile/Vic-Alcabasa

Quantum Computer Growth Path

Development Path

The quantum computer is a giant by DNA, but embryonic in its development.

When fully unfolded of its nature, the quantum computer will be a Titan. Fortunately, information technology (IT) developed under Q1, particularly the supercomputer, has provided us with a sufficient platform of technological knowledge and experience to gestate it. We have made a start. I can hardly believe it, but I am confident we shall at some stage see Titans[25] among us. We might want to call the first one Prometheus, the Titan who gave mankind fire. This one will give us the universe.[i]

It is said the euphoria for the quantum computer has gone over the top and only the optimists, romantics and hard heads are battling to build one, fuelled by the continued competing investments to gain possible defence and strategic advantages from this machine. I am with the optimists and romantics. Like many, I believe Moore's Law has run its course with the supercomputer, and we need a quantum leap.

I cannot imagine anything that could be more beneficial to mankind in the long-term: the next great Gift of God. If we are ever meant to do so, the quantum computer is the nearest thing we have stumbled upon that will give us the power to crack the door and enable us to simulate (and indeed re-construct) matter, and even biology. If we are destined to travel in space, this will do it. If we master the Titan, we will on earth be able to do simple things like making photosynthesis, irradicate cancer, and re-cap the poles. Technically, I am told,

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[25] In Greek mythology, the Titans were the 12 children of Uranus (Heaven) and Gaea (Earth), the original family of gods. Jupiter (Zeus), who ruled Olympus, was a descendant.

we are close to being able to put a billion bits into a conventional chip. All we need, for a start, is to control a million qubits. And that will be a great beginning.

However, a touch of realism is not out of place here. Below I include quotes from Mikhail Dyakonov, born in 1940 in Leningrad, Professor of Physics at Universite Montepellier, France

> "While I believe that such experimental research is beneficial and may lead to a better understanding of complicated quantum systems, I'm skeptical that these efforts will ever result in a practical quantum computer. Such a computer would have to be able to manipulate—on a microscopic level and with enormous precision—a physical system characterized by an unimaginably huge set of parameters, each of which can take on a continuous range of values. Could we ever learn to control the more than 10,300 continuously variable parameters defining the quantum state of such a system? My answer is simple. No, never."
>
> From His article-critique in IEEE Septrun,
> 15 Nov 2018.[26]

Critical Components

When it eventually takes full shape, the quantum computer, like the current generation classical computers, can be expected to have the following main component parts:

(i) computational component
(ii) memory and storage component,
(iii) I/O, controllers and peripherals, and
(iv) the communications components.

Since the quest for the quantum computer proper began in Q2, almost the entire the effort has been on **getting the**

[26] https://spectrum.ieee.org/computing/hardware/the-case-against-quantum-computing

computation component going. Quite simply, no computational core, no quantum computer.

There have been enormous difficulties. Despite the investments, resources and research energies deployed, we are a long way from the first flagpole. In Q2, I focus on how far we are likely to get within touching distance of a first decently working computational model. In Q3, we look a little further over the horizon for a possible glimpse of the giant – and put a date on it.

Critical Features

The growth (scalability) of the quantum computer is limited by the inability of present technology to overcome these four factors, the abiding situation being that the more qubits are added the larger these limitations grow:

1. Rapid de-coherence of the qubit after a job.
2. De-coherence due to measurement and vibration.)
3. Increasing noise-created errors from lengthening qubit chain and electronic circuitry
4. Need for cryogenic conditions

The overriding difficulty of quantum computing is how to maintain the delicate states of superposition and entanglement over a long chain of qubits for a long enough time to run a calculation and measure it - the so-called coherence time. The more qubits are added, the greater the instability. The more the error-correction drag on the system, the slower the computer's performance.

After a decade, these critical issues have not been demolished, only abated by stop-gap measures. In Q2, they have been choking progressive growth, forcing resort to brute force, and acceptance of a "Noise Intermediate-Scale Computing" **(NISQ) era.**

Intermediate Stages

There will be intermediate stages. We can see some now.

Private enterprise has led the way. Without government and institutional investments behind them, their target has been to achieve a rate of return as soon as possible: how to make a quantum product or service that will be much valued and sell as quickly as possible. Not surprisingly the "startups" with no baggage have led the way.

One private startup company identified optimisation and developed a clear-cut limited annealing process[27] for its qubits to do just that. The runs were reasonably efficient, and the results good. They latter were exactly what the market wanted. They were the first in the market and have been making money from the word go. They have even outstripped IBM in the number of qubits deployed.

The second private startup company decided to go small and hybrid. They focused on a computational core of limited qubits, and they built a reasonably performing machine quickly. Their objective was to offer the medium-scale market a hand-held service to incorporate quantum computing wherever feasible in their client's existing productive set-up and expand from the inside. They decided to go "full stack". They built their own IC fabrication plant, they customised software and algorithms for their machine, and they involved their customers in the analysis of needs, framing the outputs and programming the computer. Their banner was "company-based service." Finally, they put their computer services on the cloud, through their computer can be integrated into any public, private or hybrid cloud. I could not determine how many clients they have and whether they have broken even so far, but as Q2 ends they are going to be in partnership in UK setting up the first quantum computer in that country, and

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[27] Annealing = a quantum system set up and programmed to run down to its lowest (optimised) energy) state.

presumably promoting their trade package of quantum services.

Three other major industrial conglomerates have also developed in-house quantum computational cores, following the general lines of development of the industry. Their objective will be to pioneer applications in their respective areas, one of them in AI. To the extent they are successful, it will foster other industries and companies to do the same to reap the intermediate stage benefits of quantum computing, and fuel overall investment.

The main stayers of the computer industry, indeed the "institutions of computing", namely IBM, Intel and Microsoft, have taken a broader view. And so have a wide range of other academic and research centres. This sector is focused on creating a "universal computer" and solving the long-term issues. IBM is the only one so far with a free-standing machine, leading on a broad front, but still institution and research based. The others are still researching the qubit and the chip. So far it is pure investment with this sector.

So much is now clear. The supercomputer will for a long time serve as the front-end and the backend of the quantum computer. The latter will progressively take on more and more of the "intractable" computing as the scale and complexity of computing requirements grow. Ultimately, the quantum computer will swallow both ends and push the frontiers forward.

The Long Term

To get out of the NISQ era, we need to get the error rate down by a factor 10-100 (as of 2019) to around $0.10^{-3.}$ The coherence time will relate directly to this,

The operation target for a gated system by 2023 (again IBM) is 1,232 qubits. By the end of the decade (2030), we need to get to 10,000 qubits, if we are to have any hope of seeing 1,000,000 qubits in action in the decade beyond.

As the computational core takes shape, the industry will address the other components, and I have not bothered with them – except for Memory and Storage. I touch on this under Q3.

It is likely, that there will be a trail of intermediate **hybrid computers,** of growing sizes and numbers, in different sectors, for different uses - even when the Titans are walking around. I cannot see that there will be more than a few of these around even then – but how wrong was Thomas Watson of IBM when in 1943, he predicted that there was a world market “for maybe five computers.” I am optimistic enough to suggest that, at the small end, we might have quantum chips in our smartphones. Even if we never achieve the quantum computer of our dreams, the hybrids will have taken us a long way forward.

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Features of the Quantum Computer

Structure of Computational Component. (Optional reading)

The following is a re-cap/synthesis of what may be called the "mainstream" model, as it is emerging:

In simple terms (in *nano* scale):

1. The computational unit itself is the qubit, with the working particle inside.
2. Qubits are coupled together, commonly in chains, sets or arrays of 2,4 up to 16, etc.
3. Sets are further coupled to form a processor, the number of sets depending.
4. Processors are further coupled together to form a Quantum Processing Unit (QPU), the number of processors again depending.
5. The QPU is reduced to a chip.

Whatever the design (in the *nano* sale):

1. Each working particle is held by means of a magnetic field, presumably the same field for all qubits.
2. Each working particle is programmed by and must be accessible to an electrical pulse, which in turn must be supplied from an external source, with appropriate delivering mechanisms.
3. Each working particle must have a readout facility, appropriately magnified to macroscale.
4. Each qubit must have lead-in and lead-out circuits and mechanisms to couple with its neighbours.
5. Every qubit must have de-coherence and noise abatement controls, usually built into the electronics, and with qubits deployed from the calculating array for this purpose.

Since, all qubits must work together, this implies cross-connectivity (in *nano* scale):

1. Through quantum gates, junctions and couplings, between sets, processors (and therefore within the QPU).
2. Couplings require mechanisms to programme them, and noise controls, and the relevant energy supplies.

Finally (in *nano* scale),

1. The above has to be settled in a cryogenic environment. (This environment is separately required for several of the earlier stages or work.)

For our purposes, we need not go further, but for information,

2. The computer's total functionality must be designed with the necessary circuitry, incorporating the QPU, and the non-computing peripherals such as the controllers, memory banks, storage, stacks, registers, caches, etc.
3. The whole has to be mounted in in the computer in whatever form the manufacturer adopts, ie PCBs, etc.

Choosing the Qubit (Optional reading)

All qubit activity takes place in cryogenic conditions, with temperatures near absolute zero. This applies to everything following in this section.

(i) Elementary particles

From the beginning, the industry has proceeded along the lines of identifying suitable materials from which, and within which, to trap and manipulate a suitable elementary particle as the working particle. Some of these have been

1. electron spin in silicon
2. electron orbitals in quantum dots,
3. electron spin in magnetic resonance,

4. nuclear spin of impurity atoms,
5. trapped ion in silicon
6. trapped ion in diamond Nitrogen Vacancy (NV) centre,
7. majorana (anyon sub-particle) in topological qubit;

The "trapped ion" is emerging (up to this point) as the best prospect for a particle-version of the quantum computer. There are already two tangible first generation computational cores of this version put out by manufacturers. I therefore include this extract to give a profile of it:

> "A trapped ion quantum computer is one proposed approach to a large-scale quantum computer. (An ion is a particle, atom or molecule with a negative electrical charge.)
>
> Ions or charged atomic particles, can be confined and suspended in free space using electromagnetic fields. Qubits are stable electronic states of each ion, and quantum information can be transferred through the collective quantized motion of the ions in a shared trap.
>
> Lasers are applied to induce interactions between the internal qubit states and the external motional states (for entanglement between qubits).
>
> Currently highest accuracy is achieved in trapped ion systems. Promising schemes to scale the include transporting ions to spatially distinct locations in an array of ion traps, building large entangled states via photonically connected networks of remotely entangled ion chains, and combinations of these two ideas.
>
> This makes the trapped ion quantum computer system one of the most promising architectures for a scalable, universal quantum computer." (Edited) [28]

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28 https://en.wikipedia.org/wiki/Trapped_ion_quantum_computer

(ii) Superconducting Circuits

The year 1999 was remarkable in that Yasunobu Nakamura and Jaw-Shen Tsai of NEC Japan, successfully demonstrated that a **superconducting**[29] **c**ircuit could be used as a qubit. This led to a global effort to develop quantum computers using superconducting circuits.

As a result, we have a new generation of "artificial atoms" or variants of superconducting qubits in use as qubits, of which the following are the most relevant:

1. Superconducting Cooper-pair box charge qubit (early model, now integrated in Nos 2 and 3)
2. Superconducting charge qubit (Transmon)
3. Superconducting flux superconducting loop qubit

The **transmon qubit** has been adopted by IBM and three others who have with their own variations produced a computational core. It represents the major qubit variant in use the industry, I therefore capture the following by way of explanation:

> "A transmon is a type of superconducting charge qubit, adopted (by IBM) as the working particle in place of the conventional elementary particle. A charge qubit[4] is formed by a tiny superconducting "island" (hole), coupled by a Josephson junction to a superconducting reservoir. The state of the qubit is determined by the number of Cooper pairs which have tunneled across the junction. The quantum superposition of charge states can be achieved by tuning the gate voltage that controls the chemical potential of the island. The charge qubit is typically read-out by electrostatically coupling the island to an extremely sensitive electrometer. (Wikipedia)"

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29 Superconductivity is a cryogenic feature. Unlike an ordinary metallic conductor, whose resistance decreases gradually as its temperature is lowered even down to near to absolute zero, a superconductor has a characteristic critical temperature below which the resistance drops abruptly to zero. An electric current through a loop of superconducting material can persist indefinitely with no power source (Wikipedia edited).

The **superconducting loop flux qubit** is the second artificial qubit variant used by two manufacturers who have produced a computational core. I capture the following for a better understanding of it:

> “Flux qubits (also known as persistent current qubits) are micrometer sized loops of superconducting metal interrupted by a number of Josephson junctions. These devices function as qubits. The flux qubit was first proposed by Terry P. Orlando et al. at MIT in 1999 and fabricated shortly thereafter.
>
> During fabrication, the Josephson junction parameters are engineered so that a persistent current will flow continuously when an external magnetic flux is applied. Only an integer number of flux quanta are allowed to penetrate the superconducting ring, resulting in clockwise or counter-clockwise mesoscopic flow in the loop to compensate for any non-integer external flux bias. When the applied flux through the loop area is closed to a half integer number of flux quanta, the two lowest energy of the loop will be a quantum superposition of the clockwise and counter-clockwise currents.
>
> The two lowest energy eigenstates differ only by the relative quantum phase between the composing current-direction states. Higher energy eigenstates correspond to much larger (macroscopic) persistent currents, that induce an additional flux quantum to the qubit loop, and thus are well separated energetically from the lowest two eigenstates. This separation, known as the "qubit nonlinearity" criteria, allows operations with the two lowest eigenstates only, effectively creating a two-level system. Usually, the two lowest eigenstates will serve as the computational basis for the logical qubit.
>
> Computational operations are performed by pulsing the qubit with frequency radiation which has an energy comparable to that of the gap between the energy of the two basis states. Properly selected pulse duration and strength can put the qubit into quantum superposition of the two basis states while subsequent pulses can manipulate the probability weighting that the qubit will be measured in either of the two basis states, thus performing a computational operation. (Wikipedia edied)

(iii) Josephson junction

For a superconducting circuit to function as a qubit, there needs to be a non-linear junction. Josephson junctions are the only electronic element that are non-linear as well as non-dissipative at low temperatures

> “The Josephson junction is essential in the construction of superconducting qubits, and of course operates in the same temperature environment where superconductivity takes place.
>
> A Josephson junction is made by sandwiching a thin layer of a non-superconducting material between two layers of superconducting material. The device is named after Brian Josephson, who predicted in 1962 that, given the conditions, pairs of superconducting electrons could "tunnel" right through the non-superconducting barrier from one superconductor to another.
>
> It is a basic feature of superconductivity that, in many metals and alloys if cooled to very low temperatures (within 20 degrees or less of absolute zero), a phase transition occurs. At this "critical temperature," the metal goes from what is known as the normal state, where it has electrical resistance, to the superconducting state, where there is essentially no resistance to the flow of direct electrical current.
>
> What occurs is that the electrons in the metal become paired. Above the critical temperature, the net interaction between two electrons is repulsive. Below the critical temperature, the overall interaction between two electrons becomes very slightly attractive, a result of the electrons' interaction with the ionic lattice of the metal.
>
> This very slight attraction allows them to drop into a lower energy state, opening up an energy "gap." Because of the energy gap and the lower energy state, electrons can move (and therefore current can flow) without being scattered by the ions of the lattice. There is no electrical resistance in the superconductor, and therefore no energy loss. There is one other important property: when a metal goes into the superconducting state, it expels all magnetic fields, as long as

> the magnetic fields are not too large.
>
> Josephson junctions can also be fashioned into circuits called SQUIDs--an acronym for Superconducting Quantum Interference Device. These devices are extremely sensitive and used in constructing hyper-sensitive magnetometers and voltmeters. A SQUID is extremely sensitive to the total amount of magnetic field that penetrates the area of the loop and is used tomeasure the results of a quantum computer run." (Edited)[30]

(iv) Silicon Chip

The computer industry (Q1) has grown up in silicon. There is extensive gate and circuit design experience that can be applied, and the industry has the infrastructure to fabricate and manufacture Quantum Processing Unit (QPU) chips in silicon. This gives a clear pathway to up-scaling. The choice of silicon also points to the way towards having a solid-state stand-alone quantum computer earlier.

Superconducting qubits are fabricated using techniques similar to those used for microelectronics. The devices are usually made on silicon or sapphire wafers. The flux qubit is distinguished from the charge qubit by the coupling energy and charging energy of its junctions. In the charge qubit regime, the charging energy of the junctions dominates the coupling energy. In a flux qubit the situation is reversed and the coupling energy dominates. Typically for a flux qubit the coupling energy is 10-100 times greater than the charging energy which allows the Cooper pairs to flow continuously around the loop, rather than tunnel discretely across the junctions like in a charge qubit. All this is embedded in the chip.

The whistle has yet to be sound which particle-based qubit will predominate. Various metals are being tested. But it is not

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30 https://www.scientificamerican.com/article/what-are-josephson-juncti/

clear to me whether they are for the “housing” only of the working particle, while the final qubit will also go in a silicon chip. To the extent the trapped iron will predominate, the final computational core will be embedded in a silicon chip. I have not noticed alternative discussion on this subject.

Quantum Gates and Circuits

The quantum gate and quantum circuit are like those used in classical computers. Their function in the quantum computational core is the same as in the classical computer, namely as instructional controls. They have been adopted in all quantum computers except in the annealing quantum computer. They apply in both particle-based and superconducting qubit cores.

The **quantum gate** is the basic unit of activation, instruction, or operation, on one or several qubits. it determines the transformation that the one or more qubits will experience after the gate is applied on them, given their initial state. They are the building blocks of quantum circuits, like classical “logical gates” and are best thought of in structural terms as sets.

The **quantum circuit or register** in turn is a sequence of quantum gates, which are “reversible transformations on a quantum-mechanical analog of an n-bit register”. The analogous structure is referred to as an “n-qubit”. The quantum computer performs calculations by switching electrical micro-pulses by means of quantum gates applied on qubits within a quantum circuit or register. To make a computer do what is wanted, one programmes or re-programmes the quantum circuits. The quantum circuit can be thought of, in structural terms, as a large set, or even a (small) quantum system.

The **quantum logical gate** is altogether different. It is the unit or ratio that reflects the total number of gates actually operational on calculating duties, after deducting the qubits and gates diverted for error-correction purposes. As may be surmised, the more gates there are the more noise there is.

Algorithms

> "An algorithm is a finite sequence of well-defined computer-implementable instructions, to solve a class of problems or to perform a computation. Algorithms are used as specifications for performing calculations, data processing, automated reasoning and other tasks.
> Starting from an initial state and initial input (perhaps 'empty), the instructions describe a computation that, proceeds through a finite number of well-defined successive states, eventually producing "output" and terminating at a final ending state. The transition from one state to the next is not necessarily deterministic; some algorithms, known as "randomised algorithms", incorporate random input. (Wikipedia edited.)

The efficacy of the quantum computer will be determined by the algorithms created. It may be said that, at the far end, the limit of the usefulness of the quantum computer will be how man learns to talk to it.

At this moment, the baby-giant can hardly do more than one run, collapsing immediately. There has been no mention of tandem computing as far as I can see.

Miniturisation and de-Cryonisation

The industry is confident with current technology of slamming one million qubits on to a chip, say the size of a plate or less. We shall leave them to worry about one billion qubits, which is still not the full technical potential stature of the Titan. Making smaller-scale use of him will be of greater short-term value.

More relevant is that the Titan's habitat appears to be the sub-zero world, somewhere beyond Pluto. De-cryonising him must be a major target if the quantum computer is going to live among us humans and benefit us in hybrid and other ways.

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Quest for the Quantum Computer

The DiVincenzo list

In the year 2000, David DiVincenzo. an IBM researcher, brought a unifying framework to the embryonic technologies being explored, with his list of criteria. They were:

1. **A scalable physical system with well characterised qubits**.
   We not only have to have a single decent qubit, but we also need the ability to create a set of them.

2. **The ability to initialise the state of the qubits to a simple fiducial state.**
   This is the equivalent to the reset button on your computer. If you can't create a clean slate to start with, it's hard to run any sort of programme.

3. **Long relevant decoherence times**.
   If you can't keep data in memory, you can't compute on it. This has a strong relationship to quantum error correction.

4. **A "universal" set of quantum gates.**
   For a quantum computer to be completely general, you must be able to execute any algorithm asked of you.

5. **A qubit-specific measurement capability.** If you can't read the results out, a computer is useless!

6. **The ability to interconvert stationary and flying qubits.**
   In order to transfer data over long distances, we need

to be able to convert from data held in something stationary (like a computer chip) to light (photons).

7. **The ability to faithfully transmit flying qubits between specified locations**.
   Obviously, we also need to be able to move those photons from one place to another with reasonable fidelity!

The first five are known as DiVincenzo's computation criteria, and the last two as his communication criteria, but many scalable quantum computer designs involve connecting smaller computers together, so the communication criteria are important for computing as well.

Pioneer Steps

Quantum superposition and quantum entanglement were first identified in theoretical terms as early as 1935 by Erwin Shrodinger. By 1976, Roman S. Ingarden published the first attempt at a Quantum Information Theory.

Not surprisingly, the US took the lead. The First Conference on the Physics of Computation was held at MIT in May 1980. Paul Beniof demonstrated that computers could operate under the laws of quantum mechanics. Richard proposed a basic model for a quantum computer

In 1988, YoshihisaYamamoto and K. Igeta, two scientists, proposed the first physical realization of a quantum computer. Their approach used atoms and photons and was the progenitor of modern quantum computing and networking protocols.

In 1991, Artur Ekert at Oxford expanded on earlier proposals for entanglement. In 1992, David Deutsch and Richard Jozsa proposed a computational problem that could be solved efficiently on a quantum computer, but for which no classical algorithm was possible. This was the earliest demonstration of the complex computational potential of the quantum computer.

The year 1994 was something of landmark. At the AT&T Bell Labs in new Jersey, one Peter Shor invented another algorithm that enabled a quantum computer to factor large integers quickly. It appeared **Shor's algorithm** could theoretically break many of the cryptosystems in use then. It sparked tremendous interest in quantum computers

US Government Initiatives

Within the year. the US National Institute of Science and Technology (NIST) organised the first Government workshop on quantum computing. Two scientists, Isaac Chuang and Yoshihisa Yamamoto, proposed a quantum-optical realization of a quantum computer.

The year 1995 saw the first US Department of Defence workshop on quantum computing and quantum cryptography, at the University of Arizona. In the same year Peter Shor proposed the first schemes for quantum error correction, and Benjamin Schumacher coined the term **"qubit**"

The year 1996 saw Lov Grover at Bell Labs invent the quantum database search algorithm. The speedup of the latter was not as dramatic as for factoring, discrete logs, or physics simulations. However, the algorithm could be applied to a much wider variety of problems.

And finally, in that year, the US Government, in a joint partnership of the Army Research Office and the National Security Agency (NSA), issued the **first public call for research proposals in quantum information processing**. At about the same time, IBM proposed a list of minimal requirements for creating a quantum computer

The year 1997 saw several key technical developments. On 1 January 1998 Daniel Loss of Basel University, Switzerland

and David P DiVincenzo of IBM published their landmark proposal: "We propose an implementation of a universal set of one- and two-quantum-bit gates for quantum computation using the spin states of coupled single-electron quantum dots. Desired operations are affected by the gating of the tunneling barrier between neighboring dots. Several measures of the gate quality are computed within a recently derived spin master equation incorporating decoherence caused by a prototypical magnetic environment."

The same year also saw researchers at MIT publish papers realizing gates for quantum computers based on the nuclear magnetic resonance (NMR), similar to the medical MRI machine. Another described the principles of topological quantum computation as a method for combating decoherence. Liquid state NMR Quantum Information Processing was also first theoretically introduced.

Initial Computing Efforts

The year 1998 saw Isaac Chuang of the Los Alamos National Laboratory, Neil Gerstenfeld of MIT and Mark Kubinec a at Berkeley create the **first quantum processor** (2-qubit) that could be loaded with data and output a solution.

The year 1999 saw a demonstration of the basic concepts of **quantum annealing** in a condensed matter system, as an alternative concept for quantum computing.

The year was remarkable that Yasunobu Nakamura and Jaw-Shen Tsai at NEC in Japan successfully demonstrated that a **superconducting c**ircuit could be used as a qubit.

In the year 2001, IBM reported the successful implementation Shor's algorithm in a 7 qubit Nuclear Magnetic Resonance (NMR) quantum computer. However, it was recognized that NMR quantum computer would never be very useful due to the poor signal to noise ratio and its liquid state computing did not possess entanglement properties.

ARDA Road Mapping Project, 2002-4.

This initiative was taken by the Advanced Research and Development Activity **(ARDA),** an agency of the US Department of Energy, with the issue of the **Quantum Information Science and Technology Road Mapping Project Report** drawn up by a widely represented but mainly US Technology Experts Panel in 2002 –updated 2004[31].

It focused on the **nine** critical areas mentioned below, with detailed analyses of each of the areas. This included the current status of work, targetted work, other requirements not yet addressed, the researchers engaged in world-wide, extensive resource references, and desired time-frames.

Section 6.1: Nuclear Magnetic Resonance Approaches to Quantum Information Processing and Quantum Computing

Section 6.2: Ion Trap Approaches to Quantum Information Processing and Quantum Computing

Section 6.3: Neutral Atom Approaches to Quantum Information Processing and Quantum Computing)

Section 6:4 Cavity QED Approaches to Quantum Information Processing and Quantum Computing

Section 6.5: Optical Approaches to Quantum Information Processing and Quantum Computing

Section 6.6: Solid State Approaches to Quantum Information Processing and Quantum Computing

Section 6.7: Superconducting Approaches to Quantum Information Processing and Quantum Computing)

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31 https://qist.lanl.gov/qcomp_map.shtml Last updated 2009.

Section 6.8: "Unique" Qubit Approaches to Quantum Information Processing and Quantum Computing

Section 6.9: The Theory Component of the Quantum Information Processing and Quantum Computing

This was probably the single most important step providing coherence and confidence in the developments that followed. The project called for a Mid-Term review in 2007 and a Term Review in 2012

It is interesting that the Canadians, Europeans, Chinese and Japanese were not included – only one Australian. The US obviously intended to control the initiative. After all they were paying for it.

The Decade that Followed

Within the year 2002. the initiatives began to spread out, and the following institutions were set up:

1 The Institute for Quantum Computing, University of Waterloo, Ontario
2 The US Defense Advanced Research Projects Agency (DARPA), and
3 The Institute for Quantum Optics and Quantum Information, (IQOQI), Innsbruck and Vienna, Austria,

In the years 2004 to 2012, the first fruits would follow, vide this selection, inter alia:

1 In the year 2004, the first working pure state NMR quantum computer was demonstrated at Oxford University and Yok University
2 In the year 2004, the first five-photon entanglement demonstrated at the University of Science and Technology of China

3 In the year 2005, the first quantum “byte[32]” was announced to have been created by scientists at Innsbruck

4 In the year 2006, University of Copenhagen developed quantum teleportation between photons and atoms

5 In the year 2007, University of Cambridge developed an electron quantum pump.

6 In the year 2007, D-Wave, a Canadian company (in joint venture with Canadian universities) launched their prototype 16- qubit quantum annealing processor at the Computer History Museum in Mountain View, California

7. In the year 2009, the NIST ran the first universal programmable quantum computer at Boulder, Colorado

8 In the year 2012, 1QB Information Technologies, Inc (1QBit), a Canadian software company based in Vancouver, established hardware partnerships with Microsoft, IBM, Fujitsu and D-Wave Systems. While 1QBit developed general purpose algorithms for quantum computing hardware, the organization primarily focused on computational finance, material science quantum chemistry and life sciences.

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[32] A quantum “byte” is eight qubits.

The Quantum Computer is Born

D-Wave Systems Inc (Canada)

D-Wave Systems, Inc., a startup private Canadian company, was the first off the blocks to make a quantum computer. They were founded in 1999 and are based in Burnaby, British Columbia, Canada. They collaborated with several Canadian universities and institutions, including UBC on whose campus they started, until 2005.

The company implemented their own technology developed from Canadian research in condensed matter physics. They targetted the market for optimisation, which was a common problem in large-scale industry.

They further focused on a process called **quantum annealing** that harnessed the natural tendency of the real-world, including quantum systems, to find low-energy states. The company explained,

> “If an optimization problem is analogous to a landscape of peaks and valleys, each coordinate represents a possible solution, and its elevation represents its energy. The best solution is that with the lowest energy corresponding to the lowest point in the deepest valley in the landscape.”

They struck paydirt. One outcome was that they were it was able to couple and use many more qubits than the others. While they would, with a dedicated machine and no competition, be able to satisfy the customer, and they have been the most successful in fact, I have not been able to judge their technical efficiency in tackling all the known difficulties of qubit computing.

TECHNICAL NOTE[33]

D- Wave has adopted the superconducting loop design for its qubit. The qubit's states are set by means of Josephson junctions which control the circulating superconductor electric circuit. Qubits are coupled to one another and inter-communicate. Computers are programmed by setting the "bias" (state) of the qubit and a "weightage" (loading) to the coupler.

"When we use a coupler, we are using another phenomenon of quantum physics called entanglement. When two qubits are entangled, they can be thought of as a single object with four possible states.

…..In summary, we start with a set of qubits, each in a superposition state of 0 and 1. They are not yet coupled. When they undergo quantum annealing, the couplers and biases are introduced, and the qubits become entangled.

The relative energy of each state depends on the biases of qubits and the coupling between them. During the anneal, the qubit states are potentially delocalized in this landscape before finally settling into (1,1) at the end of the anneal."[34]

Dedicated Task Computer - Optimisation

On May 11, 2011, D-Wave Systems announced the **D-Wave One**, an integrated quantum computer system running on a 128-qubit processor with 352 couplers. The D-Wave One was the world's first quantum computer.

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33 https://www.dwavesys.com/tutorials/background-reading-series/introduction-d-wave-quantum-hardware

34 https://docs.dwavesys.com/docs/latest/c_gs_2.html#states. There are some 128,000+ Josephson junctions in the D Wave 2000Q with its a 2048-qubits and 6016 couplers

The processor was essentially a specialised machine. Its selling points were first, it solved the customers' optimisation requirements to their satisfaction; secondly, on the evidence the company looked technologically efficient and dependable, and thirdly they produced results - fast. And, finally, the service was available on the spot -the ultimate key to competitive advantage. D-Wave had to be a full stack quantum computing company since no one else was selling this product.
A research team found that, while there was evidence of quantum annealing in D-Wave One, they saw no speed increase compared to classical computers.

On May 25, in the same year. Lockheed Martin signed a multi-year contract with D-Wave to address some of its most challenging computation problems.

In the year 2013, the processor was superseded by the **D-Wave 2**, with a 512-qubit processor and 1,472 couplers.

In June 2014, D-Wave announced a new quantum application "ecosystem" with a computational finance company IQB Information Technologies (IQB), and cancer research group DNA-SEQ.

On August 20, 2015, D-Wave released general availability of their **D-Wave 2X** computer, with 1152 qubits and 3360 couplers. This one explicitly stated that quantum speedup was not something they were trying to address. They focused instead on constant-factor performance gains over classical hardware.

In January 2017, **the D-Wave 2000Q** was released. Its processor was based on a 2048-qubit chip with 6016 couplers.

Some of D-Wave's customers included Google, NASA, the Los Alamos National Laboratory, University of Southern

California and the Universities Space Research, Association (USRA).

Advantage – Built for Business

In February 2019 D-Wave announced their next-generation **D-Wave Advantage** quantum processor. It would be "the world's most connected commercial quantum system," with 15 connections per qubit instead of 6; that the next-generation system would use the **Pegasu**s chip; that it would have more than 5000 qubits and reduced noise; and that it would be available in mid-2020.

Advantage would have 1 million Josephson junctions, compared to 120,000 in the 2000Q. The new chip topology would enable the embedding larger problems with fewer physical qubits, than the 2000Q topology. Advantage would allow for 2.5x larger-sized problems to run directly on the quantum computer. This would open a frontier of new and innovative uses across a wide range of technology sectors."

D-Wave have been marketing the new machine as "built for business". There is no comparable computing power available. The Advantage, on the other hand, would be able to handle problem-sizes of a million variables, at deliverable quantum speeds. They offered companies first-to-market advantages on many levels.

Leap

With effect from 8 October 2020, D Wave launched **Leap.** This offered cloud access to on-line computational facilities and services, including its **"hybrid solver service** ". The Advantage will not be on sale. Its services will only be available on Leap.

D-Wave provide application development services[35]. It is interesting that they also offer custom fabrication of superconducting circuits – probably quantum chips. This is obviously a useful and exportable diversification as the world demand for quantum chips grows.

Hybrid-Solver

D Wave has also launched a new Hybrid-Solver scheme, It offers an innovative way to help clients scale out their problems across their classical computing architecture and D Wave's computer, using their new hybrid solver.

D-Wave's hybrid solver divides applications into portions that are best run on the quantum system and portions best run on classical systems. Open-source software tools may be used to enable developers to build applications in familiar languages and environments, without having to understand the underlying physics of the quantum system.

The new hybrid solver – the discrete quadratic model (DQM) solver – expands the range of problems that can be addressed.

> "Instead of accepting problems with only binary variables (0 or 1), the DQM solver uses other variable sets (e.g., integers from 1 to 10, or red, yellow, and blue), expanding the types of problems that can run on the quantum computer,[36]"

Trading of ideas between the quantum and classical computing camps is likely to improve inter-support and performance on both sides. The Hybrid Solver approach attempts to use both technologies.

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35 Ocean software is a suite of tools D-Wave Systems provides on the D-Wave GitHub repository for solving hard problems with quantum computers.

36 https://www.dwavesys.com/press-releases/d-wave-announces-general-availability-first- quantum-computer-built-business

Again, there is here a lucrative second product line – building a shelf of rentable specialised short-run quantum programmes to provide hybrid support for the work of classical computers which will still pervade for years.

Assessment

D Wave raced to a five-year lead ahead of IBM. They have built on their initial tactical advantages, on the face of it amazing technical mastery to run up to 5,000 qubits. No one in the market could afford to overlook an obviously competitive tool like Advantage. Martin Lockheed and NASA-Google immediately contracted for their original computer s soon as it came on line. As Q2 ends, with the Advantage becoming available, the Jülich Supercomputing Centre in Germany is already in the que up to pick up one, while D-Wave have a partnership with Volkswagen AG (Germany) aimed at applying their quantum computing technology to Volkswagen's real-world computing challenges.

The bottom line is that their technology works and they have been making money. The Advantage has a huge immediate market potential, notwithstanding any ultimate limits of its annealing technology or its design slanted for optimisation. There is nothing to match it. And it isn't even American!

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RIGETTI COMPUTING (US)

Rigetti Computing were another startup company for the quantum market, founded in 2013 and based in Berkeley, California. Their founder Chad Rigetti worked at IBM with its quantum group before starting this company.

The image and market stance of the company may be gauged by its own "approach[37]"

> "Rigetti Computing is an integrated systems company. We build quantum computers and the superconducting quantum processors that power them. Through our Quantum Cloud Services (QCS) platform, our machines can be integrated into any public, private or hybrid cloud."[38]

Rigetti project a dual image, On the one hand, the company develop and build chips for quantum computing. On the other hand, they are a full stack "Quantum Shop", offering a complete Technology Stack to power practical applications, with total client support.

TECHNICAL NOTE

> Rigetti have adopted the superconducting electric circuit technology, reaching the qubit by a through-silicon vias and superconducting flip-chip cap bonding, from above. .
>
> Rigetti use gated architecture for their processors.

Fab -1

Wafer fabrication and chip manufacture are integral constituents of Rigetti's strategy.

> "Quantum processor chips are the foundation of our technology stack. We design linear and nonlinear chip components and produce mask-sets to be fabbed in our manufacturing facility, **Fab-1.** In the latter, we combine modern silicon semiconductor and MEMS processing technologies to produce state-of-the-art superconducting qubits and device layers for microwave circuitry".

Fab-1 incorporates the latest semiconductor technology, but unlike traditional fabs operates in rapid-iteration mode. The

37 https://www.rigetti.com/about
38 ibid

company claim they could produce an entirely new design for a 3D integrated quantum circuit in about 2 weeks. Fab-1 was held to be a key advantage in their market posture. It is also their development tool – a fab is a lab for improving the qubit.

Hardware

By February 2016, the company had begun testing a three-qubit chip using aluminum circuits on a silicon wafer. In time, they released the following hardware onto their shelves:

1. 17 December 2017, **19Q Acorn**, 19 qubits
2. 4 June 2018, the **8Q Agave**, 8 qubits
3. 30 November 2018, the **16Q Aspen-1**, 16 qubits
4. 20 May 2020, the **Aspen 8**, 31 qubits

The Quantum Shop

Rigetti position themselves in the market as a company with a full stack capability to partner a client to adopt quantum technology. Their penchant or specialty is hand-holding the client to do so progressively by integration with the existing systems, through hybrid stages of quantum application development. The interface with the client can start as small as the latter is ready to go, ie “low latency”.

The company do this by a suite of software and development tools which enable the client to steer its own system development and define its quantum programme configuration. The company further stand by to build a chip for the client if needed – in fact *de facto* offer to do so at some sage if required. This is a highly admirable way to transfer ownership to the client and generate expertise in their own product.

Forest

In June 2017, the company announced beta availability of a quantum cloud computing platform called **Forest 1.0.** They claimed it to be the world's first full-stack programming and execution environment for quantum/classical computing.

Users could develop algorithms for quantum/classical hybrid computing, and learn how quantum computers and algorithms worked, using its Quantum Virtual Machine (QVM) running in the cloud. The platform allowed coders to write quantum algorithms for a simulation of a quantum chip with 36 qubits.

Quantum Cloud Services

The preceding was subsumed at some point by Rigetti's Quantum Cloud Services (QCS) platform. The strategy here was to integrate its machines into any public, private or hybrid computing environment or cloud. QCS offered users an on-premises dedicated access point to their quantum computers. This access point was a fully configured Quantum Machine Image (QMI) bundled with Forest and its Self-Development Kit (SDK).

Software and Applications

The company's own custom instruction language, **Quil**, which stands for Quantum Instruction Language, facilitates hybrid quantum/classical computing, and programmes can be built and executed using open source tools. Forest includes **pyQuil**, a set of open-source **Python** tools for building and running Quil programmes.

Assessment

My impression is that Rigetti's uniqueness lies in being "small", versatile, probably price-attractive, and quick off the ground. with therefore promise of being able offer medium scale companies, as well as other enterprises, institutions, and specialist operations (like a hospital), the advantage of quantum computing possibilities. Their forte will be a short run up time, and quick results.

Rigetti can in that sense bring quantum computing to industries outside the help of the big boys.

UK Partnership

The company are focusing on a strategy of partnerships. On 2 September 2020, Rigetti announced they would lead a consortium to accelerate the commercialisation of quantum computing in the UK. The three-year programme would build and operate the first quantum computer in the UK, make it available to partners and customers over the cloud, and pursue practical applications in machine learning, materials simulation, and finance.

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IBM

The “grandad” of computing companies, IBM were founded in 1911 and are now headquartered in New York.

IBM’s mission statement is gives the following major points.

- Leadership in Information technology.
- Networking the world.
- Improvement of life.

Although not the first (that belonged to Cray) IBM have been in the forefront in the field of supercomputers. IBM still have 40 of the top 500 super computers in the world, including their flagship, the Summit - which at 122.3 TFlops (Rmax) was No 1 – until overtaken this year by Japan’s Fugaki, at 415,53 TFlops (Rmax).

IBM Strategy -Quantum Advantage

IBM were a member of the DARPA Road Mapping Project Experts Panel and have been in the frontline of quantum computing development.

IBM are chasing a very different measure of success, something they call "**Quantum Advantage**." It objective is the most thorough and comprehensive exploration and development of Q2 technology *per se,* on an open-source sharing basis.

Thence, one can foresee that in the long-term IBM will lead the quantum computer to take its place alongside the supercomputer, and naturally surpass if not succeed it. At the same time, one can look forward through IBM to quantum computing becoming the instrument of universal application.

TECHNICAL NOTE

At the heart of IBM quantum systems is its superconducting transmon qubit.

A charged qubit is formed at a tiny superconducting "island", between a Josephson junction and a superconducting reservoir. The state of the qubit is determined by the number of "Cooper pairs" (of electrons) which tunnel across the junction.

The transmon is designed to have reduced sensitivity to charge noise and achieves this reduced by significantly increasing the ratio of the Josephson energy to the charging energy.

Measurement, control and coupling of the transmon are performed by means of microwave resonators applying quantum electrodynamics.

The transmon qubit is embedded in semiconductor material (silicon and berrium). IBM uses silicon technology to fabricate its processor chip.

Qubits are fabricated using techniques similar to those used for microelectronics. The devices are usually made on silicon or sapphire wafers using electronic beam lithography “.

IBM Q Series

Wikipedia gives the following list of IBM quantum computers by birthdate:

IBM Q5 Tenerife, 5 qubits, 2016\
IBM Q5, Yorktown, 5 qubits,2016
IBM Q14, Melbourne, 14 qubits, 2016
IBM Q16, Ruschlikon, 16 qubits, 2017 (retired), 2018
IBM Q17, 17 qubits. 2017
IBM Q20, Tokyo, 20 qubits, 2017
IBM Q20, Austin, 20 qubits, 2018 (retired)
IBM Q System One. 20 qubits
IBM Q53, 53 qubits, Oct 2019

IBM Q Network

In 2017, IBM announced the first 12 clients to tap into their new **IBM Q Network.** This provided access to their (then top-line) quantum computing systems to explore practical applications for business and science. They included: JPMorgan Chase, Daimler AG, Samsung, JSR Corporation, Barclays, Hitachi Metals, Honda, Nagase, Keio University, Oak Ridge National Lab, Oxford University and University of Melbourne.

The network grew to be a worldwide community of leading Fortune 500 companies, startups, academic institutions, and national research labs working with IBM to advance quantum computing and foster the growing quantum computing ecosystem based on IBM’s open-source quantum software and developer tools.

IBM Quantum Experience

In 2017, IBM also released the **IBM Q Experience**, an online interface for the public via the cloud. It allowed the building and running of quantum algorithms and gave access to BM’s prototyping processors. It included an internet forum and a set of tutorials. As of May 2018, there were two 5-qubit and one 16-qubit processors available. The IBM Q Experience also contained a library, teaching users how to use IBM’s Quantum Composer.

Currently, there were over 200,000 registered users of the IBM Q Experience, and since its launch in May 2016, its users had run over 140 billion executions and published more than 200 scientific papers.

IBM Q System One

At the 2019 Consumer Electronics Show (CES), IBM unveiled the IBM Q System One, which they claimed to be the world's first integrated universal quantum computing system, designed for scientific and commercial use. It incorporated classical computation, to provide cloud access and hybrid execution of quantum algorithms. The IBM Q System One operated on a 20-qubit computer.

Typically, quantum computers had to sit in a specialised lab. The IBM Q System One was different. It was stand-alone. The IBM Q System One was the first universal quantum computer able to operate beyond the confines of a research lab. It was a fully integrated machine that combined quantum and classical parts, designed to be used both for research and business applications. At nine feet tall and nine feet wide, the system was still large, the size of a large wardrobe, but it had all a company would require for quantum computing, including cryogenics. Its users were part of the IBM Network and used IBM Q Experience. And they also had access to Qiskit, an open-source quantum computing software development framework.

By 2021, IBM would be delivering an IBM Q System One, one each, to Germany and Japan, to be located at their research institutes, and the first to go overseas. These countries will benefit from having direct access to a dedicated quantum computer – not just to systems shared among many users worldwide on the cloud. These will provide more capacity, capability, and opportunity for much larger numbers and variety of users in these countries, with support from IBM, to develop applications of quantum technology.

IBM Q Quantum Computation Center

IBM also announced plans to open their first IBM Q Quantum Computation Center for commercial clients, later that year. This new center would host advanced cloud-based quantum computing systems.

The center would be accessible to members of the IBM Q Network. Several of their quantum systems were also available to the public, allowing users to access them through Qiskit and the IBM Quantum Experience.

Quantum Volume

IBM announced in January 2020 that they had hit a world record Quantum Volume[39] of 32. The company had said they had since reached a Quantum Volume of 64 in August 2020, through a series of new software and hardware techniques applied to a system already deployed within the IBM Q Network. But two months before, Honeywell claimed prior success by achieving a Quantum Volume of 64 in Jun 2020 (see further down for Honeywell).

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39 Quantum Volume is an IBM-developed measurement growing in popularity in the external technical community that determines how powerful a quantum computer is.

IBM Q System One, just like any other then existing quantum computer, had not yet reached Quantum Advantage – meaning it could not yet out-perform a traditional computer. Still, it had produced a Quantum Volume of 16, which reflected some of the lowest error rates IBM ever measured.

The 53-qubit IBM-Q 53, which came online in October 2019, attained a world record of Quantum Volume 64 in Aug 2020, matching Honeywell.

IBM Road Map 2023

This IBM notification issued in September 2020 is reproduced in full further on under Q3. It is worth here noting the key milestones:

.- In 2021, they will debut the 127-qubit **IBM Quantum Eagle** processor. Eagle will feature concurrent real-time classical compute capabilities that will allow for execution of a broader family of quantum circuits and codes.

.- In 2022, they will release a 433-qubit **IBM Quantum Osprey** system, with efficient and denser controls and cryogenic infrastructure.

.- In 2023, they will debut the 1,121-**qubit IBM Quantum Condor** processor, incorporating lower critical two-qubit errors and longer quantum circuits. Condor as will be an inflection point, a milestone to explore potential problems that can be solved more efficiently on a quantum computer than on the world's best supercomputers.

Assessment

As far as I can see, the long-term terms future of quantum computing rests safely with the strategic leadership of IBM. Their investments in solving the host of problems associated with the qubit will be the world's gain, if not theirs in the short run.

Albeit the IBM Q System One can stand alone and has a QV of 16, I have not been able to sense how versatile or efficient it is in undertaking standardised jobs.

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GOOGLE INC

Founded in 1998, Google are an American multinational technology company that specialise in Internet-related services and products. They are considered one of Big Four technology companies in the U.S, alongside Amazon, Apple and Microsoft.

In 2015, Google and NASA reported that their new 1097-qubit D-Wave quantum computer had solved an optimization problem in a few seconds, a 100 million times faster than a regular computer chip.

IN 2018, Google announced the creation by their Artificial Intelligence (AI) division of a 72-qubit quantum chip, called "Bristlecone, achieving a new record.

In 2019 Google's Artificial Intelligence division created the Sycamore.

TECHNICAL NOTE

Google uses superconducting loops. Its quantum chip is composed of 54 qubits

On its record-breaking run, Google's Sycamore (also see below) had 53 qubits (one was defective), 1,113 single-qubit gates, 430 two-qubit gates, and a predicted measurement on each qubit of a total fidelity of 0.2%. This fidelity was resolved within a few million measurements. In Google's model, entangling larger and larger systems did not introduce additional error sources beyond the errors measured at the single- and two-qubit level.

Sycamore calculated the probability distribution by sampling the circuit — running it one million times and measuring the observed output strings.

Sycamore

The following is a remarkably clear description from the Google's AI Quantum Team:

"Sycamore consists of a two-dimensional array of 54 transmon qubits, where each qubit is tenably coupled to four nearest neighbours, in a rectangular lattice. The connectivity was chosen to be forward-compatible with error correction using surface code. A key systems engineering advance of this device is achieving high-fidelity single- and two-qubit operations, not just in isolation but also while performing a realistic computation with simultaneous gate operations on many qubits.

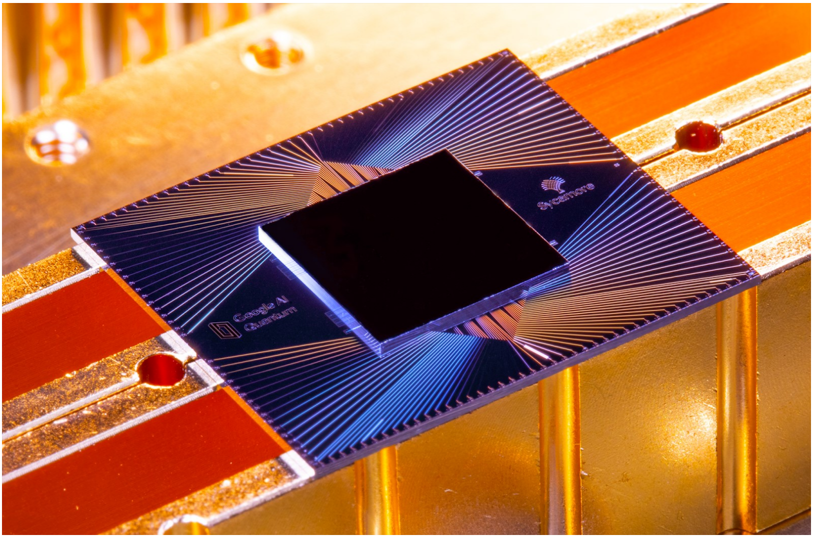
In a superconducting circuit, conduction electrons condense into a macroscopic quantum state, such that currents and voltages behave quantum mechanically. Transmon qubits can be thought of as nonlinear superconducting resonators at 5–7 GHz. The qubit is encoded as the two lowest quantum eigenstates of the resonant circuit. Each transmon has two controls: a microwave drive to excite the qubit, and a magnetic flux control to tune the frequency. Each qubit is connected to a linear resonator used to read out the qubit state. Each qubit is also connected to its neighbouring qubits using a new adjustable coupler. Our coupler design allows us to quickly tune the qubit–qubit coupling from completely off to 40 MHz One qubit did not function properly, so the device uses 53 qubits and 86 couplers."[40]

Quantum Supremacy

Google group claimed that its 53-qubit computer performed, in 200 seconds, an arcane task that would take 10,000 years for IBM's Summit supercomputer. But IBM rebutted

[40] https://www.qmunity.tech/post/quantum-supremacy-with-sycamore

Google's claim declaring that, by tweaking the Summit, the latter completed the task in 2.5 days. Therefore, the threshold for "quantum supremacy"—doing something a classical computer cannot[41]—had not been crossed.



Sycamore
chiphttps://commons.wikimedia.org/wiki/File:Google_Sycamore_Chip_002.pn
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Google Partnership with Forschungszentrum Jülich (FJ)

In July 2019, Google and Forschungszentrum Jülich (FJ) of Germany, the latter an active participant in the EU's Quantum Flagship Programme, announced a partnership to develop quantum computing technology. The joint work will focus on training, algorithm development, and mutual use of quantum hardware. which includes regular research exchange.

[41] Quantum Supremacy means a quantum computer doing something a classical computer cannot do or do even in a very prolonged time-frame, say 1.000 years.

Researchers on both sides will perform simulations on supercomputers at the JSC, and experiment with Google’s quantum processors.

Forschungszentrum Jülich (FJ) is and plans to offer a publicly accessible European quantum computer with 50-to-100 superconducting qubits. The mention of “mutual use” of quantum hardware is interesting. Given Google’s steady progress in processor development, many observers have wondered when (or if) they would offer broader access to their quantum platform the way that IBM, Rigetti, and D-wave Systems have all done via web portals. Google’s Bristlecone quantum processor has 72 qubits. Forschungszentrum Jülich will experiment with Google’s processor but no mention was made of whether it is a candidate chip for Forschungszentrum Jülich’s system.

Chemical Simulation

Developing an ability to predict chemical processes would be an outstanding breakthrough. Chemists currently do most of it through trial and error. Prediction would open up the door to the development of a wide range of new materials with still unknown properties. Sadly, current computers lack the exponential scaling that would be required for such work. Because of that, chemists have been hoping quantum computers would one day step in to take on the role

Google's AI Quantum team has conducted the largest chemical simulation on a quantum computer to date. They did it by pairing the quantum system with a classical computer. The was used to analyze the results given by the Sycamore machine and then to provide new parameters. This process was repeated until the quantum worked its way to a minimum value

Assessment

While the Sycamore's performance was essentially a speed-test. Like a new Ferrari model, the declared technical specifications are impressive They show mastery of the qubit ahead of the pack.

Google are enough of a universe on their own, with enough resources, to experiment with optional applications, and in due course deploy a quantum computer in-house. With the latter developed to supercomputer reliability and full transactional potential, we could see early results in accentuated Internet functionality, and they could run away with AI.

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Honeywell

Founded 114 years ago, Honey International Inc are a US multinational company headquartered in Charlottesville, North Carolina. Honeywell are a Fortune 100 company. They operate primarily in four areas of business: aerospace, building technologies, performance and materials and safety, and productivity solutions. They therefore have enormous internal industrial strength and expertise (and their own market base for quantum services.)

Honeywell, who had been out of the computer business since the Honeywell 6000 in the late 1980s, have re-emerged in the quantum computer field.

Honeywell announced their quantum computing efforts in late 2018 and had a team of more than 100 scientists, engineers and software developers devoted to the effort. In Jun 2020, Honeywell had a quantum computer running client jobs with a Quantum Volume of 64. Honeywell reached that milestone with just a 6-qubit system, beating IBM's then record of 32 with a 53-qubit machine. (IBM would also hit 64 inn August 2020.)

TECHNICAL NOTE

Honeywell's new H1 generation of computer features what they call their differentiated quantum charge-coupled device (QCCD) trapped-ion technology".

Honeywell create trapped-ion qubits using an isotope of rare-earth metal called **ytterbium**, and use integrated photonics on them. The process to create ions is as follows: precision lasers remove an outer electron from an atom to form a positively charged ion. Then, lasers are used like tweezers to move ions into position. Once in position, oscillating voltage fields hold the ions in place. One main advantage of ions lies in the fact that it is natural instead of fabricated. All trapped-ion qubits are identical. A trapped-ion qubit created on earth would be the perfect twin of one created on another planet.

The photonics developed for the ion trap are the first to be compatible with violet and blue wavelengths used. Traditional photonics materials have very high loss in these.

All the manipulation of the ions takes place inside a vacuum chamber containing the trapped-ion processor chip. The chamber protects the ions from the environment and prevents collisions with air molecules. Lasers are also used to perform the necessary quantum operations on each qubit. Because lasers and optical components are large, they are y located outside the vacuum chamber. Mirrors and other optical equipment steer and focus the laser beams through the vacuum chamber windows onto the ions.

The number of trapped-ion qubits is 32. For quantum computers to be truly useful, millions of qubits are needed. That means many thousands of lasers will be required to control and measure the millions of ion qubits. The current method of controlling lasers makes it challenging to build trapped-ion quantum computers beyond a few hundred qubits.[42]

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[42] https://www.honeywell.com/us/en/press/2020/10/honeywell-releases-next-generation-of-quantum-computer

Under Honeywell's current quantum plans, the computer remains in-house, and customers will connect directly to systems housed by the company. Honeywell will use quantum computing to solve issues for its key verticals such as oil and gas and industrials and have a partnership to make their systems available in Microsoft Azure’s Quantum eco-system.

Honeywell Ventures have invested in Cambridge Quantum Computing and Zapata Computing. Both companies have expertise in cross-vertical algorithms and software. Cambridge Quantum Computing focus on chemistry, machine learning and augmented cybersecurity while Zapata invent algorithms and build quantum software to take on supercomputers.

Honeywell are said to investing in two quantum computing software providers and partnering with JPMorgan Chase to develop quantum computing algorithms for financial services.

System Model H1

On October 29, 2020, Honeywell outlined its plans to jumpstart the industry, and introduced is first quantum computer, the **System Model H1.** It features 10 fully connected qubits and has a Quantum Volume[43] (QV) rating of 128.

Honeywell said H1 had unique capabilities, such as mid-circuit measurement and qubit re-use, that derived at least in part from Honeywell’s control systems expertise. Honeywell stated their commitment to rapidly increase their systems’ QV by “at least” an order of magnitude annually for the next five years.

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[43] Quantum Volume (QV) is a composite metric with many elements – gate error rates, decoherence times, qubit connectivity, operating software efficiency, etc, developed by IBM and is generally adopted by the industry The QV of 128 is the highest yet reported. IBM’s highest rated systems are QV 64.

IBM and D-Wave both sell standalone systems but also offer web-based access to their own quantum computers. Most observers say the latter approach is likely to dominate, at least near-term, because quantum computers can be tricky to operate and maintain and because advances are happening so quickly.

Subscription Plan

Honeywell are making the H1 directly accessible to enterprises via a cloud API, as well as through Microsoft Azure Quantum, and partners Zapata Computing (collaboration and workflow) and Cambridge Quantum Computing (software and algorithms).

A subscription service provides customers access to Honeywell's computers. Currently, there are two subscription levels (standard and premium) based on timed access to the computers. During the dedicated hours, subscribers have access to Honeywell scientists for real-time cooperation.

Honeywell Debuts Roadmap to H5

Honeywell say their methodology them to systematically and continuously 'upgrade' the H1 generation of systems through increased qubit count, higher fidelities and unique feature modifications.

The company have already begun integration activities for their H2 generation as well as development activities in support of the H3 generation. The following is a schematic of their generational development roadmap 2020-25, with a wide margin to 2030

Honeywell Generational Roadmap 2020-25/30

Model H1 (2020-1)	Model H2 (2022)	Model H3 (2023)	Model H4 (2024)	Model H5 (2025/30)
Linear	*Race Track*	*Grid*	*Integrated Optics*	*Large Scale*
Current Technology	Multi-layer fabrication demonstrated	Junction Transport demonstrated	Photonic devices designed and tested	Iron tap tiling strategy developed
10-40 qubits	Massive scaling of qubits and computing power. Iron trap fabrication in Honeywell's foundry.			
2-Qubit Fidelity >99.5%				
Conditional quantum logic	Key enabling technologies already demonstrated for general upgrades.			
Mid-circuit measurement				
Machine performance	Noise Intermediate Scale Quantum Era (NISQ)		Fault-Tolerant Quantum Computing	
QV Target	640	6,400	64,000	640,000

In June 2020, H0 reached a QV of 64, But in October 2020, Honeywell announced its H1 at a QV of 128. That is part of its plan to increase performance by at least a factor 10 reaching 640,000 by 2025.

Honeywell have also detailed H2, H3, H4 and H5 quantum computer design plans. They intend to replace today's straight-line ion trap with increasingly complicated arrangements, including a looped "racetrack" in the H2 already in testing today, and increasingly large crisscrossing lattices for the H3, H4 and H5.

One big motivation for the new designs is cramming in more qubits. That will be important to move beyond today's “kicking-the-tires” calculations into more serious work and attaining the QVs they target.

Assessment

Honeywell are a huge horizontally integrated industrial conglomerate working on quantum computing development. Honeywell can therefore tap into their collective expertise across their broad technology and product base. It would seem they have decided to develop a full-fledge quantum computer. This seems to mean they intend to enter the market. Perhaps, they have a head start. But I have not been able to judge the quality of their QV. Some years ago, I bought an Honeywell 19-station “mini” computer system with software for Accounts training. It was a failure and costly write-off. The bravado of their forward targeting based on climbing the first step does not add my confidence in their plans until I see more hard data.

I have also yet been unable to assess whether Honeywell would do better with general-purpose in-house capabilities versus tapping into outside sources that explicitly support their component industries.

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IonQ

IonQ were co-founded by Christopher Monroe and Jungsun Kim, professors at the University of Mary and Duke University respectively, in 2015.

Their individual interests and research in trapped ion technology became a partnership when the company were seeded by New Enterprise Associates with $2 million to commercialize the technology.

On 1 Oct 2020, one week after Honeywell launched their H1 with a QV of 128, IonQ announced their "5th-generation" quantum computer, with 32 qubits and a Quantum Volume (QV) of more than 4,000,000. In fact this volume was attained with only 22 qubits available – presumably the rest were used in error correction, etc.

TECHNICAL NOTE

> IONQ'S quantum computer's architecture featured 32-qubits using trapped ion technology. The details ae similar to that of the Honeywell HI, see relevant Technical Note.
>
> The new quantum computer also included another new development. It allowed random access on all-to-all gate operations. This improvement will I understand allow a more efficient software compilation of applications
>
> IonQ also incorporated a new error correction code, that used only 13 qubits.[44]

From information available. their latest release, the 5th, almost tripled the 11 qubits in their previous quantum computer. The next, the 6th and 7th generations, still in development, would be smaller (presumably physically) but more powerful than their respective predecessors when released.

Robert Niffenegger, a member of the Trapped Ion and Photonics group at MIT Lincoln Laboratory[45], has said he was not surprised at the large jump in the number of qubits. "Honestly, I think a lot of people were just holding their

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44 https://www.rumblerum.com/quantum-computer/#About_IonQ_and_its_new_5th_generation_quantum_computer

45 See under Significant Breakthroughs under Q3.

breath until they [IonQ] announced. They've published papers on ways of cooling chains of 20 ions that have hinted that they had much more than the 11 ions they put on the cloud - the question was just how many?"

Honeywell conceded that “the inability to correct qubit errors is one of the reasons we cannot build quantum computers larger than a few hundred qubits. Finding a solution to error correction is important to the future of quantum computing.”

IonQ Explains

Jung-sang Kim, co-founder and Chief Technology Officer explained why IonQ decided to **calculate** quantum volume rather than run the quantum volume algorithms: "We have a temp[orary] solution for some of the optics that allowed us to have confidence in the gate fidelity that allowed us to calculate approximate QV. As we speak, we are putting in the final production optics and will be able to get a final number on the machine. The four million number required only 22 qubits with 99.9% fidelity, and so we expect the final QV to only be limited by the gate fidelity rather than number of qubits."

Had all 32 qubits been used in IonQ's calculation instead of just 22 qubits, the claimed, expected quantum volume would have exploded from 4 million to a quantum volume of over 4 billion. That would be 31 million times greater than any quantum volume ever published.
Another quantum theorist said that two-qubit gates would have needed nothing less than 99.96% fidelity to achieve a quantum volume of that magnitude. It will be settled, because according to Chris Monroe IonQ will soon publish a research paper on the new processor.

Assessment

IonQ is still a lab operation. If the H2 performs as targetted, and IonQ can develop the software stack fast enough for the computer to prove its value via cloud, by client and pubic trials and tests to be facile and efficient, then IonQ may well be a leader of the pack.

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Quantum Supremacy

Supercomputers

With all the talk about the quantum computer, it is easy to forget that the supercomputer is perhaps the greatest single achievement made possible by QM1. As of the present, and for quite some time to come I imagine, the supercomputer will run the world.

As of June 2020, 226 of the world's **500** [46]most powerful supercomputers were in China, a figure which doubled that of its nearest competitor, the United States, which accounted for nal 113 supercomputers. Together, the two nations account for around two-thirds of the world's most powerful supercomputers. Europe was third with 105.

The latest, 55th, edition of Top 500[47] marks the first time an Arm-powered supercomputer is at the top of the list. The world's new fastest is named Fugaku, rated at 513.855 petaflops. It is powered by Fujitsu's 48-core A64FX SoC. It is installed at the RIKEN Center for Computational Science (R-CCS) in Kobe, Japan.

The most powerful US supercomputer presently is IBM's **Summit or OLCF-4** at Oak Ridge National Laboratory, with a rated speed of 200.795 petaflops. Summit is the first supercomputer to have notched exaflop speed (a quintillion operations per second), achieving 1.88 exaflops. It is expected to reach 3.3 exaflops using mixed-precision calculations.

46 https://en.wikipedia.org/wiki/TOP500
47 https://www.top500.org

Quantum Supremacy.

Assuming quantum computers were competing against supercomputers capable of up to a quintillion Floating-point Operations per Second (1.0 exaflops) on standardised tasks, researchers calculate that quantum computers could reach Quantum Supremacy[48] with 208 qubits with IQP[49] circuits, 420 qubits with QAOA[50] circuits and 98 photons with Boson Sampling[51] circuits. When I began writing this, the prognosis was 400 qubits.

If the performance standards of Honeywell and IonQ are realised, some experts believe that 80 to 150 very high-fidelity qubits and logic gates might open the way for individual units to reach Quantum Advantage[52] and even Quantum Supremacy.

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48 Quantum Supremacy means a quantum computer doing something a classical computer cannot do, not even in a very prolonged timeframe.
49 Instantaneous quantum polynomial (IQP) circuit.
50 Quantum approximate optimization algorithm (QAOA)
51 https://www.nature.com/articles/s41534-017-0018-2
52 Quantum Advantage means a quantum computer being able to perform better than a supercomputer in a range of functions.

World Scrambles to Go Quantum

Looking Over the Hill

While the race for the quantum computer was on, mainly in the US, the rest of the world got ready for what would come after, see the accompanying composite table of investments and researchers globally, during the last few years[53].

Investment and Research in Quantum Technology

No	**Country***	**Research -ers*** No	**Invest- ments*** Euros Millions	**Invest- ments**** US$ Millions
1	USA	1217	360	1.200
2	Canada	347	100	766
		1564	460	1966
	EU	2445	550	1,100
3.	Germany	553	120	3,100
4.	UK	453	105	1,300
5.	France	224	52	1,600
6.	Italy	216	36	
7.	Switzerland	197	67	
8	Spain	155	225	
9	Austria	108	35	
10	Poland	101	12	
11	Denmark	73	22	
12	Netherlands	94	27	177
13	Sweden	62	15	
14	Finland	51	12	
		2287	2213	5,977

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[53] The two sets of investment figures are not comparable. Their time frames, coverage and bases of collection are not declared, and different. Figures broadly depict relative country activity in last 2-3 years and 4-5 years, respectively. EU and its member -country figures ae shown separately.

15.	China	1912	220	10,000
16	Japan	329	63	470
17	Australia	249	75	94
18	Singapore	136	44	109
19	South Korea	78	13	37
20	Brazil.	104	104	
21	India			1,000
22	Israel			360
23	Russia			663
		2,808	519	13,252
	GLOBAL		3,282	22,000

- From: UK National Quantum Technology Programme, undated, probably 2019[54]

** From QURECA[55]

China

According to the TOP 500 rankings on the Internet, China has a whopping 226 of top 500 supercomputers, with a total of 45% of the system share. She held positions Nos 4 and 5 on the Top 10.

In 2017 China started building the world's largest quantum research facility in Hefei, central China's Anhui province, with the goal of developing a quantum computer. China has been pouring billions of dollars into funding quantum research, with a particular focus on uncrackable encrypted communication, enabling it to dodge US surveillance.

The leading institution in this field is The University of Science and Technology (USTC), one of the country's most prestigious schools, based in Hefei near Shanghai. Pan Jianwei, is widely

54 https://epsrc.ukri.org/newsevents/pubs/quantumtechroadmap/

55 https://www.qureca.com/overview-on-quantum-initiatives-worldwide/

recognized as one of the foremost experts in this field. China has one quantum computer as of now.

There is a race on by China to overtake the US as the world's supreme power, politically, militarily, and economically. At the heart of this lies who commands technology, and it not difficult to grasp that this means in the end who has superior mastery of quantum computing. This underlies the US' frenzied take-off in Q1. It also explains the massive investments and deployment of manpower by China to catch up in the second half of the last decade, as may be seen in the above consolidated table. In September 2020, the US (the Trump Administration) placed embargos on the export of US microchip technology to China.

The National Laboratory for Quantum Information Sciences is a US$10 billion project due to open in 2020 also at Hefei. "Our plan is that by 2020, or maybe as soon as next year, to achieve 'quantum supremacy' with calculation power one million times to all existing computers around the world combined," Pan was quoted as saying *by Anhui Business Daily,*[56]

China has gone into critical areas of application, as well as in computing. It has developed and demonstrated Quantum Key Distribution (QKD) features via China's satellite (*Micius*, launched in August 2016) and ground-based quantum communications over the Quantum Beijing–Shanghai Trunk, in use since September 2017.

China sees this field as an opportunity to leapfrog[57] the US, The Institute of Physics and IOP Publishing, in partnership with the Chinese Physical Society (CPS) and the University of Science and Technology of China (USTC) are launching their

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56 https://www.scmp.com/news/china/society/article/2110563/china-building-worlds-biggest-quantum-research-facility

57 https://www.technologyreview.com/2018/12/19/1571/the-man-turning-china-into-a-quantum-superpower/

inaugural international quantum science conference online later this morning (19 Oct 2020), with impressive international sponsorship and participation. They are obviously trying to pre-empt EU's Quantum 2020 event starting on 20 Nov 2020. I attended both.

US

Of the 500 TOP supercomputers in the world, only 113 now are US. Of the TOP10, the US has four, with the IBM Summit being No 2,.to Japan's Fugaka. China took over the lead in 2016 and now has 226 supercomputers.

On the other hand, there were 27 quantum computers in operation in 2019, and all were American and in the US. Of these 15 were IBM, 4 D-Wave, 3 Rigetti, 2 Google and 1 Honeywell.

On December 21, 2018, President Donald Trump, with strong bipartisan support, signed into law the National Quantum Initiative Act (NQIA). It provided a USD1.2 billion budget for the first five years of a 10-year plan to boost research and accelerate the development of quantum information science and technology applications in the US.

The NQIA created the National Quantum Initiative (NQI) and authorised three agencies— the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF), and the Department of Energy (DOE), to implement the bulk of the programmes. The programme will be based on a 10-year plan

The 10-year plan will expand quantum research through new investment; increase efforts to provide the training and education needed to build a workforce skilled in quantum; create an interagency process to coordinate the activities of the different federal agencies, liaise with industry, and leverage existing federal investments such as the national laboratories, and create a network of quantum centers throughout the country

The NQIA gives NIST three roles that are traditionally within its mandate. First, to deal with research and development of the measurement and standards infrastructure. Second, to help train quantum scientists and expand the quantum work-force. Third, to stablish or expand collaborative ventures with industry and other government agencies.

The NQIA gives the NSF its natural role of developing research programmes and supporting graduate education in the quantum information sciences. The NSF is responsible for creating multidisciplinary centers for quantum research and education

The DOE is a natural partner of the NQI, by virtue of its responsibility for energy. It has a long history of supporting high-performance computing, and its laboratories, such as Sandia National Laboratories have conducted some of the fundamental research on quantum information. It is required to establish research centres, inter alia, to support research conducted by the DOE.

The 2019 National Defense Authorization Act established a programme to coordinate and accelerate the DOD's quantum research and development efforts and manage a balanced portfolio of fundamental and applied quantum research and transition into deployable technology. This year's National Defense Authorization Act is expected to expand the DOD's quantum

The Quantum Industry Coalition, which represents the industry, has defined the guiding principles

-. <u>Set broad goals</u> for quantum research and development: The goals should focus on results that help strengthen the U.S. economy and national security.

-. Exchange information: Compiling and sharing of non-sensitive information about public- and private-sector.

-. Accelerate research and development toward usable results:

-. Advance U.S. national security: Excessive or unwieldy secrecy and export control requirements will stifle U.S. quantum research

-. Promote workforce development: American quantum companies need to have access to a pool of qualified American workers. Educational institutions should be incentivized to respond to projected industry demand.

- Work with U.S. allies as appropriate: Many of our closest allies are home to leading companies and research institutions in the field that can help advance U.S. priorities in partnership with industry.

The NQIA has provided the national framework for the government, the institutions, and the private sector to share and benefit from one another in the next lap of the Q2. The most promising would be IBM's Master Plan 2023.

EUROPEAN UNION (EU)

Of the TOP500 supercomputers, there are now 71 in Europe., according to a biannual ranking of the world's 500 fastest supercomputers. Of the TOP 10, Europe has two in Italy, the HPC5 (INVIDIA/Dell at No 6 and the Marconi 100 (IBM/INVIDIA) at NO 9, and the Piz Daint (Cray) at No 10 in Switzerland.

Europe it has not built a quantum computer yet. She has an impressive range of research centres dabbling in quantum technology. One commentator has drolly pointed out that Europe's supply chain was weak. She produced only 5% of the industry's high-performance (HPC) hardware.

Quantum Manifesto 2016

In May 2016, the European Union (EU) launched the Quantum Manifesto, a New Era of Technology. The spirit was clear: “No single country can make it on its own, cooperation is essential to succeed. Now it is time to act together at European level to live up to this major European initiative”.

The manifesto spanned the four major areas of challenge in quantum technology, (1) Communications, (2) Simulators. (3) Sensors, and (4) Computers, with targets in the short-term (5 years), mid-term (10 years) and long-term (20 years). The manifesto did not include project budgets, but independently the EU had announced that €1.0 billion was being deployed.

Quantum Flagship 2018

After the Graphene Flagship and the Human Brain Project, the **Quantum Flagship** (QFlag) @ Quantum Technologies, was the third large-scale research and innovation initiative funded by the EU. It was launched in October 2018 and subsumed the earlier manifesto.

With a budget of at least €1 billion and a duration of 10 years, the QFlag has brought together research institutions, academia, industry, enterprises, and policy makers, in a joint and collaborative initiative on an unprecedented scale.

The programmes involve 140 projects invited for consideration and up to 5,000 researchers. All partners have a strong network in their individual countries and in Europe to support a powerful European Quantum Flagship initiative

The long-term horizon is a “Quantum Web”, incorporating quantum computers, simulators and sensors interconnected via quantum networks distributing information and quantum resources.

Thus, the QFlag will:

1. Prepare a European Quantum Flagship Strategic Research Agenda
2. Coordinate access to infrastructure, foster applications of Quantum Technology and facilitate the transfer of results to industry.
3. Increase awareness of Quantum Technology (QT) in Europe, both with end-users and the general public.
4. Foster education and training in QT, as well as a “quantum aware workforce”.
5. Coordinate the QT stakeholders and link the flagship activities to national programmes.

Quantum Flagship Projects (optional reading)

The EU has allocated €132 million as the budget for the “ramp up” period of the first three years (2018-2021) for 20 projects. The following samples reflect the targetted transformation of Europe

1 Open Super Q Vision
Open Super Q project targets to build a hybrid high-performance quantum computer of up to 100 qubits and to sustainably make it available at a central site for external users.

2 AQTION
_Advanced quantum computing with trapped ions This project focuses on scalability, availability, and applicability aspects of trapped-ion quantum computers

3 macQsimal
Miniature Atomic vapour-cells quantum devices for SensIng and Metrology Applications

4 iqClock
Integrated Quantum Clock. Will have a large impact on telecommunications (e.g. network synchronization, traffic bandwidth, GPS), geology (e.g. underground exploration, monitoring ice sheets), astronomy (e.g. low-frequency gravitational wave detection, radio telescope synchronization), and other fields.

5 Qombs
Quantum simulation and entanglement engineering in quantum cascade laser frequency combs. This project will move from the fundamental quantum simulation protocols to prototypes and eventually to the industrial production and commercialisation of the new devices.

6 PASQuanS
Programmable Atomic Large-Scale Quantum Simulation, PASQuanS will perform a decisive transformative step for quantum simulation towards programmable analogue simulators addressing questions in fundamental science, materials development, quantum chemistry and real-world problems of high importance in industry.

7 UNIQORN
Affordable Quantum Communication for Everyone: Revolutionizing the Quantum Ecosystem from Fabrication to Application. The outcomes of the project will provide the building blocks for quantum devices that can be used in home appliances and maybe even in smart phones one day.

8 QRANGE
Quantum Random Number Generators: cheaper, faster and more secure. The generation of random numbers plays a crucial role in many applications in science and impacting society, in particular for simulation and cryptography
9 QIA
Quantum Internet Alliance. The Alliance (QIA) targets a Blueprint for a pan-European **Quantum Internet** by ground-breaking technological advances, culminating in the first

experimental demonstration of a fully integrated stack running on a multi-node quantum network

10 CiViQ
Continuous Variable Quantum Communications. The goal of the CiViQ project is to open a radically novel avenue towards flexible and cost-effective integration of quantum communication technologies, and in particular Continuous-Variable QKD[58], into emerging optical telecommunication networks

11 MicroQC
Microwave driven ion trap quantum computing. The objective of MicroQC is to demonstrate fast and fault-tolerant microwave two-qubit and multi-qubit gates and to design scalable technology components that apply these techniques in multi-qubit quantum processors.

12 PhoQuS
Photons for Quantum Simulation The main objectives of this project are to fully understand the superfluid and quantum turbulent regimes for quantum fluids of light and to achieve simulations of systems of very different nature, ranging from condensed matter to astrophysics

13 PhoG
Sub-Poissonian Photon Gun by Coherent Diffusive Photonics. We want to create a family of novel, “cheap” and reliable, quantum sources with user-selected properties, PhoGs, that will enhance the performance of many protocols.

14 SQUARE
Scalable Rare Earth Ion Quantum Computing Nodes. This project aims at establishing individually addressable rare earth ions as a fundamental building block of a quantum computer, and to overcome the main roadblocks on the way towards scalable quantum hardware.

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[58] QKD = Quantum key distribution

15 QMiCS
Quantum Microwave Communication and Sensing. QMiCS' long-term visions are (i) distributed quantum computing & communication via microwave quantum local area networks (QLANs) and (ii) sensing applications based on the illumination of an object with quantum microwaves (quantum radar).

16 2D-SIPC
Two-dimensional quantum materials and devices for Scalable Integrated Photonics Circuits.

17 S2QUIP
Scalable Two-Dimensional Quantum Integrated Photonics. The project will develop scalable cost-effective on-chip quantum photonic hybrid microsystems by integrating two-dimensional semiconductor materials (2DSMs) in state-of-the-art CMOS compatible nanophotonic circuits.

18 ASTERIQS
Advancing Science and Technology thro Rough DIamond Quantum Sensing. ASTERIQS will exploit quantum sensing based on nitrogen-vacancy (NV) centres in ultrapure diamond to bring solutions to societal and economical needs for which no solution exists yet.

Nineteen EU countries have signed on to develop a **joint quantum communication infrastructure** across the continent
.
To date, the EU has **no quantum computer**, and its target to have scalable universal quantum computer is 10 years.

Germany

All components of the German academic, research, industrial and financial sectors are involved in EU's QFlag. Germany will probably be the major player. Germany has 16 supercomputers, but no quantum computer.

In July 2020, the German government announced a €2 billion quantum effort, supplementing EU plans for €1 billion, in investment through to 2028

Germany will have the first quantum computer installed in Europe early in 2021 It will be the IBM-Quantum System One Computer to be installed in an IBM computer center near Stuttgart. The agreement is with the Fraunhofer-Gesellschaft, an applied research institute headquartered in Munich, and the goal is to work together on advancing quantum computing research and applications. While IBM is bringing its quantum computer to Germany, the German government, for its part, pledged to inject 650 million euros ($717 million) over two years in broader research in the field.

The IBM quantum computer in Germany will allow researchers to harness the technology without falling foul of the EU's increasingly assertive stance on data sovereignty. The state-backed Fraunhofer research institute will act as the gatekeeper for the 9ft-tall IBM Q System One computer at the IBM Center at Stuttgart. The partnership follows a similar one in Japan.
T
Last year, researchers at Mercedes-Benz maker Daimler used IBM's quantum computers to help them design next-generation lithium batteries for electric vehicles by simulating the complex chemistry of the cells. IBM already allows companies and scientific bodies to run algorithms on its US-based quantum computers, via the cloud.

D-Wave already has a partnership with Volkswagen AG (Germany) aimed at applying its quantum computing technology to Volkswagen's real-world computing challenges

France

All components of the French academic, research, industrial and financial sectors can be expected to be involved in EU's QFlag. France will undoubtedly be a major player. France has 19 supercomputers, but no quantum computer.

In January 2020, France unveiled its National Strategy for Quantum Technologies. It calls for investment of €1.4 billion over five years from sources including the public sector, private sector, local governments, and EU support. Other key elements of the plan include
. -Formation of 20 exploratory projects with annual budgets of up to €10 million per year;
.- Creation of 3 Centers of Excellence;
.- Launch of 50 quantum startups by 2024; and
.- Establishment of a late-stage investment fund of €300 to 500 million.

Italy

All components of the Italian academic, research, industrial and financial sectors can be expected to be involved in EU's QFlag. Italy will undoubtedly be a major player. Italy has 7 supercomputers, including two in the TOP500, but no quantum computer.

Italy has one of the largest scientific communities in this sector: more than 60 working groups with some of the most authoritative researchers and scientists.

The Italian Ministry of University and Research (MUR) appointed the National Research Council of Italy (CNR) to co-ordinate the Italian efforts within the European Flagship. It has been at the forefront in the development of the quantum programme, co-financing the Flagship anticipatory programmes QuantERA, leading to the success of 23 projects with Italian participants out of 38 overall.

After the award of one of the two major Flagship Simulation projects, the CNR approved the construction of an Infrastructure for Simulation and Quantum Computing (called with the acronym PASQUA) which will operate in Pisa and Florence.

In another area, Quantum Communication, which includes methods of "teleportation" of the single quantum state, will be able not only to connect the quantum computers, but also to make communication systems intrinsically unassailable.

Netherlands

Out of the TOP500 supercomputers, the Netherlands had 15. They are the NA1 to NA15, all Lenovo Xeons, all occupying rank positions from Nos 345 to 349, 365 to 370 and 373, 376, and 378 and 379. She has no quantum computer.

In February 2020, QuTech, a partnership between TU Delft and the TNO (Netherlands Organization for Applied Scientific Research), and Intel outlined the key technical features of their jointly developed a new cryogenic quantum control chip “Horse Ridge” at the 2020 International Solid-State Circuits Conference (ISSCC) in San Francisco. The paper unveiled the capabilities of Horse Ridge that address fundamental challenges in building a quantum system powerful enough to attain quantum practicability - scalability, flexibility and fidelity. (See under Significant Breakthroughs in Q3.)

UK

Out of the TOP500 supercomputers, the UK had 10 (while Ireland had 15.). Its highest ranked was the Cray X40 Xeon at the UK Meteorological Office, which stood at No 32. UK has no quantum computer

Her first quantum computer will be a Rigetti, jointly owned with Rigetti Computing of US. The £10m, three-year project, co-funded by government and industry, will build the quantum computer at Abingdon, Oxford. It will also be a first commercial computer undertaking client computing jobs, following Rigetti's unique full-stack services.

National Quantum Technologies Programme

In the Autumn of 2013, the UK government announced an investment of £270 million over five years in a National Quantum Technologies Programme (UKNQTP).

During the first phase of the programme (2014 – 2019), the Engineering and Physical Sciences Research Council (EPSRC), the UK's main agency for research in engineering and the physical sciences, funded a national network of **four Quantum Technology Hubs** through a £120 million investment over five years.

As part of their investments in the second phase, EPSRC has refreshed the Quantum Technology Hubs with another £94 million investment in the four hubs over five years.

The primary focus of the UKNQTP are four 'hubs' for quantum technologies:

- Quantum Hub for Sensors and Metrology, led by the University of Birmingham
- Quantum Communications Hub, led by the University of York,
- Quantum Hub for Networked Quantum Information Technologies, (NQIT), led by the University of Oxford
- Quantum Hub for Quantum Enhanced Imaging (QuantIC:), with a central team at the University of Glasgow

The programme is a coordinated effort between the Department for Business, Innovation and Skills (BIS), the Engineering and Physical Sciences Research Council (EPSRC), Innovate UK and the National Physical Laboratory (NPL), in partnership with the Defence Science and Technology Laboratory (DSTL) and the Government Communications Headquarters (GCHQ).

National Strategy Roadmap, 2015

A National Strategy was published in March 2015 and was followed by a roadmap. The quantum technology road identified seven groups of technologies believed to have near (0-5 years), mid (5-10 years) or long-term (10-plus years) potential for commercial exploitation.

<u>Short -erm (0-5 years):</u>

- components for quantum systems
- quantum clocks
- non-medical imaging technologies (electro-magnetic, gravity imagers, single photon imaging)
- quantum secure communications (point-to-point secure communications)

<u>Mid-term (5-10 years):</u>

- medical imaging technologies
- navigation (precision inertial navigation)
- second generation components (solid-state, miniaturised, self-contained quantum devices, for example accelerometers)

<u>Long -term (10 years+)</u>

- quantum secure communications (complex network communication)
- quantum technologies in consumer applications
- O quantum computing

Japan

Of the TOP500 supercomputers, Japan has 29, including the Fugaku (Fujtsu) at REIKEN, the world's No 1.

Quantum Roadmap

Japan targets to develop full-fledged quantum computers for a broad range of uses by around 2039. Industry, academia, and government are expected to join forces on the effort, which promises to yield innovations in fields like manufacturing and financial services.

Under the government road map, Japan will aim to produce a 100-qubit machine in about 10 years, followed by a more powerful, full-fledged quantum computer by around 2039.

The proposed road map calls for building at least five quantum innovation centers over the next five years.

Japan sees quantum computing as a priority area for research and development alongside artificial intelligence and biotechnology.

The technology will be one "moonshot" R&D programme in which the government will invest a total of 100 billion yen.

The road map also covers related areas such as sensors, communications, and encryption, as well as materials. With quantum computing expected to transform fields like telecommunications, drug manufacturing, finance and logistics, Japan aims to apply the technology to the country's existing strengths such as the development of materials.

The government will seek about 30 billion yen ($276 million) in funding for quantum research for the budget year beginning April 2020, roughly double the year-earlier request.

IBM quantum computing hardware comes to Japan

Thanks to the Japan-IBM Quantum Partnership, a new initiative led by IBM and the University of Tokyo, IBM quantum computing hardware comes to Japan
.
The partnership follows a similar one in Germany. Both deals see IBM's recently released commercial quantum computer IBM-Q System One installed locally, bringing the number of installations worldwide to three.

As with the German agreement the goal is to work together on advancing quantum computing research and applications. While IBM is bringing its quantum computer to Japan, the latter government, for its part, pledged to inject USD717 million over two years in broader research in the field.

The aim in Japan is three-fold: to get universities across Japan to take part in accelerating quantum computing research and education; to engage industry and advance practical research in applications; and to develop and commercialize quantum computing system hardware components for building future quantum machines.

IBM already has a head-start in Japan with a hub at Keio University in Tokyo launched in 2017, which is collaborating with four industry partners in the country: MUFG Bank, Mizuho Financial Group, JSR Corporation and Mitsubishi Chemical Company. Together with Keio, these industry partners have pursued and published groundbreaking work on applying quantum computing to understand the complex processes in Lithium-ion batteries, discover new materials for making semiconductor chips, improve the accuracy of risk analysis in finance, and improve the efficacy of machine learning for a broad set of use cases across industries. The new deal will bring the hub into the broader Japan-IBM Quantum Partnership framework as more companies join, spanning finance, chemistry and materials, pharmaceuticals, automotive manufacturing, and logistics.

But that's only one component of the deal. Another one is to set up a technology center at the University of Tokyo to develop quantum computing system hardware for next-generation quantum computers, with a lab to test advanced components and equipment in cryogenic conditions.

Finally, the third aspect of the collaboration is to advance quantum computing research and to get more young people interested in pursuing a career in the field. Universities across Japan will have access to the IBM Q System One machine – a unique resource that should help foster a broader future workforce.

Russia

Of the TOP500 supercomputers, Russia has 2, the NVIDIA Tesla V100, which ranks at No 35, and the other the Lomonosov-2, which ranks at No.130. At present they also have two other supercomputers serving the military.

Russia has launched an effort to build a working quantum computer, in a bid to catch up with US and China.

India

Of the TOP500 supercomputers, India has 2, the Pratyush, Cray XC40 Xeon at No 66 and the Mihir, Cray XC40, Xeon at No. 119. She has no quantum computers.

Quantum technology has been given a massive boost in India's latest budget, receiving 80 billion rupees (US$1.12 billion) over five years as part of a new national quantum mission.

India's considerable investment in the field places it alongside the United States, Europe and Russia.

India's investment, to be administered by the Ministry of Science and Technology, is a considerable increase on past commitments. In 2018, a quantum-technology research programme received US$27.9 million over five years, as part of the National Mission on Interdisciplinary Cyber-Physical Systems.

The new mission will oversee the development of quantum technologies for communications, computing, materials development and cryptography. It will coordinate the work of scientists, industry leaders and government departments.

Overall, India's Science Ministry, which oversees the department of science and technology; biotechnology; and scientific and industrial research, received 144 billion rupees in the 2020–21 budget, a 10.8% increase over promised funds in the 2019–20 budget.

SINGAPORE

Of the TOP500 supercomputers, Singapore has four, all of them being the Lenovo C1040, Xeon ES-2673v4 20 C 2.3 GHz, and ranked Nos.354.355, 364 and 374, respectively.

Thanks to the investment in the Centre for Quantum Technologies (CQT), Singapore is a world-player in the quantum field. The Centre was established in 2007 at the National University of Singapore (NUS).

In April 2020, IBM and the NUS announced a three-year collaboration to find ways to use quantum computing to solve real-world problems and train quantum scientists. The collaboration gives NUS researchers access to IBM's powerful quantum computing systems via cloud.

The CQT is perhaps one model of how countries and centres without a quantum computer can help foster the quantum industry, and leap-frog developments into the quantum market.

In 2018, it helped spawn Horizon QC. This was the latter's cue-in. "As hardware development continues to advance, learning to harness the power of quantum processors for business applications will become the main barrier to adoption." It is developing tools to automatically accelerate programmes written for conventional computers, helping conventional software developers make the leap to programming quantum computers.

Another CQT-linked startup company Entropica Labs is also working on software for quantum computers, At Entropica, "we create the models, algorithms and software tools to make quantum computing useful."

The above Singapore based companies are two among 12 companies named as partners by Rigetti, when they introduced their new Quantum Cloud Service (QCS) at the TechCrunch Disrupt conference in San Francisco, in September 2018

The Singapore Management University (SMU), Fujitsu & A*Star have gone into partnership to tap the potential of quantum computing. There are 13 semiconductor manufacturers in Singapore. I wonder how many could do qubits. The Nanyang Technological University (NTU) has a Quantum Engineering department, exploring the application of quantum technology outside quantum computing.

(Back to TOC)

Where We are

It has been slightly over 20 years since creation of the **first quantum processor** (2-qubit) that could be loaded with data and output a solution. As we close Q2, we are here:

Comp -any	**Total Units**	**Yr**	**Quantum Computer**	**Off-Shore/Cloud Computing**
D-Wave	6	2011	D-Wave One	128-qubit. Annealing
		2013	D-Wave Two	512-qubit. Do
		2015	D-Wave 2X	1152 qubits. Do
		2017	D-Wave 2000Q	2048 qubits. Do
		2020	D-Wave Advantage	5640 qubits. Do, Market ready
		2020	LEAP	Cloud-based client access to quantum computing. (Oct 2020)
Rigetti	3	2017	19Q Acorn	19 qubits
		2018	FOREST 1.0	Quantum Cloud Services
		2018	8Q Agve	8 qubits. Superconducting
		2018	16 Q Aspen 1	16 qubits. Do
		2020	31 Q Aspen 8	31 qubits. Do. Market ready
Google	3	2018	Bristlecone	72 qubits. Superconducting
		2019	Sycamore	53 qubits. Do. r
IBM	28	2016	IBM Q5 Tenerife,	5 qubits. Superconducting
		2016	IBM Q5, Yorktown	5 qubits. Do
		2016	IBM Q14, Melbourne	14 qubits. Do
		2017	IBM Q17	17 qubits. Do
		2017	IBM Q20, Tokyo	20 qubits. Do
		2017	IBM Q Experience	Cloud-based professionals access to quantum computing.

		2019	IBM Q53 (QV 64)	53 qubits. Do
		2019	IBM Q Network	Cloud-based client access to quantum computing
		2019	IBM System One (QV 16)	20 qubits. Do. Market ready
		2019	IBM Q65. Hummingbird	65 qubits, Do. Cloud use.
		2019	IBM Q Quantum Computation Center	Cloud-based Client access to integrated quantum computing services
Honeywell	2	2020	Honeywell H0 (QV 64)	6 qubits. Ion Trap
		2020	Honeywell H1 (QV 128)	32 qubits. Ion Trap
IonQ	1	2020	IonQ-5th (QV 4 million)	32 qubits. Ion Trap.

Over twenty years, we have five different manufacturers of quantum computers and some 40[59] units around, and significant cloud access. Individual quantum computers have demonstrated Quantum Supremacy on specific jobs, but no computer is within sniffing distance of Quantum Advantage[60],

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* * *

[59] Based on List of Quantum Processors (Wiki), adjusted to exclude retirees and including latest available this year. Unfortunately, some companies (except IBM) fudge their figures of those actually with clients, ie sold/

[60] Quantum Advantage means out-performing the supercomputer on standardised tasks, and thereon on grow to take on tasks supercomputers cannot perform or will take a long time, like 1,000 years .

THIRD QUANTUM GENERATION (Q3)

Quantum Advantage

Quantum Advantage[61]**,**

Quantum Advantage is reached when a quantum computer having attained hardware and software maturity and operating within acceptable limits of efficiency, can out-perform supercomputers in a range of specified tasks – with significant actual and potential gains.

As at 2019, the US National Academy of Sciences in its Report Quantum Computing: Progress and Prospects made this assessment:

> "The time to create a large fault-tolerant quantum computer that can run Shor's algorithm to break RSA 2048, run advanced quantum chemistry computations, or carry out other practical applications likely is more than a decade away. These machines require **roughly 16 doublings of the number of physical qubits, and 9 halvings of qubit error rates.**[62]**"**

The report assessed that, as at the technology of 2018, to reach Quantum Advantage, the industry would need to reach a minimum qubit scale of 2^{16} =65,536, at the improved error rates and logical qubit attainment. As a 2021, IBM will (hopefully) attain a qubit scale of 127 ($2^{127)}$ well surpassing it – on qubit count alone.

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61 Quantum Advantage means out-performing the supercomputer on standardised tasks, and thereon on grow to take on tasks supercomputers cannot perform or will take a long time, like 1,000 years .

62 https://www.nap.edu/read/25196/chapter/1

Significant Breakthroughs

IBM

Looking Ahead

IBM have taken the long view that, despite the extraordinary engineering challenges and sensivities, the focus must be to build a quantum computer that would be a stable, efficient and comfortable-to-work-with machine that would meet the exponentially widening computing needs of the next generations.

It had to be scalable. And it should preferably be able to operate in a normal environment (as near as can be) and in the double-long run be portable to enterprise level at least - both by down-scaling and by cloud.

The quantum computer should work seamlessly with supercomputers, and eventually succeed them.

Dario Gil, IBM's relatively new director of research, painted an intriguing portrait of the future of computing along with a rough idea of how IBM thinks we'll get there, at last month's (September 2019) MIT-IBM Watson's Research Week held at MIT.

> "We're beginning to see an answer to what is happening at the end of Moore's law. It's a question that has been the front of the industry for a long, long time," said Gil in his talk. "And the answer is that we're going to have this new foundation of bits plus neurons plus qubits coming together, over the next decade [at] different maturity levels – bits [are] enormously mature, the world of neural networks and neural technology, next in maturity, [and] quantum the least mature of those. [It] is important to anticipate what will happen when those three things intersect within a decade."

> "Not by coincidence IBM Research has made big bets in all

three areas. It's neuromorphic chip (True North) and 'analog logic' research efforts (e.g., Phase Change Memory) are vigorous. Given the size and scope of its IBM Q Systems and Q networks, it seems likely that IBM is spending more on quantum computing than any other non-governmental organization. Lastly, of course, IBM hasn't been shy about touting Summit and Sierra supercomputers, now ranked one and two in the world (Top 500), as the state of the art in heterogeneous computing architectures suited for AI today. In fact, IBM recently donated a 2 petaflops system (Satori) to MIT that is based on the Summit design and well-suited for AI and hybrid HPC-AI workloads.[63]

IBM Roadmap

IBM forecasts: "**This roadmap puts us on a course toward the future's million-plus qubit processors.**"

"The future's quantum computer will pick up the slack where classical computers falter, controlling the behavior of atoms in order to run revolutionary applications across industries, generating world-changing materials or transforming the way we do business.

Today, we are releasing the roadmap that we think will take us from the noisy, small-scale devices of today to the million-plus qubit devices of the future. Our team is developing a suite of scalable, increasingly larger and better processors, with a 1,000-plus qubit device, called IBM Quantum Condor, targeted for the end of 2023. In order to house even more massive devices beyond Condor, we're developing a dilution refrigerator larger than any currently available commercially. This roadmap puts us on a course toward the future's million-plus qubit processors thanks to industry-leading knowledge, multidisciplinary teams, and agile methodology improving every element of these systems.

All the while, our hardware roadmap sits at the heart of a larger mission: to design a full-stack quantum computer deployed via

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[63] https://www.hpcwire.com/2019/10/14/crystal-ball-gazing-ibms-vision-for-the-future-of-computing/

the cloud that anyone around the world can program.

Simultaneous to our efforts to improve our smaller devices, we are also incorporating the many lessons learned into an aggressive roadmap for scaling to larger systems. In fact, this month we quietly released our 65-qubit **IBM Quantum Hummingbird** processor to our IBM Q Network members. This device features 8:1 readout multiplexing, meaning we combine readout signals from eight qubits into one, reducing the total amount of wiring and components required for readout and improving our ability to scale, while preserving all of the high-performance features from the Falcon generation of processors. We have significantly reduced the signal processing latency time in the associated control system in preparation for upcoming feedback and feed-forward system capabilities, where we'll be able to control qubits based on classical conditions while the quantum circuit runs.

Next year, we'll debut our **127-qubit IBM Quantum Eagle** processor. Eagle features several upgrades in order to surpass the 100-qubit milestone: crucially, through-silicon vias (TSVs) and multi-level wiring provide the ability to effectively fan-out a large density of classical control signals while protecting the qubits in a separated layer in order to maintain high coherence times. Meanwhile, we've struck a delicate balance of connectivity and reduction of crosstalk error with our fixed-frequency approach to two-qubit gates and hexagonal qubit arrangement introduced by Falcon. This qubit layout will allow us to implement the "heavy-hexagonal" error-correcting code that our team debuted last year, so as we scale up the number of physical qubits, we will also be able to explore how they'll work together as error-corrected logical qubits—every processor we design has fault tolerance considerations taken into account. With the Eagle processor, we will also introduce concurrent real-time classical compute capabilities that will allow for execution of a broader family of quantum circuits and codes.

The design principles established for our smaller processors will set us on a course to release a **433-qubit IBM Quantum Osprey system in 2022.** More efficient and denser controls and cryogenic infrastructure will ensure that scaling up our processors doesn't sacrifice the performance of our individual qubits, introduce further sources of noise, or take up too large a footprint.

In 2023, we will debut the 1,121-qubit IBM Quantum Condor processor, incorporating the lessons learned from previous processors while continuing to lower the critical two-qubit errors so that we can run longer quantum circuits. We think of Condor as an inflection point, a milestone that marks our ability to implement error correction and scale up our devices, while simultaneously complex enough to explore potential Quantum Advantages—problems that we can solve more efficiently on a quantum computer than on the world's best supercomputers.

The development required to build Condor will have solved some of the most pressing challenges in the way of scaling up a quantum computer. However, as we explore realms even further beyond the thousand qubit mark, today's commercial dilution refrigerators will no longer be capable of effectively cooling and isolating such potentially large, complex devices.

That's why we're also introducing a 10-foot-tall and 6-foot-wide "super-fridge," internally codenamed **"Goldeneye,"** a dilution refrigerator larger than any commercially available today. Our team has designed this behemoth with a million-qubit system in mind—and has already begun fundamental feasibility tests. Ultimately, we envision a future where quantum interconnects link dilution refrigerators each holding a million qubits like the intranet links supercomputing processors, **creating a massively parallel quantum computer capable of changing the world.**

Knowing the way forward doesn't remove the obstacles; we face some of the biggest challenges in the history of technological progress. But, with our clear vision, a fault-tolerant quantum computer now feels like an achievable goal within the coming decade."[64]

[64] **IBM Road Map 2023**This notification in Google is reproduced with some pruning of paragraphs, not text."
https://www.ibm.com/blogs/research/2020/09/ibm-quantum-roadmap/

INTEL (and QU Tech)

Scaling the Quantum Computing System

Tangle Lake

In October 2017, Intel had released their first quantum chip of 17-qubits. In January 2018, at the CES (formerly known as the Consumer Electronics Show), Intel unveiled their next qubit, a superconductor quantum **test chip** of 49-qubits, code-named “Tangle Lake”. The chip was named after a chain of lakes in Alaska, a nod to the extreme cold temperatures and the entangled state that quantum qubits required to function In. This device represents the third generation of quantum processors produced by Intel.

Tangle Lake represented progress toward Intel’s goal of developing a complete quantum computing system – from architecture to algorithms to control electronics.

The need to scale to greater numbers of working qubits is why Intel, in addition to investing in superconducting qubits, is also researching another type called spin qubits in silicon. Spin qubits could have a scaling advantage because they are much smaller than superconducting qubits. Spin qubits resemble a single electron transistor, which is similar in many ways to conventional transistors and potentially able to be manufactured with comparable processes. In fact, Intel have already invented a spin qubit fabrication flow on its 300mm process technology.

With its own quantum chip, all Intel needed was a cryogenic control chip.

Horse Ridge

To grow to mature proportions, the quantum computer must have scalability. Intel teamed up with QuTech of the

Netherlands to address this precise challenge. The result is called Horse Ridge—an integrated circuit named after one of the coldest spots in Oregon.

They have designed and fabricated a CMOS[65] integrated circuit able to control up to 128 qubits, which can operate at 3 K (-270 °C) and can therefore be described as a cryo-CMOS circuit." CMOS is the same technology employed for standard microprocessors. Using CMOS therefore enables the reliable fabrication of very complex circuits comprising billions of electrical components, as required for large-scale quantum computers.

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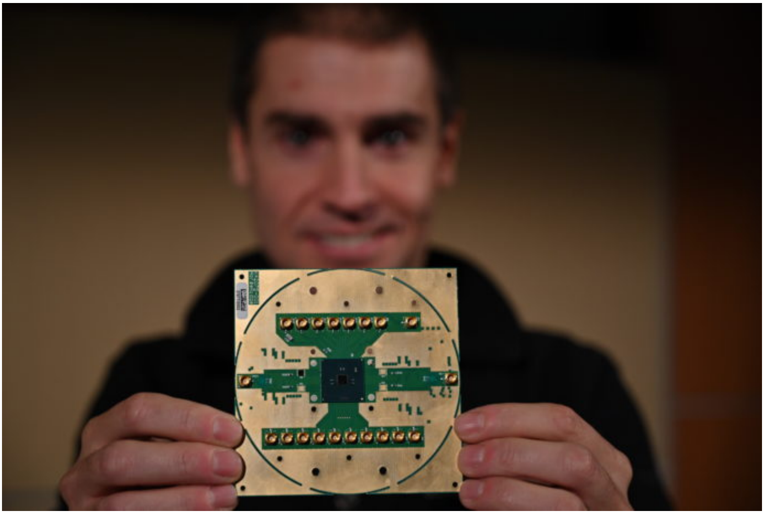
[65] Complementary Metal Oxide Semiconductor)

Intel and QuTech Unveil Details of First Cryogenic Quantum Computing Control Chip, 'Horse Ridge'

In view of its momentous potential importance, we include the following announcements in full (with minor textual improvements.):



Stefano Pellerano, principal engineer at Intel Labs, holds Horse Ridge. The new cryogenic control chip. Attribution: from the quoted article & Wiki Commons

INTEL NEWS RELEASE – 19 FEBRUARY 2020

Intel Labs, in collaboration with QuTech - a partnership between TU Delft and TNO (Netherlands Organization for Applied Scientific Research) – unveiled its new cryogenic quantum control chip "Horse Ridge" in a research paper released at the 2020 International Solid-State Circuits Conference (ISSCC) in San Francisco. The paper unveils key technical capabilities of Horse Ridge that address fundamental challenges in building a quantum system powerful enough to demonstrate quantum practicality: scalability, flexibility and fidelity.

“Today, quantum researchers work with just a small number of qubits, using smaller, custom-designed systems surrounded by complex control and interconnect mechanisms. Intel’s Horse Ridge greatly minimizes this complexity. By systematically working to scale to thousands of qubits required for quantum practicality, we’re continuing to make steady progress toward making commercially viable quantum computing a reality in our future.”
–Jim Clarke, director of quantum hardware, Intel Labs

Why It’s Important:
The quantum research community is at mile one of a marathon toward demonstrating quantum practicality. Applying quantum computing to practical problems hinges on the ability to scale to, and control, thousands of qubits at the same time with high levels of fidelity. Horse Ridge greatly simplifies today’s complex control electronics required to operate such a quantum system by using a highly integrated system-on-chip (SoC) for faster setup time, improved qubit performance and efficient scaling to larger qubit counts required for quantum computing to solve practical, real-world applications.

Key technical details[66:] (optional reading)

Scalability: The integrated SoC design, implemented using Intel’s 22nm FFL (FinFET Low Power) CMOS technology, integrates four radio frequency (RF) channels into a single device. Each channel is able to control up to 32 qubits leveraging “frequency multiplexing” – a technique that divides the total bandwidth available into a series of non-overlapping frequency bands, each of which is used to carry a separate signal.

Leveraging these four channels, Horse Ridge can potentially control up to 128 qubits with a single device, substantially reducing the number of cables and rack instrumentations

[66] https://newsroom.intel.com/news/intel-qutech-unveil-details-first-cryogenic-..quantum-computing-control-chip-horse-ridge/#gs.m0a5vq

previously required.

Fidelity: Increases in qubit count trigger other issues that challenge the capacity and operation of the quantum system. One such potential impact is a decline in qubit fidelity and performance. In developing Horse Ridge, Intel optimized the multiplexing technology that enables the system to scale and reduce errors from "phase shift" – a phenomenon that can occur when controlling many qubits at different frequencies, resulting in crosstalk among qubits.

The various frequencies leveraged with Horse Ridge can be "tuned" with high levels of precision, enabling the quantum system to adapt and automatically correct for phase shift when controlling multiple qubits with the same RF line, improving qubit gate fidelity.

Flexibility: Horse Ridge can cover a wide frequency range, enabling control of both superconducting qubits (known as transmons) and spin qubits. Transmons typically operate around 6 to 7 GHz, while spin qubits operate around 13 to 20 GHz.

Intel is exploring silicon spin qubits, which have the potential to operate at temperatures as high as 1 kelvin. This research paves the way for integrating silicon spin qubit devices and the cryogenic controls of Horse Ridge to create a solution that delivers the qubits and controls in one streamlined package.[67]

QU TECH NEWS RELEASE- 18 FEBRUARY 2020

"QuTech has resolved a major issue on the road toward a working large-scale quantum computer. QuTech, a collaboration of TU Delft and TNO, and Intel have designed and fabricated an integrated circuit that can controlling qubits at extremely low temperatures. This paves the way for the **crucial integration of qubits and their controlling electronics in the same chip.** The scientists have presented their research during the ISSCC Conference in San Francisco.

Quantum computers: "This result brings us closer to a large-

[67] https://newsroom.intel.com/news/intel-qutech-unveil-details-first-cryogenic-..quantum-computing-control-chip-horse-ridge/#gs.m0a5vq

scale quantum computer which can solve problems that are intractable by even the most powerful supercomputers. Solutions to those problems can make a strong impact on everyday life, for instance in the fields of medicine and energy," said team lead Fabio Sebastian from QuTech and the Faculty of Electrical Engineering, Mathematics and Computer Science.

Extreme temperatures: "There are many issues to be resolved before we have a working large-scale quantum computer," said Sebastiano. "The quantum information stored in qubits can rapidly degrade and become unusable unless qubits are cooled down to temperatures very close to absolute zero (-273 degrees Celsius, or 0 Kelvin). **For this reason, qubits typically operate inside special refrigerators at temperatures as low as 0.01 K, controlled by conventional electronics working at room temperature.**

Scaling up: One wire is required to connect each qubit to the control electronics. While this is feasible for the small number of qubits now in operation, the approach will become impractical for the millions of qubits required in useful quantum computers. "It would be equivalent to taking the 12-megapixel camera on your mobile phone and trying to individually wire each of the million pixels to a separate electronic circuit," said Sebastiano. "A more viable solution is to operate the electronics controlling the qubits at extremely low (cryogenic) temperatures, so they can be placed as close as possible to the qubits.[68]"

Assessment

Intel's Horse Ridge is a major break-through addressing the industry's more serious problem area of error control. This in turn will enhance the scale-up of qubits. It will immediately be hugely welcomed the superconducting qubit fraternity, as well as those working with other qubit alternatives, like the quantum dot, etc. It will also be adaptable to enhance various

68 https://venturebeat.com/2020/02/18/intel-and-qutech-unveil-horse-ridge-cryogenic-control-chip-for-quantum-computing/

non-photonic supporting functions of the trapped ion chip (see next section below).

MIT

First Trapped-Ion Quantum Chip with Fully Integrated Photonics

Superconducting qubits, used by IBM and several others, constitute our current mainstream technology. Even so, trapped-ion qubits are the most mature qubit technology. It dates back to the 1990s and its first use in atomic clocks. Honeywell and IonQ are today the front-line proponents of trapped ion qubits.

On 21 October, 2020 (last week) , *Nature* published[69] an article **"Integrated multi-wavelength control of an ion qubit"** under the names of 11 researchers from the Massachusetts Institute of Technology (MIT) headed by Professor R J Niffenegger, which could be a turning point in the current quantum computer race. They had figured out how to use optical fibers and photonics to carry laser pulses directly into the qubit chamber and focus them on the individual ions in the chip. They announced successful development of an trapped ion qubit chip with fully integrated photonics.

The outstanding feature was delivering all the required frequencies of laser light, and carrying out the manipulations thereof, through a device plugged directly into the qubit chip itself and addressing the qubits therein, in the cryogenic chamber.

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69 https://www.nature.com/articles/s41586-020-2811-x

TECHNICAL NOTE

Abstract (of article)

> “Trapped atomic ions can form the basis of high-fidelity quantum information processors and high-accuracy optical clocks. However, current implementations rely on free-space optics for ion control, which limits their portability and scalability.
>
> Here we demonstrate a surface-electrode ion-trap chip using integrated waveguides and grating couplers, which delivers all the wavelengths of light required for ionization, cooling, coherent operations and quantum state preparation and detection of qubits.
>
> Laser light from violet to infrared is coupled onto the chip via an optical-fibre array, creating an inherently stable optical path, which we use to demonstrate qubit coherence that is resilient to platform vibrations. This demonstration of CMOS-compatible integrated photonic surface-trap fabrication, robust packaging and enhanced qubit coherence is a key advance in the development of portable trapped-ion quantum sensors and clocks, providing a way towards the complete, individual control of larger numbers of ions in quantum information processing systems”[70].

Honeywell and IonQ both create trapped-ion qubits using an isotope of rare-earth metal called ytterbium. In its chip using integrated photonics, MIT used an alkaline metal called **strontium.** The process to create ions is essentially the same. Precision lasers remove an outer electron from an atom to form a positively charged ion. Then, lasers are used like tweezers to move ions into position. Once in position, oscillating voltage fields hold the ions in place. One main advantage of ions lies in the fact that it is natural instead of fabricated. All trapped-ion qubits are identical. A trapped-ion

[70] https://www.nature.com/articles/s41586-020-2811-x

qubit created on earth would be the perfect twin of one created on another planet.

Dr. Robert Niffenegger, a member of the Trapped Ion and Photonics Group at MIT Lincoln Laboratory, led the experiments and explained why strontium was used for the MIT chip instead of ytterbium, the ion of choice for Honeywell and IonQ. "The photonics developed for the ion trap are the first to be compatible with violet and blue wavelengths," he said. "Traditional photonics materials have very high loss in the blue, violet and UV. Strontium ions were used instead of ytterbium because strontium ions do not need UV light for optical control.[71]"

In the Honeywell case, all the manipulation of ions takes place inside a vacuum chamber containing a trapped-ion quantum processor chip. In addition to creating ions and moving them into position, lasers perform necessary quantum operations on each qubit. Because lasers and optical components are large, it is by necessity located outside the vacuum chamber. Mirrors and other optical equipment steer and focus external laser beams through the vacuum chamber windows and onto the ions.

The largest number of trapped-ion qubits being used in a quantum computer today is 32. For quantum computers to be truly useful, millions of qubits are needed. Of course, that means many thousands of lasers will also be required to control and measure the millions of ion qubits. The problem becomes even larger when two types of ions are used, such as ytterbium and barium in Honeywell's machine. The current method of controlling lasers makes it challenging to build trapped-ion quantum computers beyond a few hundred qubits.

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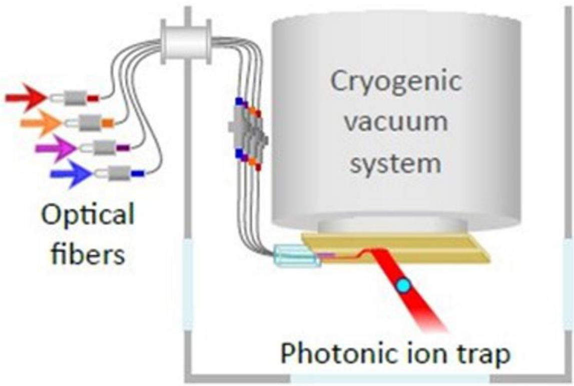
[71] https://www.forbes.com/sites/moorinsights/2020/10/26/mit-lincoln-laboratory-creates-the-first-trapped-ion-quantum-chip-with-integrated-photonics/?sh=41f63861126a

Rather than resorting to optics and bouncing lasers off mirrors to aim beams into the vacuum chamber, MIT researchers have developed another method to use optical fibers and photonics to carry laser pulses directly into the chamber and focus them on individual ions on the chip.

A trapped-ion strontium quantum computer needs lasers of six different frequencies. Each frequency corresponds to a different color that ranges from near-ultraviolet to near-infrared. Each color performs a different operation on an ion qubit.

"Lincoln Laboratory researchers have developed a compact way to deliver laser light to trapped ions. In the Nature paper, the researchers **describe a fiber-optic block that plugs into the ion-trap chip, coupling light to optical waveguides fabricated in the chip itself.** Through these waveguides, multiple wavelengths [colors] of light can be routed through the chip and released to hit the ions above it."



(Diagram reproduced as part of the Internet article.)

In other words, rather than using external mirrors to shine lasers into the vacuum chamber, MIT researchers used multiple optical fibers and photonic waveguides. A block equipped with four optic fibers delivering a range of colors was mounted on the quantum chip's underside. According to Niffenegger, "Getting the fiber block array aligned to the waveguides on the chip and applying the epoxy felt like performing surgery. It was a very delicate process. We had about half a micron of tolerance, and it needed to survive cool down to 4 Kelvin."[72]

Dr. Niffenegger expressed his thoughts about the long-term implications of his team's development.

> "I think many people in the quantum computing field think that the board is set and all of the leading technologies at play are well defined. I think our demonstration, together with other work integrating control of trapped ion qubits, could tip the game on its head and surprise some people that maybe the rules aren't what they thought. But really I just hope that it spurs more out of the box ideas that could enable quantum computing technologies to break through towards practical applications."
>
> Analyst Notes:
> Integrating optical waveguides into ion traps represents a step forward toward the goal of building a useful quantum computer with thousands to millions of qubits. MIT's technique also provides a development path for portable trapped-ion quantum sensors and clocks.
>
> Integrated photonics is inherently resistant to vibrations. With external lasers, vibrations cause pulses to miss the ion. Integrated optics should eliminate most effects of vibrations. The stability offered by integrated photonics will help qubits maintain quantum states longer so that deeper and more complex computations can be performed.
>
> Initially I had some concerns about loss of optical power due to compromises that may have been made in the grating coupler to accommodate different wavelengths. Keep in mind there are

[72] https://www.forbes.com/sites/moorinsights/2020/10/26/mit-lincoln-laboratory-creates-the-first-trapped-ion-quantum-chip-with-integrated-photonics/?sh=6f399bbf126a

four fibers and six colors. The shortest of the six laser wavelengths is 405 nm and the longest is 1092 nm. Dr. Niffenegger pointed out there are separate gratings for the shortest and longest wavelengths. He also said there are some power losses, but they are in the path from where light enters the optical waveguide to where it exits the coupler grating. Despite this minor optical power loss, tighter focus provided by the existing diffraction gratings provides enough power for operations on the ions.

Dr. Niffenegger and the MIT research team will focus future research on reducing two qubit gate errors caused by heating of the motional state of ion qubits. The rate at which ions heat up is much higher in traps with integrated photonic chips than traditional surface traps without photonics:”[73]

IonQ

On 3 Oct 2020 (this month), **IonQ** announced their 5th-generation quantum computer, with 32 qubits and a Quantum Volume (QV) in excess of 4,000,000. If this became accepted in applications of the relevant scale to test this QV in full action, it would represent a “quantum leap” for the industry.[74]

IonQ explained they decided to calculate the quantum volume rather than run the quantum volume algorithms: They were putting in the final production optics and would be able to get a final number on the machine. The four million number required only 22 qubits with 99.9% fidelity

IoQ’s quantum computer used trapped ion technology, like that of Honeywell’s HI. The quantum computer also allowed random access on all-to-all gate operation, and incorporated a new error correction code that used 13 qubits. We await details of this possible breakthrough. For the moment, I am resting with what we have.

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[73] Ibid

[74] https://ionq.com/news/october-01-2020-most-powerful-quantum-computer

Assessment

MIT's integrated photo tonics of the trapped ion qubit looks very promising indeed, if on further development it can prove superior and more cost effective to the Horse Ridge in the realms of error elimination and qubit up-scaling. It could give the trapped ion the advantage in the intermediate term, especially as it seems the qubit control system of the superconducting qubit relies on radio frequencies rather than light. But there is still a long way to go. It depends also on the weight of investment. The one that breaks the NISQ barrier first will win. Perhaps there is a place for both, and more than two technologies.

It is necessary however to surface from the present technical experimentation and incremental gains. We are still fumbling. A quantum computer is only meaningful when we can carry out a broad range of the next generation of computations that the supercomputer cannot do, at an acceptable level of technical mastery and efficiency. Quantum Supremacy and Quantum Advantage are meaningless terms in the context of achieving this.

In the next section, we look at an alternative technology.

MICROSOFT

The Microsoft Way

Before we proceed to discussion of the topological qubit, because of its potentially sweeping value, I quote Microsoft (slightly abridged):

> "MICROSOFT 6 June 2018
> "While many people assume that quantum computers will replace classical computers, in reality, both technologies will work together to solve these problems. It can be helpful to think

of a quantum computer as a specialized processor used for applicable scenarios. Similarly, as classical computers run computations, the workloads or problems best suited for quantum could be processed by the quantum computer.

The Full Stack

The process of building a quantum computer includes creating the raw materials needed to make topological quantum devices, fabricating the cold electronics and refrigeration systems, and developing the overall infrastructure needed to bring the solution to life. In addition, our system includes everything you need to program the quantum computer, including a control system, software, development tools, and Azure services—a combination we refer to as our full quantum stack.

Because quantum and classical work together, Microsoft Azure is a perfect environment for quantum processing and deployment. With data stored in Azure, developers will be able to access quantum processing alongside classical processing, creating a streamlined experience.

As many scenarios will use both quantum and classical processing, Azure will streamline workflows as real-time or batch applications, later connecting results directly into business processes.

As with Intel, fault-free scalability is at the heart of their aim of harvesting the quantum computer's exponential potential (2^n). The noise and decoherence management issues are seen as near intractable barriers towards achieving exponential levels of growth. These arise from two sources (1) the communication and control baggage around the qubit itself, and (2) maintaining fidelity and flexibility with growing scale. Again, like Intel, Microsoft are bringing to bear their enormous experience and capacity to find a chip that help make the breakthrough.[75]

The Topological Qubit

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75 https://cloudblogs.microsoft.com/quantum/2018/06/06/the-microsoft-approach-to-quantum-computing/

For general purposes, “topology” is a branch of mathematics describing structures that experience physical changes such as being bent, twisted, compacted, or stretched, yet still maintain the properties of the original form. When applied to quantum computing, topological properties create a level of protection that helps a qubit retain information despite what’s happening in the environment.

The topological qubit achieves this extra protection in two different ways according to Microsoft:

> “Electron fractionalization. By splitting the electron, quantum information is stored in both halves, behaving similarly to data redundancy. If one half of the electron runs into interference, there is still enough information stored in the other half to allow the computation to continue.
>
> Ground state degeneracy. Topological qubits are engineered to have two ground states—known as ground state degeneracy—making them much more resistant to environmental noise. Normally, achieving this protection isn’t feasible because there’s no way to discriminate between the two ground states. However, topological systems can use braiding or measurement to distinguish the difference, allowing them to achieve this additional protection.” [76].

[76] (https://cloudblogs.microsoft.com/quantum/2018/05/16/achieving-scalability-in-quantum- computing/

Route to topology

On 27 March 2020, the Microsoft Quantum Team announced that they had found a new topology that met their requirements. It would be useful for the non-initiate (like me) to read this note first:

TECHNICAL NOTE

> A topological quantum computer is a theoretical quantum computer that employs two-dimensional quasiparticles called anyons whose world lines pass around one another to form braids in a three-dimensional space-time (i.e., one temporal plus two spatial dimensions). These braids form the logic gates that make up the computer. The advantage of a quantum computer based on quantum braids over using trapped quantum particles is that the former is much more stable. Small, cumulative perturbations can cause quantum states to decohere and introduce errors in the computation, but such small perturbations do not change the braids' topological properties. This is like the effort required to cut a string and reattach the ends to form a different braid, as opposed to a ball (representing an ordinary quantum particle in four-dimensional spacetime) bumping into a wall.
>
> Alexei Kitaev proposed topological quantum computation as early as in 1997. While the elements originated in the purely mathematical realm, experiments in fractional quantum work have indicated they may be created in the real-world using semiconductors - made of gallium at a temperature of near absolute zero and subjected to strong magnetic fields. 77

THE MICROSOFT QUANTUM TEAM on 27 March 2020 announced:

> "Our qubit architecture is based on nanowires, which under certain conditions (low-temperature, magnetic field, material choice) can enter a topological state. Topological quantum hardware is intrinsically robust against local sources of noise, making it particularly appealing as we scale up the number of qubits.

77 https://en.wikipedia.org/wiki/Topological_quantum_computer

An intriguing feature of topological nanowires is that they support Majorana[78] zero modes (MZMs) that are neither fermions nor bosons. Instead, they obey different, more exotic quantum exchange rules. If kept apart and braided around each other, similar to strands of hair, MZMs remember when they encircle each other. Such braiding operations act as quantum gates on a state, allowing for a new kind of computation that relies on the topology of the braiding pattern.

A topological qubit is constructed by arranging several nanowires hosting MZMs in a comb-like structure and coupling them in a specific way that lets them share multiple MZMs. The first step in building a topological qubit is to reliably establish the topological phase in these nanowires.

While exploring the conditions for the creation of topological superconductivity, the team discovered a topological quantum vortex state in the core of a semiconductor nanowire surrounded on all sides by a superconducting shell. They were very surprised to find Majorana modes in the structure, akin to a topological vortex residing inside of a nanoscale coaxial cable.

With hindsight, the findings can now be understood as a novel topological extension of a 50-year-old piece of physics known as the Little-Parks effect. In the Little-Parks effect, a superconductor in the shape of a cylindrical shell – analogous to a soda straw – adjusts to an external magnetic field, threading the cylinder by jumping to a “vortex state” where the quantum wavefunction around the cylinder carries a twist. The quantum wavefunction must close on itself.

Thus, the wavefunction phase accumulated by going around the cylinder must take the values zero, one, two, and so on, in units of 2π. This has been known for decades. What had not been explored in depth was what those twists do to the semiconductor core inside the superconducting shell. The surprising discovery made by the Microsoft team—experiment and theory—was a twist in the shell, under appropriate

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[78] A Majorana particle is a sub-elementary particle or quasiparticle and is its own antiparticle. Because particles and antiparticles have opposite conserved charges, Majorana have zero charge.

> conditions, can make a topological state in the core, with MZMs localized at the opposite ends.
>
> While signatures of Majorana modes have been reported in related systems without the fully surrounding cylindrical shell, these previous realizations placed rather stringent requirements on materials and required large magnetic fields. This discovery places few requirements on materials and needs a smaller magnetic field, expanding the landscape for creating and controlling Majoranas."[79]

Microsoft Azure

While fumbling about for its topological solution, Microsoft scored earlier with its software-cloud component. Azure was announced in October 2008, and released in February 2010, as Windows Azure before being renamed Microsoft Azure on in March 2014.

Microsoft Azure is a cloud computing service created for building, testing, deploying, and managing applications and services through Microsoft-managed datacenters. It provides:

.- Software as a Service (SaaS)

.- Platform as a Service (PaaS),and

.- Infrastructure as a Service,

.- Storage Services, and

.- Data Management Services.

Azure had 94 points of presence worldwide as of April 2020.

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79 https://cloudblogs.microsoft.com/quantum/2020/03/27/new-physics-discovery-microsoft-quantum-topology-with-a-twist/

Assessment

Microsoft's topological qubit is potentially the most far-reaching promise for the future: to replace the absurdly finicky and inefficient electron (and artificial electron) by using a quasiparticle in the topology of Einstein's space-time. We could be looking at a mutant, before our current first baby is fully born. It makes me shiver to think we are applying the physical laws of space-time in the nanosphere to do quantum computing of a potentially universal scale.

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NISQ Era

Error Rate

In their Report on “Quantum Computing: Progress and Prospects, 2019 (review as of mid-2018) the US National Academy of Sciences highlighted the overriding obstacle to the quantum computer to be:

> “A scalable, fully error-corrected machine (which can be thought of using the abstraction of logical qubits) capable of a larger number of operations appear to be far off. While researchers have successfully engineered individual qubits with high fidelities, it has been much more challenging to achieve this for all qubits in a large device.
>
> The average error rate of qubits in today’s larger devices would need to be reduced by a factor of 10 to 100 before a computation could be robust enough to support error correction at scale, and at this error rate, the number of physical qubits that these devices hold would need to increase by at least a factor of 105 in order to create a useful number of effective logical qubits.
>
> The improvements required to enable logical computation are significant, so much so that any predictions of time frames for achieving these requirements based upon extrapolation would exhibit significant uncertainty.”[80]

While the factors of improvement might be optimistically revised today, the scale and measure of the obstacles are no less formidable.

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80 https://www.nap.edu/read/25196/chapter/1

NISQ Era

In view of the still decades-long time-frame necessary to achieving a quantum computer reflecting its true potential, and the huge investments that must still be made, the NAS Report stresses the importance of registering some commercially viable returns, particularly in the 2020s. The report urges that this be with the **"Noisy Intermediate-Scale Quantum"** (NISQ) computer. It noted that computers in this range, on the order of hundreds of higher-quality qubits, while not fault tolerant, are robust enough to conduct some computations before decohering, and be applied in the market place. They will provide the next platform.

At a lecture at the California Institute of Technology, on 1 Jan 2018, John Preskill, Professor of Theoretical Physics, first defined the term:

> "For this talk, I needed a name to describe this impending new era, so I made up a word: NISQ. This stands for Noisy Intermediate-Scale Quantum. Here "intermediate scale" refers to the size of quantum computers which will be available in the next few years, with a number of qubits ranging from 50 to a few hundred.250 qubits is a significant milestone, because that's beyond what can be simulated by brute force using the most powerful existing digital supercomputers. 3"Noisy" emphasizes that we'll have imperfect control over those qubits; the noise will place serious limitations on what quantum devices can achieve in the near term."[81]

Preskill called the technology "noisy" because we cannot yet adequately control the qubits. In the absence of greater control, the error rates involved when executing an algorithm across quantum gates – the logical circuits operating on a set of qubits – can be persistent and relatively high.

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81 https://www.researchgate.net/publication/322243414_Quantum_Computing_in_the_NISQ_era_and_beyond

Preskill called the technology “intermediate scale” due to the number of qubits currently available on quantum devices. To achieve sustainable quantum supremacy, researchers estimate that the industry will need machines running between 208 and 420 qubits, depending on the type of circuit used. To put that in perspective, the most powerful machine unveiled by IBM, still in prototype, boasts 53 qubits. Honeywell’s latest machine only has 6. This machine, however, has a stated QV of 64, same as IBM’s latest machine.

The NISQ quantum stack will be hybrid by necessity. The classical elements will handle a range of tasks from data preparation and parameter selection to post-processing and data analysis. He said the quantum elements will be limited to very specific—albeit powerful—acceleration or co-processing roles for particular problems.

The challenges posed by the hybrid nature of the stack will require management of workflows for the effective orchestration of the various components.

NISQ Critical Path

The NAS report further elaborated that the NISQ phase should (must) achieve two technical break-throughs for the next stage of massive qubit increase and acceptable fault-tolerant performance:

- First, bring the error rate and the physical-logical qubit ratio down to established acceptable levels of efficiency and reliability, and

- Second, focus on the development of quantum-side algorithms, both libraries of common-ser strings, progressively longer, and specialised algorithms for key industrial and other application areas. After error limitations, the report identifies algorithms as the next in the critical path.

Roadway to Quantum Advantage

To re-state, Quantum Advantage is reached when a quantum computer performing within acceptable limits of efficiency, can out-perform supercomputers in a range of specified tasks – with significant actual and potential gain.

To re-quote, as at 2019, the NAS report made this assessment:

> “The time to create a large fault-tolerant quantum computer that can run Shor’s algorithm to break RSA 2048, run advanced quantum chemistry computations, or carry out other practical applications likely is more than a decade away. These machines require **roughly 16 doublings of the number of physical qubits, and 9 halvings of qubit error rates**.[82]

To achieve the above, the report highlighted some key technical advances that were needed:

- Decreased qubit error rates to better than 10^{-3} in many-qubit systems to enable QEC[83].
.
- Scaling the number of qubits per processor while maintaining/improving qubit error rate.
.
- Creating more algorithms that can solve problems of interest, particularly at lower qubit counts or shallow circuit depths to make use of NISQ computers.

.- Refining or developing QECCs that require low overhead; the problem is not just the number of physical qubits per logical qubit, but to find approaches that reduce the overall drag.
.
- Establishing inter-module quantum processor input and output (I/O).

82 https://www.nap.edu/read/25196/chapter/1
83 QEC/QECC = Quantum Error Correction Codes

The report assessed that, as at the technology of 2018, the industry would need a decade to reach the minimum qubit scale of 2^{16} =65,536, at the improved error rates and logical qubit attainment. On qubit count alone, IBM's Quantum System One has breached this figure with 20 qubits. They expect to go to 127 qubits in 2021.

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Road to Quantum Achievement

It is useful to re-cap the following terms used to mark the stages in the growth of the quantum computer:

Quantum Advantage - Quantum Advantage is reached when a quantum computer performing within acceptable limits of efficiency, can out-perform supercomputers in a range of specified tasks – with significant actual and potential gain.

Quantum Supremacy - A quantum computer may be said to achieve quantum supremacy when it is able to solve a problem that a classical computer cannot solve at all no matter how much time it takes.

Quantum Achievement – Quantum Achievement Is best understood as the point in time when "quantum supremacy" computers are pervasively in use, substantially taking over from supercomputers. This state is also referred to as our Quantum Goal. (We will have achieved this when under Moore's law the next replacement technology is already born.)

Taking Stock

While we can see our goal, it is still not possible to define the route we shall take to establish individual Quantum Advantage or even limited Quantum Supremacy in the marketplace.

All three breakthroughs reviewed above can have far reaching effects. IBM's superconducting qubit technology is leading the way and Intel's Horse Ridge will greatly enhance its capability to deal with error and thrust the qubit numbers forward. However, Honeywell's (and IonQ's) parallel successes with the more stable trapped ion cannot be ignored. We must also seriously look at MIT's breakthrough in integrating the photonics on which this technology depends directly into the qubit itself. This will give the trapped ion qubit the greater potential. And lastly, we cannot ignore Microsoft's topological qubit, presently under design. This goes one step further down-scale, using the Majorana quasiparticle as the working particle. The latter is engineered and manipulated in a topological environment combing quantum and space-time parameters, a frontier not as far as I am aware fully defined yet. Conceptually more stable and manageable, without the de-coherence problems of the others, this can in fact be the mutant technology giving us the best option for the "big daddy" quantum computers of the future.

Lastly, we need to take notice of DNA computing. I have not mentioned it in Q3 but do so further under Q4. My conclusion at the end of that section is: I have every expectation that we shall have at least invented the **hybrid DNA-Quantum** computer by Q4, with massive on-line storage and powerful tandem quantum computing.

Looking Down the Road

While D Wave and others have strung more qubits together into purpose-designed working quantum computers, there is no doubt in my mind that we had best ride with IBM in looking into the prospects of the quantum computer.

Let us be optimistic and project that, starting with the **1,121-qubit IBM Quantum Condor** processor promised in 202 and with parallel breakthroughs, the qubit growth will be 100% a year straight line. We should hit 10,000 qubits by 2030. Let us be further optimistic that, with yet other improvements, we shall be out of the NISQ era by then and have pole-vaulted NAS's Quantum Advantage with several quantum computers and possibly some clearing the Quantum Supremacy benchmark.

We should at that point be in significant deployment in the manufacturing and other sectors in a range of specialised applications, whether still semi-hybrid or not. There should be significant spin-offs in telecommunications, biomedicine, chemicals and pharmaceuticals, materials development, and social management. There could be some breakthrough in the Internet of Things (IoT). The US will, I am sure, hope for a better electoral voting system.

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There is no reason to suppose that Moore's Law would not begin to apply. We could be moving out of the silicon age. The qubit processor could be loosening its cryogenic entrapment. We might have begun on the neuromorphic quantum chip.

If we achieved the qubit scale in the preceding decade, there would not be any reason not to project a 100% a year straight-line growth from 2030 to 100,000 in 2040, and another round of say 50% a year straight line growth from the latter base in the decade following to 500,000 in 2050. From then, doubling in the decade following would probably seem straightforward.

By 2050, Quantum Supremacy will be the norm. By then the qubit will probably be a quasiparticle creature entirely of the nanosphere, fed by neurosensory input, and driven by AI. I have no doubt we shall have our unified theory of everything by then.

Quantum Achievement

Let us be reminded that the full-grown quantum computer mankind looks to inherit and transform civilisation is 1,000,000 qubits and growing This is our Quantum Goal.

At a million qubits, we shall map the stars and travel around at warp speed "to explore strange new worlds, to seek out new life and new civilizations, and to boldly go where no man has gone before". In the nanoworld, we should have counted every virus and held them at bay if not harnessed them for industrial purposes.

The full transformation of the world will take longer, perhaps by the end of the millennium. By then, we will be unrecognizable and we will have asked and answered all the questions we dare not ask today. We will have taken command of most of the micro, meso and macro problems of our universe, and solved our energy needs. We would be on the verge of the next social evolution – the Age of Artificial Intelligence (AI) in transcendent control of matter.

I will add a touch of realism from Daniel Loss, Professor of Physics at the University of Basel who looks even further "….the physical systems intended to serve as qubits must have a number of special properties in addition to their quantum physical properties: for example, the qubits must be small enough that you can **ideally accommodate 100 millions of them on a chip with an area of one square centimeter**; otherwise, it will not be possible to build a manageable computer. **It must also be possible to switch the qubits from ON to OFF and vice versa at high speed – ideally a billion times a second,** as is customary with electrical circuits in modern computers.[84].

My final comment is: we took 50 years to evolve the supercomputer of today. What is there to say we cannot have our full-grown quantum computer, the Titan walking among us, in perhaps the same time.[85]

Quantum Data

Data already is, and if not yet will in time be, the most abundant item or commodity in our world. As from the Information Age, we are totally dependent on its storage and retrieval for day-to-day transactions, not to mention capturing historical data trails and archives like the Wayward Machine. It is already massive. The growth will be exponential. Most of it will in time be quantum generated. But there is a big problem: by its nature, we cannot save or duplicate information on a quantum computer.

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84 https://journals.aps.org/pra/pdf/10.1103/PhysRevA.57.120

85 Dr Chandra might name him HAL

I include the following article (edited), which deal with this problem succinctly:

> "Quantum computers are so powerful exactly because of their data density. But quantum mechanics has its drawbacks. Its laws permit superposition, but they also forbid anyone from copying a quantum particle. It's called the 'no-cloning theorem,'" says physicist Stephanie Simmons of Simon Fraser University in Canada. Say that a quantum computer programs an atom to be in a specific quantum state that represents a set of numbers. It is physically impossible for the computer to program another atom to be in the exact same quantum state. All that computing power is of little use if you can't back up your work.
>
> So, Simmons proposes a roundabout way of storing quantum data: First, you'll need to convert it into binary data---translating the numbers that describe quantum superposition into simple 1's and 0's. Then, you store that converted data in a classical storage format. In other words: hard drives. Super compact ones, because the size of each quantum data file from a 49-qubit computer will be on the scale of 40,000 videos.
>
> To store that much data, quantum computer developers need new data storage technologies, Simmons says. Commercial drives aren't compact enough right now. A single quantum file would occupy a stamp-sized area on a solid-state hard drive. So, physicists are hunting for reliable, super-compact hard drives made of new materials."
> Sophia Chen, WIRED
> 15 March 2017[86]

This has to be a major pro-occupation of Q4.

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86 https://www.wired.com/2017/03/quantum-computers-used-hard-drives-made-dna/

FOURTH QUANTUM GENERATION (Q4)

There Be Titans (Q4)

The benefits that Quantum Mechanics (QM) gave us in Q1 will continue to grow cumulatively and keep us morphing. Information technology and telecommunications, among others, will take us to the day of the Titans.

Quantum Physics

In the realm of Quantum Physics, the Quantum Revolution is far from having run its course. Even in our simple review, we have noticed that the Fundamental Forces are still not tied up. The ticklish reality of instant information teleportation between entangled entities needs to be fully reconciled with Einstein's proposition that nothing can travel faster than light. The atom has still not been fully studied. There has been the need to postulate another layer of elementary particles, i.e., the preon. And other researchers are experimenting with anyons, phonons and other quasiparticles.

Quantum Physics has still to penetrate the cryogenic world beyond absolute zero, which nowhere exists in the natural universe and which valiant attempts have been made in laboratories to near-create. To do so would indeed be like teleporting to the Boomerang Nebula, 5,000 light years away, where our quantum computer would be at home in the bright sunshine of -272 degrees Celsius, lowest recorded in the universe. The speculations and deductions suggest that matter might behave the same way in both ends of the journey but different from on earth. Perhaps, thereat might lie knowledge of dark matter, and that other world of anti-matter that might have happened.

In all cases, the quantum computer will be the necessary tool for observation, experimentation, calculation and travel.

In the areas of applied QM, the evolution will be exponential, as one discovery will trigger the next and as more hybrid computers strengthen and escape NISQ. Leading fronts will include materials, chemical and energy management, medicine, weather and environment control, security, and further progress towards the Internet of Things.

I close by looking some areas of development, both to reflect the impact of QM and to point to exciting paths of growth in our proximate future.

The Electron-Microscope

The single and compound lens light-microscopes that most of us have been familiar with in school and at work were invented in the nineteenth century or earlier. Those light-microscopes were limited by to 500x or 1000x magnification, and a resolution of 0.2 micrometers.

In 1931, Max Knoll and Ernst Ruska invented the first electron-microscope. Quantum optics had arrived. They built a transmission electron-microscope (TEM), one that transmits a beam of electrons through the specimen. In 1942, Ruska built the first scanning electron-microscope (SEM) that transmitted a beam of electrons across the specimen. Ruska's principles still form the basis of modern electron-microscopes. It represented the key advance from the light or optical microscope to the technology of the charged particle (electron or ion) scan of the subject matter, with a magnification of up to two millionths ($2x10^{-6}$).

Optical microscopes continued to be widely in use even today. New (QM) light sources, halogen, fluorescent and

LED, all improved or added a greater versatility. Boom stands led to extensive commercial applications. Digital microscopes followed in 1986, basically incorporating a camera. It allowed for live image transmission to a TV or computer screen and inter alia revolutionised micro-photography.

In the labs, the electron-microscope (SEM) combined with computers has become the indispensable window into the nano world allowing researchers to view specimens at nanometer size. The TEM is a popular choice for nanotechnology as well as semiconductor analysis and production. SEMs are approximately 10 times less powerful than TEMs, but they produce high-resolution, sharp, black and white 3D images.

Cryo-electron microscopy (Cryo-EM) was a mode developed in the 1970s. It allows for viewing specimens in cryogenic conditions. Cryo-EM technology has advanced to the point that it can produce structures with atomic-level resolution. The latest improvements won the Nobel Prize in 2017.

The scanning probe electron-microscope is the current front-line working technology. It runs a probe, whose metallic tip can be as small as an atom, over a microscopic surface. The probe can measure a number of things as it rolls over the subject, from physical depth to electronic and magnetic forces. These microscopes can resolve subjects smaller than a nanometer. An earlier version was called the scanning tunneling microscope.

A variant of the scanning probe electron microscope, also known as the atomic force microscope, uses the atomic force between atoms to map out the specimens, operating in the picometer (1.0×10^{-12} pm) range.

At the top end, the electron-microscopes have grown to be formidable frontier-breaking Q3 research machines. The

US$27 million electron-microscope at Lawrence Berkeley National Labs can capture images to a resolution of half the width of a hydrogen atom.

In 2016, Hitachi of Japan developed an “atomic-resolution holography electron microscope” and achieved a world’s highest resolution. The results indicated that the electron-microscope could transfer crystal-structure information of at resolution of 43 pm [87] $(4.3x10^{-12})$ The electron microscope visualised specimen structures and electromagnetic fields in 3D at the atomic level.

The electron-microscope gave us the Human Genome. It is our primary weapon today against the Covid-19 virus. Having, in fact, given us more than the quantum computer (so far), the electron microscope now stands ready to conquer the future. The Electron Microscope is already a Titan[88].

James Webb Space Telescope

We might with profit look at what has been going on at the other end of the visual spectrum, namely space. We have had Voyager 1 and 2, Hubble, Kepler, and TESS – and the man on the moon, among other things. And, just last month, September 2020, the world largest radio-telescope became operational in Pingtang, in southwest China. All of this has been achieved with Q1 technology.

Next year, in September 2021[89], we shall see man take yet another giant step, the launching of the James Webb Space Telescope (JWST). This telescope will be the largest, most

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[87] pm =picometer $(1.0x10^{-12})$

[88] I was intrigued that there is already one, the Titan Krios Cryo-Electron Transmission microscope, at University of Colorado, Boulder. It is over 8 feet tall, weighs in at more than 2,000 pounds, and is considered state-of-the-art in life sciences and structural biology research

[89] https://scitechdaily.com/images/James-Webb-Space-Telescope-Key-Facts.jpg

powerful and most technologically challenging space telescope ever built; 100 times more powerful than Hubble

It will orbit the Sun 1.5 million kilometers from the Earth (Hubble at 560 million kilometers), and it will peer back over 13.5 million years to see the first galaxies born.

The JWST will study every phase in the history of our universe, ranging from the first luminous glows after the Big Bang, to the formation of solar systems capable of supporting life on planets like earth, to the evolution of our own solar system. It will hunt for the unobserved formation of the first galaxies, as well as to look inside dust clouds where stars and planetary systems are forming today. I am bowled over that we are planning all this on Q1 technology. Imagine coupling JWST with a quantum computer. We shall be able to model the universe.

The JWST will be another Titan, if not already one.

DNA

Quantum Biology

DNA (Deoxyribonucleic Acid) is the molecule that contains within it all the instructions and information about an organism. With cryo-EM, it is possible to look into, manipulate and work with DNA at the atomic level, ie the quantum world.

This has already given rise to nanotechnology in a variety of biological-quantum and quantum-biological fields, with crossovers. Molecular electronics, for example, operates in the biological medium in a regime where quantum effects apply. In the chemical realm, a general-purpose programming language is expressed using a set of chemical reaction networks (CRNS) This gets translated to domain-level DNA design and then implemented using a set of DNA strands. This opens gates to the design and synthesis of biochemical controllers since the expressive power of CRNs is equivalent to a Turing machine[90].[

There are a multiple of methods for building a computing device based on DNA, each with its own advantages and disadvantages. Most of these build the basic logic gates from a DNA basis, including enzymes.

Perhaps we are not far from having a DNA-based “nano-computer” to study the sub-atomic biological domain. We shall then have Quantum Biology.

DNA Data Storage

DNA is Nature’s own storage device. It stores, preserves and transmits biological data down the line. It has even got its own purpose designed code: a linear, non-overlapping sequence of the nitrogenous bases: Adenine (A), Guanine (G), Cytosine (C) and Thymine (T). These are the "alphabet" of letters that are used to encode information in DNA.

It is estimated that the supply of silicon, which is used in current hard-drive storage, will run out in 20 years. One solution is using DNA for storage. The need for alternative off-line data storage has been engaging scientists for some time. The same article quoted previously provides this extraordinary information (edited):

> “So, one alternative storage contender is DNA. Published earlier this month in “Science”, scientists demonstrated a method that could store 215 petabytes, or 215 million gigabytes, in a single gram of DNA. At that density, all of humanity’s data could fit in a couple of pickup trucks. Unlike conventional hard drives, which only store data on a two-dimensional surface, DNA is a three-dimensional molecule. That extra vertical dimension lets DNA store much more data per unit area.

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90 Technical model of a fully functioning computer

> Plus, it lasts a long time. We can read DNA from skeletons thousands of years old to very high accuracy."
> Sophia Chen, WIRED
> 15 March 2017 [91]

In summary from different sources, the features of DNA for use as an information storage device are :

- Long lived, stable and easily synthesized.
- Needs no active maintenance.
- Stores digital files without electricity for thousands of years.
- Stores at room temperature
- Lasts for tens of thousands of years.
- Stores 2.2 petabytes in one gram of DNA.
- Highly reliable.

The option is, however, far from ready for large-scale use. One factor is the cost. And compared with other forms of data storage, writing and reading to DNA is relatively slow. And there is a lot technological work to be done and algorithms to write. Nevertheless, an air of optimism pervades that this is the road to go – the answer to Quantum Data. Perhaps, soon, those giant Google and Amazon data centers will be replaced by a couple of pickup trucks of DNA.

CEO Hyun-jun Park of Catalog Technologies, an MIT spinoff, claims his company is making DNA data storage economically feasible for the first time. “DNA storage is nothing new … we humans have been using it for millions of years.” The race is now on to build a commercially viable DNA data storage technology, with Microsoft and several startups, including Catalog Technologies. Catalog’s goal is to offer DNA data storage-as-a-service to customers that need to store petabytes of data in archives.

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91 https://www.wired.com/2017/03/quantum-computers-used-hard-drives-made-dna/

It seems Nature, that devised DNA to record, preserve and transmit our human genes, had also foreseen our progress to the Quantum State, and providentially will do the same for our data. DNA looks promisingly to subsume the role of the data bank in the Age of the Titans.

The future is yet to unfold. Researchers at IBM recently published that they stored a bit in a single atom and successfully read the data back. So basically, it is possible to encode one bit per atom. You can't get more dense than that, says physicist Chris Lutz of IBM. Commercial hard drives store a bit in at least 100,000 atoms---and even a DNA base pair is made of some thirty atoms. So, we shall see.

DNA Computing[92]

DNA computing is an emerging field. It originally started with the demonstration of a computing application by Len Adelman in1994, about the time the principles of the quantum computer were first being demonstrated. It has now been expanded to several other avenues such as the development of storage technologies, nanoscale imaging, synthetic controllers and reaction networks. **Fundamentally, it uses DNA, biochemistry and molecular hardware, instead of the traditional silicon-based technology**.

DNA computing is a form of parallel computing, in that it takes advantage of the many different molecules of DNA to try many different possibilities at once. For certain specialised problems, DNA computers are faster and smaller than other computers. Furthermore, particular mathematical computations have been demonstrated to work on a DNA computer. There are also a multiple of methods for building a computing device based on DNA, each with its own advantages and disadvantages. Most of these build the basic logic gates from different DNA bases, including enzymes.

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92 Mainly from https://en.wikipedia.org/wiki/DNA_computing

However, one of the challenges of DNA computing is speed. While DNA as a substrate is biologically compatible, ie. it can be used at places where silicon technology cannot, its computation speed is still very slow. Its readout is also very slow.

On the other hand, the slow processing speed of a DNA computer (the response time is measured in minutes, hours or days, rather than milliseconds) is compensated by its potential to make a high amount of multiple parallel computations. This allows the system to take a similar amount of time for a complex calculation as for a simple one. (This is achieved by the fact that millions or billions of molecules interact with each other simultaneously.) However, it is also much harder to analyze the answers given by a DNA computer than by a digital one.

Another issue is that DNA computing does not provide any new capabilities from the standpoint of computability. For example, if the space required for the solution of a problem grows exponentially with the size of the problem, it still grows exponentially with the size of the problem on DNA machines. For very large problems, the amount of DNA required is too large to be practical.

While the prospects of DNA data storage look good, and DNA is extensively involved in biological and biochemical nanotechnology, the question whether it can form the basis to build a quantum computer (better than the quantum computer) is still out. Besides storage, one other factor that may make a difference is that it can function on the surface, ie is non-cryogenic.

Personally, I have every expectation that we shall have at least invented the **hybrid DNA-Quantum** computer by Q4, with massive on-line storage and powerful tandem quantum computing.

DNA of Things (DoT)[93]

The concept of the DNA of Things (DoT) was introduced in 2019 by a team of researchers from Israel and Switzerland. DoT encodes digital data into DNA molecules, which are then embedded into objects. This gives the ability to create objects that carry their own blueprint, similar to biological organisms. In contrast to the Internet of Things (IoT), which is a system of interrelated computing devices, DoT creates objects which are independent storage objects, completely off -grid

As a proof of concept for DoT, researchers 3D-printed a Stanford bunny which contains its blueprint in the plastic filament used for printing. By clipping off a tiny bit of the ear of the bunny, they were able to read out the blueprint, multiply it and produce a next generation of bunnies.

Well, perhaps we should stop here. Otherwise, we shall be into cloning. (Dolly was a gift of QM also.)

DNA and Expanded Artificial Genetic Code

Scientists have successfully created an organism with an **expanded artificial genetic code** This success could eventually lead to the creation of organisms that can produce medicines or industrial products organically, - and life forms.[94]

Without doubt, DNA in its various roles, is another biological Titan – possibly the Mother of all Titans, carrying our past into our future.

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93 https://www.nature.com/articles/s41587-019-0356-z
94 https://en.wikipedia.org/wiki/Expanded_genetic_code

Internet of Things (IoT)

The Internet has been perhaps the most amazing bequeathment of Q1. It is the backbone of the Information Age and will continue so as we progress to the next Age of Artificial Intelligence. It is our most important infrastructure. It connects not just people but systems and operations. The Internet will and must grow exponentially. It will propel a quick solution of the data storage problem.

The next development, already happening, is the Internet of Things (IoT). I quote Wikipedia - that marvelous Internet facility which has enabled this whole Brief, (edited).

> “The Internet of things (IoT) describes the network of physical objects—“things”—that are embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the internet.
>
> The IoT has evolved due to the convergence of multiple technologies, real-time analylyctics, machine learning, commodity sensors, and embedded systems. Traditional fields of wireless sensor networks, control systems, automation (including home and building) and others have also l contribute to enabling the Internet of things.”[95]

Infrastructure

Telecommunications

Needless to say, our Telecommunications networks, which now thickly enmesh the world, must also grow exponentially. Quietly serving not only the expanded Internets but everything, from the airplane to the housewife,

95 https://en.wikipedia.org/wiki/Internet_of_things#cite_note-5

AI

Artificial Intelligence (AI) machines assess and respond to the external environment, learning, manipulating information, reasoning and making decisions, as programmed to do. AI will be pervasive at the level of automation. They will be incorporated more and more into things, making life better. They will carry out our onerous productive processes, and they will monitor and maintain our systems and infrastructure. They will be deployed where man cannot go, like in deep earth, sea and space. It is not too far-fetched that we will manufacture nano-robots to enter and maintain our bodies. AI will maintain our computers and other Titans. Finally, when married to the quantum computer, AI will write all our algorithms, and exponentially increase our ability to process and comprehend information. AI is one of great benefits of QM. So long as we do not allow them human passions and desires, they will be fine.

Age of the Titans,

The Titans once ruled the world. In the second Age of the Titans, while they will run the world, we must make sure we rule the Titans.

CONCLUSION

Octavius might have said to Mark Anthony and Lepidus
“When we get to 2^n cubits[96] , let us build three quantum models, one of man, one of the world, and the third of the universe.” Then the fun will really begin. (a Pillayism)**).**

END

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[96] Roman measure of distance (1.5 feet)

ABOUT THE AUTHOR

Gerald Francis Pillay was born in Melaka (then Malacca), Malaysia on 2 Dec 1934, son of Francis Joseph Pillay @ Odiang, a Chitty Melaka, and Janet Thomas, a Eurasian. The family migrated to Singapore in 1949. He is married to Mabel Narayanasamy, and they have two sons, Leslie married to Deirdre Goh, and Carl married to Sharon Loh. The latter have one son, Christian.

Educated at St Francis' Institution, Malacca and St Joseph's Institution, Singapore, he studied at the University of Malaya (then in Singapore), where he was a University Scholar. He won the Economics Book Prize (1956) and graduated with the B.A. Honours Upper II in Geography (1957).

Mr. Pillay served in the Singapore Administrative Service from 1957. He served in Home Affairs, PMO, Public Service Commission, Defense, Foreign Affairs and Telecommunications, before posting in 1971 to Education as Deputy Secretary (Technical Education).

In 1974 he transferred to the newly formed Industrial Training Board as Secretary. He retired in 1989 as the Deputy Director (Deputy CEO) of the board, which had enlarged to become the Vocational and Industrial Training Board – predecessor of the present Institute of Technical Education (ITE). Altogether he had 33 years in the public service.

In 1989, he formed GFP Consultancy. For another 17 years, until his second retirement in 2006, he practised as a consultant in Technical Education, serving international agencies such as the World Bank, UNDP, UNESCO and ILO, and employers and employers' organisations. In 1992-3, at their request for an External Commissioner, the Singapore Government nominated Mr. Pillay to serve on Botswana's Presidential National Commission on Education.

Mr. Pillay was Aide-de-Camp (Extra) to Tun Yusof bin Ishak, Yang di Pertuan Negara (Head of State), Singapore, 1961-64 He was twice Club President and four times a Cabinet Officer, of Lions Clubs International District 308 A1 and predecessors, 1973 to 2008. He was Secretary, Catholic Aids Response Effort (CARE) from 2007-10.

He has been Adviser to the Peranakan Indian (Chitty Melaka) Association Singapore since 2016

He has published two books: (1) The Chitty Melaka Story (2018), ISBN 978-981-11-7845-0 (e-book)
and (2) Japanese Conquest of Malaya and Singapore 194-42 (2019), ISBN: 978-981-14-0556-3 (e-book),
which may be found under his name (Search) at e-publishers www.smashwords.com.

This book and subsequent writings will be published digitally on the internet at https://geraldpillay.wordpress.com

His next work is "Virus* Biological Predator. An In-depth Review of Covid-19", ISBN 978-981-18-3046-4 (PDF), to be published on 15 Dec 2021.

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