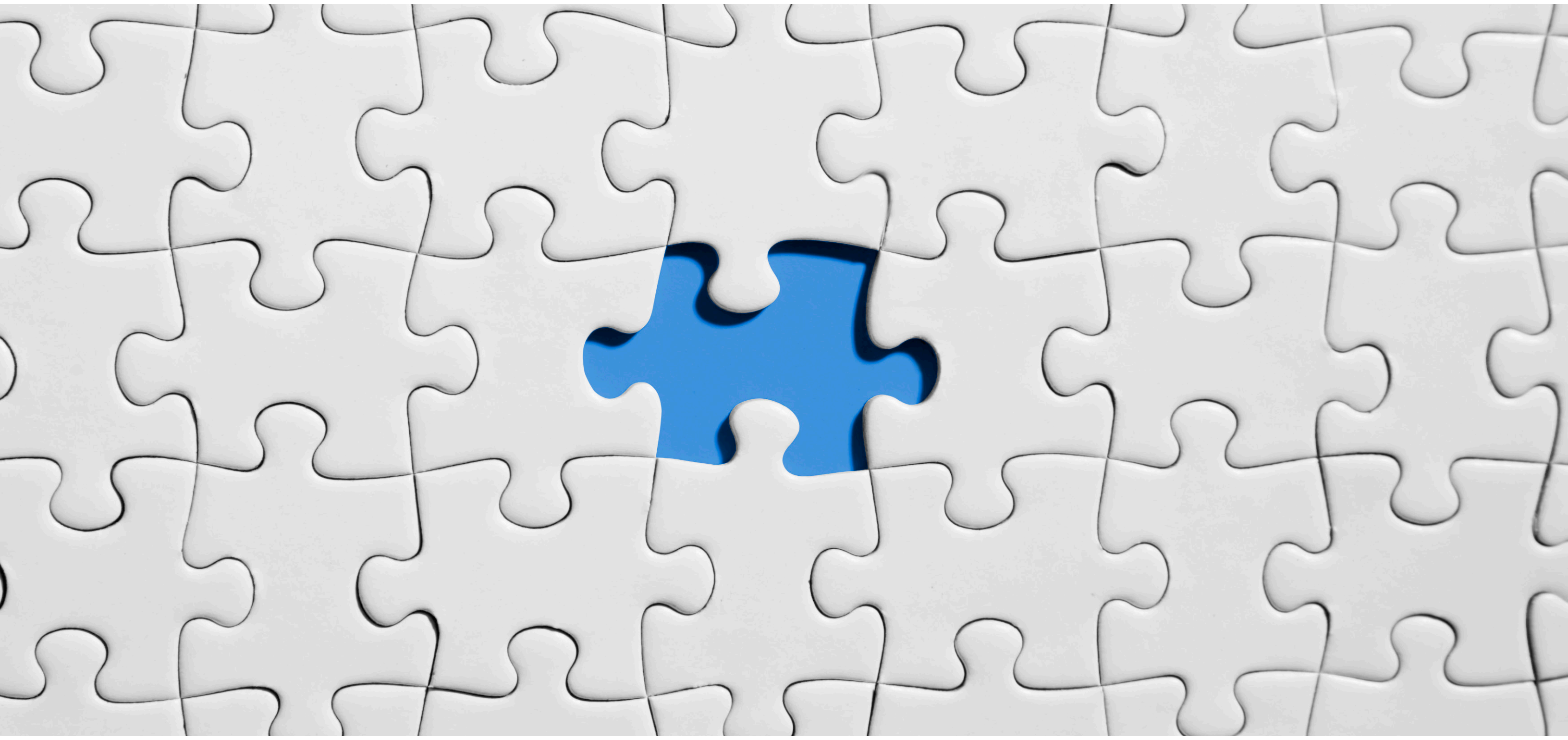
QUANTUM COMPUTING AS A SAVIOR (QCAAS)



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1. History

1.1 War and Technology: A double-edged sword

Since the dawn of time human curiosity has led to development of a plethora of different tools and techniques that have helped humans survive and thrive in the environments that they have been put in. This natural sense of curiosity has allowed humans to explore, build and innovate in ways unimaginable to any other species at any point in time. Although physically inept in comparison to the species around them, humans have made use of their intellect to craft tools and materials that can assist them on their path to advancing humanity. This deep-rooted fascination for improvement, innovation and complexity as well as the dream of a modern world allowed humans to develop and create longer lasting, more efficient tools to help facilitate development of human civilizations. Perhaps the most well-known and arguably the most important of these tools is the development of the computer and computing.

The history of the computer is an unfortunate one; it was the product of a lot of suffering and agony. Humans seem to be the most innovative when constrained under time and pressure. Development of the actual computer was gradual with a spike here and there caused by major events during war times. A huge amount of human life was taken away in the process of creation to gain this privilege we now possess. One can also say that all developments were due to an overlapping of technological breakthroughs in both computing and electronics. The efforts made mainly (and unknowingly in parallel) by Americans and Europeans led humanity to what is now the modern-day computer. Alan Turing of Great Britain and the American-Hungarian John von Neumann are often credited as the 'fathers of computers'.

1.1.1 The American Heritage

1.1.1.1 Census Counting Machine

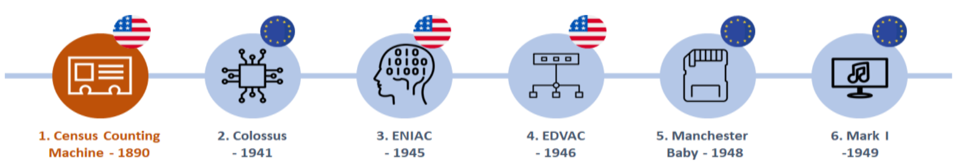

Figure 1

It all started with the American 'census counting machine' in 1890. The American census (counting of population) in 1890 was a tedious manual task that only a machine could solve. Performing the census took too much time to do by hand; it was impossible to tabulate all people before the next census was due. This is when John Billings who was responsible for statistical analysis for the 1880 and 1890 census with the aid of Herman Hollerith created a system for the censuses. Punched cards the size of a dollar bill were used to indicate people's information (citizenship, marital status, etc.) (Figure 3). Essentially the punched card could be treated as predecessors to today's national identification cards. These cards were put into an electromechanical sorter which sorted people in a particular city and sort them by gender or other properties (Figure 2). After the success in the 1890 census Hollerith set up the tabulating machine company in 1896 which evolved into tabulating-recording company in 1911 and finally the International Business Machines Corporation (IBM) in 1924.

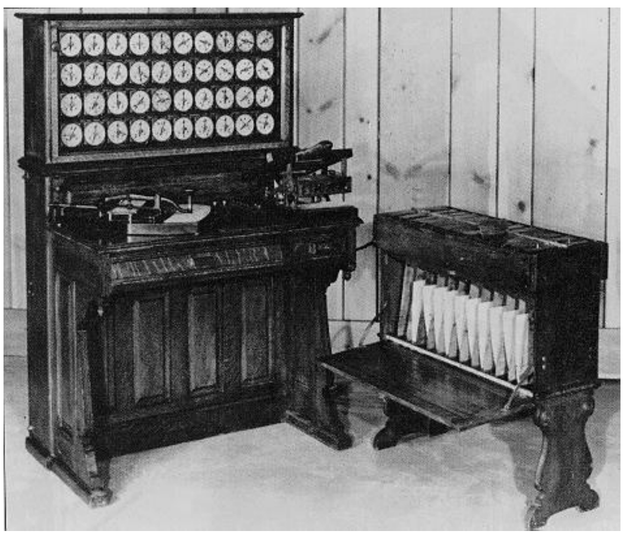

Figure 2: The tabulating machine

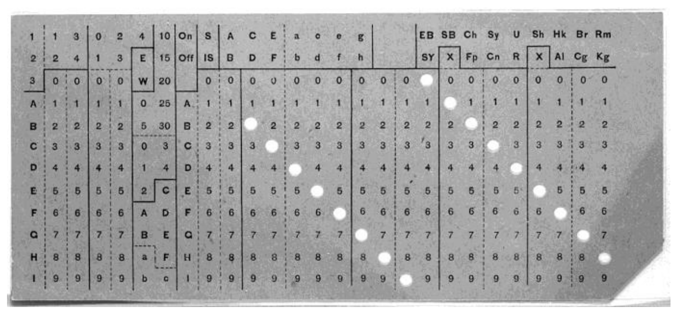

Figure 3: Punched Card

The next major step was the mechanizing of arithmetic, which was required for the First World War. This nullified the idea of punching cards. These advanced machines were required to perform arithmetic operations for ballistics (calculate the flight of shells fired from guns and the fall of bombs dropped from an aircraft). After the First World War, a series of joint ventures, starting in 1933, between the US Army, multiple universities, IBM and the American Astronomical Society led to the creation of improved calculating machines and difference tabulators. This contributed to IBM moving out of the punched card system and into the modern field of electronic computers which were required for the Second World War (1939-1945).

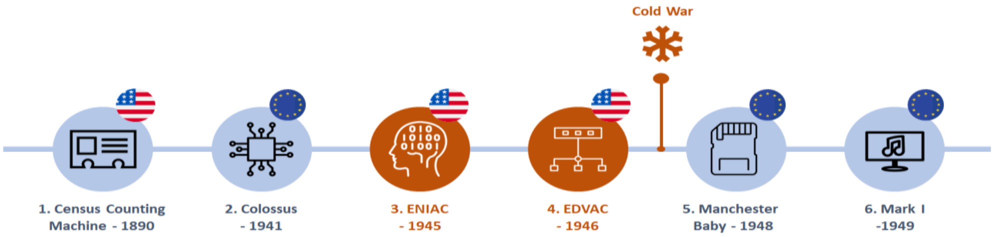

Figure 4

1.1.1.2 EDVAC The First step Towards the Modern Computer

Further developments took place in 1943. A project began for a digital electronic computer and after almost two and a half years (1945) the Electronic Numerical Integrator and Computer (ENIAC) was completed which was of particular importance as it was put to use during the Cold War (1947-1953). It weighed 30 tons, equivalent to 5 fully grown elephants. It used IBM punching cards for input and output and would take weeks to program for a certain problem. Before ENIAC was complete, a new machine was already being secretly devised called the Electronic Discrete Variable Automatic Computer (EDVAC) which was picked up by Von Neumann. During this period, an engineer demonstrated how decimal numbers can be turned into binary, a significant stepping stone towards modern user-friendly computers.

EDVAC's design was unprecedented. It separated into different units a central processing unit (CPU) to do arithmetic calculations, a memory system and some sort of control system and input output devices, with data flowing between them. The last yet most important of the units was a less visible one; a means of communication between the other four units, especially the memory and the CPU, called a bus. This structure is still used in our desktop computers. In this type of setup problems are solved serially, step by step going through a chain of instructions in a sequence. In contrast to a more distributed architecture favored by Alan Turing where different pieces of the problem are tackled by different parts of the machine simultaneously. The serial method is slower but needs less hardware, while the parallel approach avoids the problem of parts being idle while another part is finishing a task. In 1945 von Neumann sold his 'EDVAC' ideas to IBM as it was a condition for his contract to work with them, leading his team to leave the project and create their Universal Automatic Computer (UNIVAC) which outdated 'EDVAC' by the time it was completed.

1.1.2 The Scene in Europe

1.1.2.1 Turing's Genius

One can say that the first steps in the computer system started in America, yet in parallel the European contribution was also of immense importance. British Alan Turing saw how a mechanical process carried out by a team of people can also be carried out by a machine. In 1937 Turing introduced the revolutionary idea in his famous paper 'on computable numbers' where he described how 'Turing machines' (computers) work. The uniqueness of the paper lies in its description of modern-day computer structure of how machinery (hardware) could in theory perform any task following the appropriate sets of instructions (software). The initial Turing machine operates by reading and writing symbols (binary) on a long piece of paper that is divided into squares/cells which would contain 1 or be blank corresponding to 0 (Figure 5).

Figure 5 Turing machine

Turing, fueled by the war raging across Europe at the time, became interested in cryptography and was a first choice to work for the Government Code and Cipher School (GC&CS) then based in London. GC&CS recruited mathematicians at the time to conquer the German Enigma ciphering machine. An electromechanical machine, then known as 'Bombas' was devised by the Polish to crack Enigma. The improved model made by Turing got renamed into 'Bombes' and little

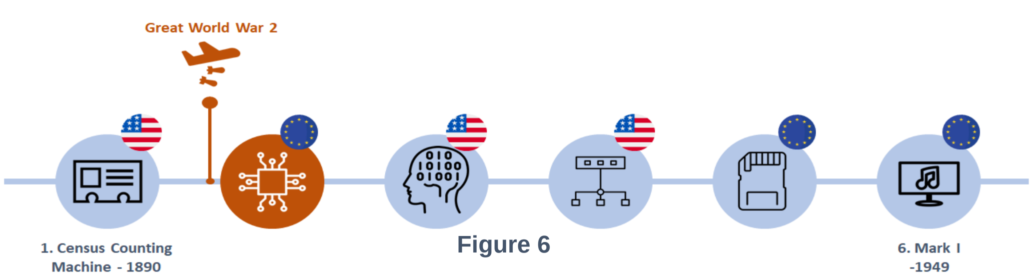

Figure 6

did anyone expect that this Bombes was a reason behind shortening the war and eventually saving millions of lives!

1.1.2.2 The First Electronic Computer

Turing however was not involved in the successor to his machine, the first electronic computer, 'Colossus'. Again, inspired by the Germans radio traffic and signals that were being sent between Berlin and Greece called Tunny in 1941. Tunny used teleprinter language, not Morse code. A prototype machine was created – 'Heath Robinson' – that used photoelectric detectors and light passing through the holes in tapes to read and write. It did that by comparing an encoded message with a code containing all the possible settings of one group of wheels in the Tunny machine known as chi wheels. The Heath Robinson prototype was both too slow and inaccurate to be relied on to crack Tunny. Engineer Thomas Flowers was asked to work on Heath Robinson, where he used electronic valves for switching which bore the revolutionary 'Colossus'. It ended up breaking the first Tunny code – ten times faster than Heath Robinson – one year after its creation in 1944.

An interesting development took place after the Second World War. Turing collaborated with the National Physical Laboratory (NPL) to create yet another revolutionary paper named 'Proposed Electronic Calculator' which described how multiple computer programs could work on the same computer. Turing even went to the extent of proposing an artificial intelligence engine called the Automatic Computing Engine (ACE). In 1950 NPL actually produced the first ACE pilot model, using electronic valves.

On the commercial side everything changed in 1954 with the introduction of the first desk side personal computer called G15 by Bendix Corporation. Theoretically, this machine – the size of a tall kitchen refrigerator – can be used to compute any computable sequence, meaning it can do various tasks depending on the given binary coded instructions. Hypothetically it can be a TV, a navigation aid, a console used to play games and a calculator to solve mathematical problems – not too different from the device from which you are likely reading this.

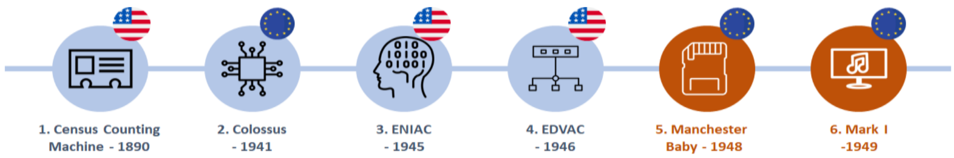

Figure 7

1.1.2.3 Digital Music and Writing

Apart from the commercial side, the academic field made a lot of progress in 1949, introducing the first Cambridge computer called an Electronic Delay Storage Automatic Calculator (EDSAC) which stemmed from the American 'EDVAC' mentioned earlier. EDSAC was followed by the Manchester baby which was the first computer to successfully run a program on a stored program electronic computer, it had a RAM of 128 bytes. Then the 'Mark I' was developed, which used teleprompter paper tape to communicate with the computer to program it and receive the results; this was in use until the 1960s. Then the more commercial 'Ferranti Mark I' was created in the 1950s. At the time it was touted as the most powerful supercomputer ever made due to it having a huge RAM of 1 kilobyte which was more than anyone had imagined could be possible. Mark I is of special importance as Turing was the first to use it on two of the most recognizable and popular computer features to date. The first being a program to play musical notes by adjusting the speed of beeps sent to a loudspeaker. Second, he wrote his letters on the Mark I computer's keyboard becoming the first person to use a word processor.

1.2 Electronic Developments

As mentioned earlier, computing and electronics advances are the main components of our modern computing technology. Advances in electronics were much more subtle yet crucial. In America, electronic valves incentivized the need for automatic telephone exchanges and television. At the beginning of the 1900s the vacuum tube was invented to control the flow of electrons and by the 1920s the cathode-ray tube was invented having control of both the time and space in which the electron flow was controlled. This mastery over the control of electrons would later be refined to represent on and off switches corresponding to 1 and 0 states of binary.

Germany's invasion of Poland in 1939 motivated the development of a technique to sort and switch electron pulses in a vacuum tube so that a single tube can perform simple arithmetic computations in binary. This development of a technique called the 'Computron' is now what we know as a calculator. In 1943 the Radio Corporation of America (RCA) worked on a data storage device now known as random access memory (RAM) using vacuum tubes then known as the 'Selectron'. This incremental progress and introduction of electronics led to the technology we now possess.

1.3 Old but Gold

Von Neumann and Turing deserve equal praise for the computers of today. Yet the fact remains that the European approach was superior to the American one. Pioneer Alan Turing's philosophy was to minimize the amount of hardware by maximizing the use of software. Meanwhile, the American approach was described by Turing as ‘the American tradition of solving one's difficulties by means of much equipment rather than by thought’. To put this into perspective each IBM punch card represented only a cell in the endless tape of a Turing machine. As time went by, progress was ongoing, valves became transistors and chips, machines became smaller, faster and more available, but there was no change in the logical structure of computers. Punch cards were replaced by magnetic tape and discs and now, solid-state memory devices. Today, the number of transistors per chip has passed the billion mark. For perspective, that is like a billion-valve Manchester baby devices or EDVAC on a single chip only a few hundred square millimeters in size.

1.4 New Era

It was only a matter of time, starting in the mid-1970s, until the likes of Michael Dell, Steve Jobs and Bill Gates picked up the ball. This era saw a dramatic explosion of innovation in the fields of computer design, technology and most importantly software. The creation of the modern graphical user interface, especially the mouse, and the commoditization of computers led to it being an integral part of daily life (Figure 8). Then came the next big thing, the adoption of the internet in households which changed humanity forever. Dell made the most of the internet opportunity becoming one of the first corporations taking sales online as early as 1996 which remains an integral part of Dell's success.

Figure 8: Personal Computer (PC) introduced in 1981.

1.5 Cloud and XaaS Emerges

1.5.1 Cloud

We recently hit a turning point where we found ourselves at the limits of our computing ability and the marginal benefits of computers (data centers) are falling. This decrease in benefits is an effect caused by the immense amounts of raw data which makes it harder to scale IT infrastructure. Even if the scaling was solved there remains a list of problems like control, management and maintenance. Our third platform world needs technology that solves these problems, such as flexibility in scaling, simplified infrastructure management and availability with a focus on business continuity and agility. These needs are what has given birth to an entirely new branch in the computing spectrum, affecting people in terms of new roles and a shift in IT skills. In addition, processes like automation, self-service and agile methodologies for more efficient IT deployment arose and technologies like orchestration, service catalog, flash drives, and software-defined infrastructure emerged.

This new branch is what we refer to as cloud computing. It is the bridging of both existing platforms as well as the new ones. The National Institute of Standards and Technology (NIST) describes cloud computing as ‘A model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources, (e.g. servers, storage, networks, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction’ (Figure 9). This simply means that cloud computing is similar to common infrastructure hardware with one exceptional additional layer of virtualization to abstract these resources and make them available to anyone with network access. These abstracted resources are analogous to the usage provided by a utility service like electricity, where a consumer simply plugs in an electrical appliance to a socket and turns it on. The consumer is

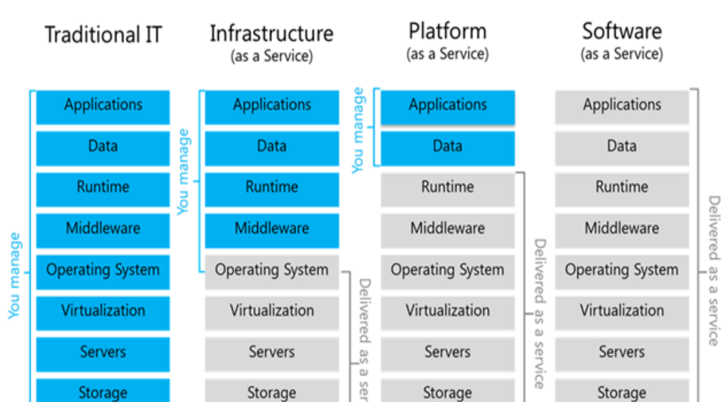

Figure 9 Different deployment models

unaware of how the electricity is generated or distributed and only pays for the electricity used. In the end, the consumers pay only for the services that they use, which is either based on a subscription or resource consumption.

1.5.2 Anything as a Service

Cloud computing can be divided into models that dictate the amount of control one has over the underlying infrastructure and its management, commonly known as Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service (SaaS). From an end user perspective 'Software as a Service' is the only interesting model as it serves as a platform for most of our everyday uses on smart phones. Consequently, we will be taking software as a service under the loupe as its of particular interest in the sense that it bore the idea of the Anything as a Service model (XaaS).

The evolution of XaaS has provided and will keep providing virtually endless opportunities to continuously redefine the computing industry. XaaS creates an expanding cosmos of services that add value to our everyday lives and take business efficiency to the next level. XaaS has often been used as an umbrella term to encompass SaaS, PaaS, and IaaS. There are also other examples to which this umbrella extends like storage as a service, desktop as a service, and disaster recovery as a service. The XaaS model is not limited to online services for the IT world, one can witness some of these opportunities that came to everyday life in the following examples. Transportation-as-a-service is being fulfilled by companies like Uber; grocery-as-a-service is being offered by chains such as "Amazon's Whole Foods"; and accommodation-as-a-service is a lodging rental service provided by Airbnb. Tech giants now even provide quantum computing as a service (QCaaS) for the masses to start delving in that technology until it is globally commoditized. This is just the tip of the iceberg with many more on the way.

Tech giants now provide an environment to construct algorithms of quantum nature including machine learning, tests them on quantum circuit simulators and then they are run on different quantum hardware technologies. From both examples we can grasp that companies are already moving towards the future and providing QCaaS for the masses to start delving in that technology until it is globally and widely available for use.

1.5.3 The global Pandemic

According to the Technology and Services Industry Association (TSIA) the COVID-19 pandemic made the trend stand out even more. A dramatic increase was seen of 13% in the growth of service revenue for software companies and quite the opposite effect of -9.6% growth in product revenue for software companies. The overall trend of service versus product spending can be seen in Figure 10 below. The research findings concluded that in Q3 2020 technology providers responded quickly and effectively to operating virtually which explains why companies based on XaaS business models also proved to adapt better throughout the COVID-19 situation. Naturally, demand for XaaS offers accelerated and 90% of technology providers seemingly intend to deliver more services remotely post-pandemic. The most telling finding was 99% of technology providers intend to leverage the financial benefits of a more virtual workforce, though concerns remain in leadership teams about maintaining culture and collaboration, especially with new hires in a virtual workplace.

1.5.4 Dell: Project APEX

Dell's Project APEX is leveraging this trend by initiating the move into a more outcome- rather than product-oriented mentality. They plan to deliver a radically simplified 'as a Service' and cloud experience to fulfill customer demand for a simpler IT experience. Customers also now have a consumption mentality where they only want to incur OpEx expenses leading to the orange downward slope of hardware revenue in Figure 10. Dell Technologies cloud console is a new way to manage a unified and seamless experience for cloud and as-a-service. Dell is leveraging this with its unique placement by combining edge cloud, private cloud and public cloud into one offering. This ultimately allows business to focus on business activities rather than on IT infrastructure which improves operational efficiency in the long run.

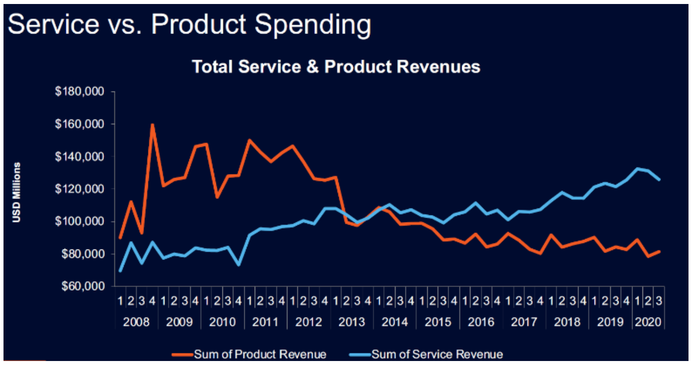

Figure 10 service vs product spending trend

2. Quantum Computing as a Service

2.1 Traditional vs. Quantum

Now that we have a better understanding of XaaS, let's talk more about quantum computing as a service (QCaaS). We first must dissect its components. QCaaS is divided into the ‘as a Service’ aspect of it which was mentioned earlier, in addition to the actual quantum computing aspect which consists of algorithms and hardware. To better understand the quantum computing aspect involved we will compare it to the current traditional computing methods.

2.1.1 Traditional Way

Computing saw a great deal of improvement in both hardware and software over the years since it was first created, yet the fundamentals remain the same. Our current computing ways have not changed much since the war days of Turing and Von Neuman. Binary is the underlying method of all the computations that take place in the device you are using right now. A computer is made up of very simple components doing very simple things. Representing data, the means of processing it, and control mechanisms. Computer chips contain modules, which contain logic gates, which contain transistors. A transistor is the simplest form of a data processor in computers, basically a switch that can either block, or open the way for information coming through. This information is made up of bits which can be set to either 0 or 1. Combinations of several bits are used to represent more complex information.

For example, the actual binary code that your computer uses to represent the letter ‘A’ is ‘01000001’, ‘B’ is ‘01000010’ and ‘C’ is ‘01000011’. Transistors are combined to create logic gates which still do very simple tasks. For example, an AND Gate sends an output of 1 if all its inputs are 1, and an output of 0 otherwise. Combinations of logic gates finally form meaningful modules, say, for adding two numbers. Once you can add, you can also multiply and once you can multiply, you can basically do anything. Since all basic operations are simpler than first grade math, you can imagine a computer as a group of 7-year-olds answering basic math questions. A large enough group of them could compute anything from astrophysics to Mario Bros. In a nutshell, a transistor is just an electric switch. Electricity is electrons moving from one place to another.

However, with parts getting smaller and smaller, delving into the quantum world us the only way for technology to advance. So, a switch is a passage that can block electrons from moving in one direction. Today, a typical scale for transistors is 14 nanometers, which is about 500 times smaller than a red blood cell. We are approaching a real physical barrier for our technological progress.

As transistors are shrinking to the size of only a few atoms, electrons may just transfer themselves to the other side of a blocked passage via a process called Quantum Tunneling. In the quantum realm, physics works quite differently from the predictable ways we're used to, and traditional computers no longer makes sense. Scientists are trying to use these unusual quantum properties to their advantage by building quantum computers.

2.1.2 Quantum Computing

Now for quantum computing I will take you on a small detour through physics; specifically quantum physics and the peculiar dual nature of light. Reality is not what it seems to be. People even as early as Plato knew that the world around them consists of small particles that are in constant motion. Nowadays with technological advancement humans discovered these small particles and the subatomic level of reality. Quantum physics is the field of physics that takes the most basic parts of our universe under the loupe. Our universe at the subatomic level is very different to the reality we experience every day, but it is reality, nonetheless. This very quantum reality is where quantum computing draws all its supreme computing powers from and bestows humanity with an unprecedented hope for future advances. It was renowned physicist Richard Feynman, who in 1982 first argued that regular classical computers cannot simulate quantum phenomena. At that time, it was purely a theoretical concept as neither the technologies nor the proper research was available to even begin imagining building a functioning quantum computer. Quantum computers now make use of quantum bits (qubits) which can be anything that exhibits quantum behavior – an electron, an atom or even a molecule – if the environment is right. Qubits secret power stems from the quantum properties like entanglement and superposition which makes it superior to the traditional ways of computing.

2.1.2.1 Entanglement

The first property, entanglement, of quantum physics used in quantum computers is an inexplicable link between two particles that can be exploited to have quantum communication (Figure 11). These links can be taken advantage of, however, scientists have yet to find an actual explanation behind its nature. In fact, even Einstein could only refer to it as ‘spooky action at a distance’. In theory, with entangled particles we could have quantum communication, meaning that communication could be instant regardless of the distance between the particles. Imagine two particles are linked so that one particle always gives the same outcome as the other even if they are separated on opposite sides of the earth or even universe. These particles when rolled, would show the same result as each other every single time. This has also other practical implications for security since it potentially does not use any physical infrastructure to transfer this information, which means that in the future it may be impossible for communication to be intercepted or hacked without the knowledge of the information (more on security later). Now keep in mind this means entanglement is faster than the speed of light which throws Einstein's theory of relativity right out the window. This is what makes quantum physics such a disruptive field; it redefines the ground laying principles of traditional physics and our universe.

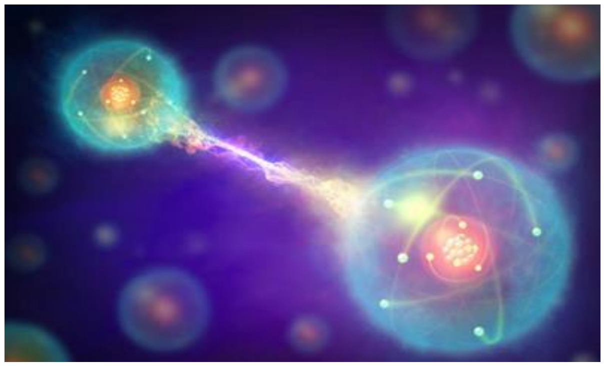

Figure 11 Quantum entanglement

2.1.2.2 Superposition

The second property is superposition, which can be observed using the double-slit experiment with light. The experiment essentially proves that an observation must be made to know if the particle behaved as a particle or as a wave. Before that, the particle is in a superposition of being both a wave and a particle simultaneously.

We can demonstrate this in an experiment with an electron gun firing electrons, representing light photons, against a sheet with two slits. We will place an "electron detector" near the upper slit. When an electron passes through the upper slit, the detector will beep and keep count of all the electrons passing through the upper slit. What we get is, as expected, a 'particle pattern' with two single stripes, as seen in Figure 12.

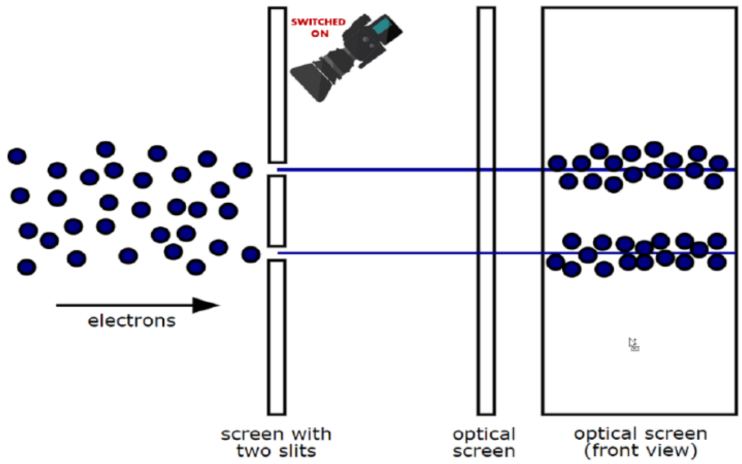

Figure12: Particle pattern

Well, so far, so good. However, the mystery begins when we leave the detector as is but turn it off and rinse and repeat the experiment. One would expect to have again a ‘particle interference’ pattern that all types of particles in nature exhibit; however, we get a pattern that can only be interpreted as a wave-like ‘interference pattern’ as seen below (Figure 13). The interference pattern can be seen as a series of dark and bright stripes. The electrons are changing their behavior just because they are somehow sensing the presence of the detector (observer).

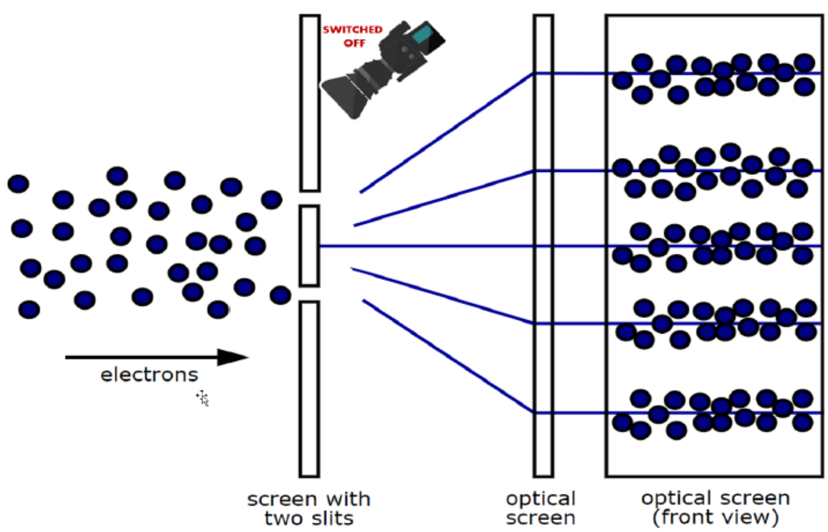

Figure 13: The double-slit electron interference pattern. Similar to what we would expect of waves

Certainly, we did see the electrons exhibit a particle pattern in the first diagram when the detector was switched on. The experiment even has variations of the speed of the electrons being fired where even if the electrons are fired over a longer period, we observe the same wave-like interference pattern. Although at first, we can trace each particle randomly landing on the screen in a localized manner at specific points, over time when the rest of electrons are fired, we end up with the same wave interference pattern build-up.

2.1.2.3 Superposition and Entanglement in Computing

Superposition is exploited in computing to be equivalent to being in a state of 1 and 0 at the same time. Current, classical, bits can be only in one of 2^4 combinations, a total of sixteen, of 1's and 0's at a time (1000,1001,1011, etc.). Qubits, on the other hand, can be in superposition of all those sixteen combinations all at once. This is due to quantum physics itself; an observer can never directly know all the vast number of qubit states at the same time; all an observer knows is the probability of what state the qubits will be in. The very act of observing or measuring the overall state of the quantum computers qubits will force the system to decide on which state it is in so instead of the quick trillions of answers we can only see one.

To better comprehend the concept of superposition, one can think of a particle as a regular coin spinning on a table where, in theory, it is not heads, 1, nor tails, 0, but both simultaneously. A superposition makes it possible to store and manipulate vast amounts of information with a relatively small number of particles. The most important thing to keep in mind here is that due to superposition, qubits have an exponential growth of computing power which we will discuss later. Qubits can therefore run all the computing possibilities at once, so it can find a solution faster on larger datasets. To put the idea of exponential power into perspective, if a quantum computer had one hundred qubits it would be more powerful, for some applications, than all the supercomputers on earth combined. Three hundred qubits could hold more numbers simultaneously than there are atoms in the universe. Just imagine what a billion-qubit computer can do?

Meanwhile, entanglement links complete modules of small quantum processors in an entangler unit in the middle as seen in Figure 14 below. The quantumized particles become quantum entangled and so the modules combined as a single quantum machine. Extending this idea, we can have an entire array of modules we can switch connections so that the module links either to a nearby neighbor or to another far away. In this way, we can have a highly connected and scalable quantum brain. Keep in mind that with each additional qubit the overall computing power doubles.

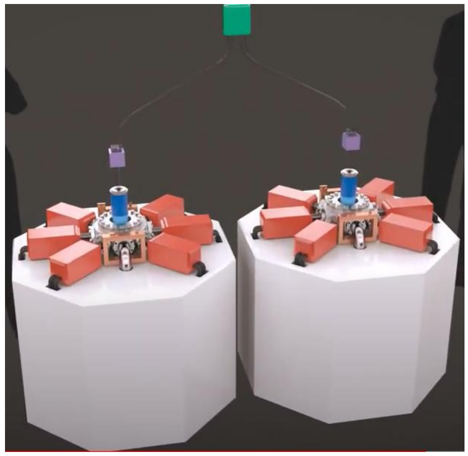

Figure 14: Illustration of a quantum processors in an entangler unit

2.1.2.4 Quantum Rationale with Quantum Cats

Qubit Manipulation is how the calculation takes place. A normal logic gate gets a simple set of inputs and produces one definite output. A quantum gate manipulates an input of superpositions, rotates probabilities, and produces another superposition as its output. So, a quantum computer sets up some qubits, applies quantum gates to entangle them and manipulate probabilities, then finally measures the outcome, collapsing superpositions to an actual sequence of 0s and 1s, giving us, probably, our answer. The reason it only 'probably' gives us the answer is that the answers that come out of quantum computers are in the form of a probability. If you repeat the question the answer will change slightly. This will be discussed further in the algorithms section.

We can illustrate this using the famous Schrödinger's cat experiment. It goes as follows, a cat and a device are put in one box (inputs), the device contains a tiny bit of radioactive substance, so small, that perhaps in the course of the hour one of the atoms decays, but also, with equal probability, perhaps none. If it decays, the device triggers a mechanism that discharges hydrocyanic acid killing the cat. After the passage of one hour, one would say that the cat still lives if no atom has decayed or the first atomic decay would have poisoned the cat thereby killing it. Now the question is, is the cat dead or alive after this hour (query)? Well, the cat in this scenario is dead and alive at the same time (superposition), as one will only know its state for sure once we get to look inside the box. This observation will trigger a collapse of the superposition into one of the two states, dead or alive (output). Both these properties, entanglement and superposition, are what enables quantum computers to store all possible solutions at once for a computation unlike our current computational technologies.

2.2 How are they Built: Hardware and Algorithms

2.2.1 Hardware

We talked a lot about the concepts and what makes quantum computers so special, let us see how they are actually made. For qubits to function in a useful way, their systems require carefully orchestrated control of their environment. This environment is achieved with difficulty using developments in domains such as vacuum, laser, optical systems, radio frequency, microwave technology, and coherent electronic controllers. The other difficulty lies in having to cool down the environment to temperatures near absolute zero (-273 degrees Celsius) keeping in mind that the record lowest temperature is -93.3 degrees Celsius which occurred in the Northern Hemisphere. These difficulties can all be averted through using the QCaaS model where one can make use of the service without worrying about the infrastructure.

To better conceptualize the components we will divide it into the four following layers: (1) the “quantum data plane” is where the qubits reside; (2) the “control and measurement plane” is responsible for performing the operations and measurements on the qubits as required; (3) the “control processor plane” determines the sequence of operations and measurements that the algorithm requires; and (4) the “host processor” a classical computer that handles communication to other components as networks, large storage arrays, and user interfaces.

2.2.1.1 Quantum Data Plane

The quantum data plane is the most important part of the computer, it includes the actual qubits and all the parts holding them in place. The data plane also measures the qubits state in addition to controlling performing different gate operations depending on the type of quantum computer one is using, a gate-based system with physical qubits or an analog computer.

2.2.1.2 Control and Measurement Plane

The control and measurement plane is basically what gives the quantum data plane instructions, indicating what quantum operations are to be performed. The control and measurement plane converts the control processor’s digital signals to the analog control signals needed to perform the task at hand. The final task of this plane is converting the analog output of measurements of qubits in the data plane to classical binary data that the control processor then makes use of. This all sounds easy, yet the analog nature of quantum gates makes it quite a challenge. Even small errors in control signals, or irregularities in the physical design of the qubit, can affect the whole computation that is performed. This issue is tackled by shielding the control signals so that they do not interfere with the qubits state and is done by vacuum, cooling, or both. System calibration is also used to solve this issue by measuring systematic errors and software to improve the control signals to decrease these errors to near zero.

2.2.1.3 Control Processor Plane and Host Processor

The control processor plane's function is simple; it creates the instructions then converts it into compiled code to commands for the control and measurement layer. The host processor is like your everyday computer, running a conventional operating system with standard supporting libraries. Its function is to run the software development tools necessary to create applications to be run on the control processor. These applications are different from those used to control today's classical computers. The host processor also provides storage and networking that a quantum application might need while running.

2.2.2 Algorithms

The manipulation of nature through code is called a quantum algorithm. Mathematicians and scientists around the world are in a race to build these algorithms for ideal quantum computers. Developing functional algorithms computers is equally important as creating the hardware, since without both, the quantum computer is not utilitarian. Quantum algorithms are divided into actual quantum algorithms with exponential computing abilities in addition to error-correction and fault-tolerance techniques. The latter techniques are used to create ideal, noise and error free, quantum computers which can then run the quantum algorithms providing speedups over the best classical algorithms for the same computational tasks.

2.2.2.1 Algorithms: Building Blocks

One of the first applications of quantum computers discovered was Peter Shor's algorithm for integer factorization. In the factorization problem, given an integer $N=p \times q$ for some prime numbers p and q, our task is to determine p and q. The bigger the prime number the longer it takes to find its factors. It was groundbreaking as people realized its threat; the security community grasped the potential of this algorithm to break the public key “cryptosystems” that protects the majority of our society's data.

Another building block is Grover's algorithm to solve NP- complete problems which are the hardest, almost unsolvable, problems in math due to their complexity. NP- complete includes the Traveling Salesman Problem, which has been described as looking for a needle in an exponentially growing haystack. The problem can be formulated as follows: ‘Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city exactly once and returns to the origin city?'. The problem's only solution is using a systematic search approach for testing each possible answer, essentially a blind guess-and-check. The algorithm searches through function inputs to ascertain whether the function returns true or not. Grover's algorithm works optimally even if the function is highly complex or even unknown and the user would like to distinguish for which exact input the function is solved or returns true. Grover's algorithm speeds up this process nearly quadratically with quantum computers.

Last is Hamiltonian Simulation Algorithms which, coming from their name, are used to simulate the dynamics of quantum systems. This was the motivation for Richard Feynman's pioneering exploration of quantum computing in the first place. These simulations require knowledge of the Hamiltonian energy operator which describes all elements and interactions of the system. From there, one can compute a close approximation to the quantum state at a future time, given some initial state of the system at the beginning. Simulations will be elaborated further in the applications chapter.

2.2.2.2 Correction Techniques

Real quantum devices are noisy. To overcome this obstacle quantum error correcting codes and fault-tolerant quantum computing have been developed. "Noise" is simply the interaction of physical and natural systems with its environment. Error-correction and fault-tolerance techniques convert a noisy quantum computer to an idealized quantum computer. The noise in quantum systems is one of the causes why, like previously mentioned above, the output or answer to a given problem is always only probably right.

Answers that come out of quantum computers are in the form of a probability, if you repeat the question the answer will change slightly, and the quantum computer will begin to approach the theoretical percentage or correct answer the more times you repeat. One might ask the quantum computer several times but getting a good answer on the second or third attempt may still be much faster than waiting for a certain answer on a classical computer. With the techniques described here, the system's accuracy increases which in turn increases the probability of the answer being right. The manufacture of fault-tolerant machines is proving to be quite a challenge, but major tech companies around the globe are facing this head on.

3. Real Life Applications

Now imagine that all this computing power is available on the cloud, open to any takers that can make use of it and further develop it. Well, all this computational power is openly available to the public. Through a regular internet connection, anyone can access a quantum computer and endeavor to implement a quantum algorithm or even create a quantum game. With multiple tech companies offering their quantum resources over the public cloud, they are taking an open collaborative approach to spur innovation so anyone can freely access and program quantum computers online. Since this immense computing power is available at one's fingertips, the scientific community is making the most of it, performing a lot of their experiments using this technology.

Being the focal intersection between computer science, physics and engineering, quantum computing has caught the eye of both the academic and corporate world for its promise of revolutionized computing performance. The fact that quantum computing can model the world by encoding the rules of physics into the operation on qubits is the main reason for quantum superiority. Essentially you are coding pure quantum physics into the fundamental essence of nature and reality, not just some mathematical approximation of reality like we do now using traditional equipment.

One may assume that the benefits of quantum computing lie in the machine world alone as corporations are investing heavily in digital security, machine learning and artificial intelligence. However, its uses can be utilized in numerous different fields. Essentially, quantum computers are good at things that have a small input and output while having a vast amount of possibilities.

3.1 Quantum Computing and Artificial Intelligence

3.1.1 Artificial Intelligence

Artificial intelligence (AI) has nearly become a household term. AI involves the building of smart machines that mimic and even surpass human intelligence. With its technology reaching unprecedented levels it has caused quite a stir in various communities around the globe. People have voiced their fears of AI taking over jobs causing mass unemployment, governments using AI to widen their surveillance and control of the masses and most popularly thanks to mainstream movies, that AI machines will effectively dominate the world in order to protect it from its destruction by humans. No one can deny these fears for now, however the level of AI technology now has not yet reached those, perhaps more far-fetched levels.

Other than the above-mentioned worries, AI can be a source of good for humanity especially if combined with the powers of quantum computing. Recently, researchers are discussing the hybrid of the two technologies. The current linear centuries-old scientific method is where one starts with a query --> develops a hypothesis --> generates a model --> tests --> results. AI disrupts this and develops a new scientific method 2.0 where instead of linearity, the method is a constant loop of enhancements represented in Figure 15 below.

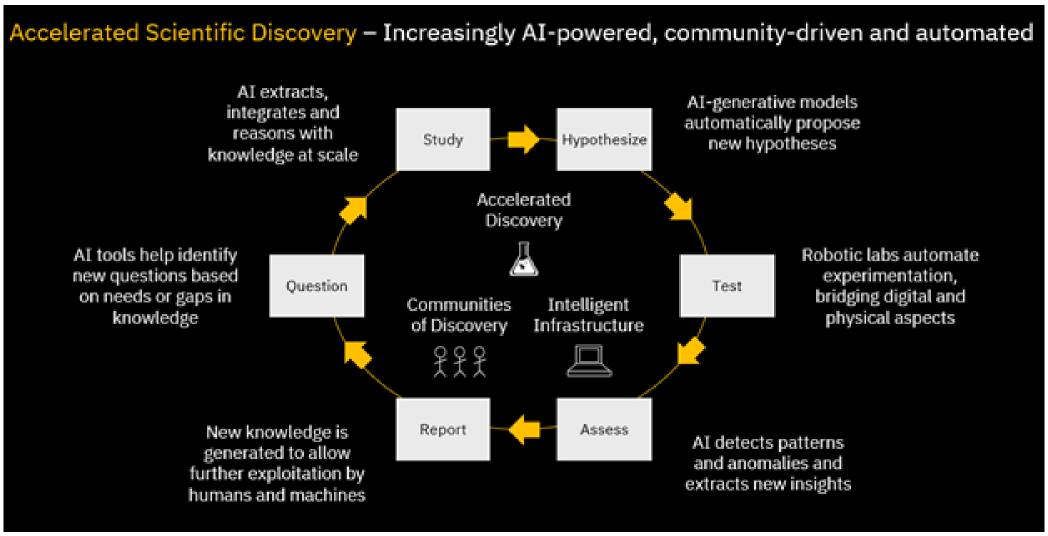

Figure 15: AI scientific method

The closed loop combines all the past knowledge of experiments, thus generating more concrete hypotheses that attain better results. Constantly operating to improve and never satisfied with the status quo until reaching near perfection is the true power of AI that human beings cannot hope to obtain alone. Just imagine the problems that could be solved by combining the powers of quantum computing with AI. Scientists can build an AI program so advanced that it will seem cognitive in nature far surpassing humans’ capabilities of thinking and solving problems.

3.1.2 Quantum Simulations

Our world itself is quantum in nature. Real-world quantum systems can't be modelled on a classical computer without making poor approximations. Therefore, the information required to describe a quantum system, our reality, can only be held by another quantum system. Generally, simulating a quantum system helps determine its structure or behavior in the context of the environment in which exists. Inaccuracy of our current machines are due to electrons' nature. Electrons are in constant motion in the real world unlike what is usually taught in school where electrons are considered as being static, as seen on the left in Figure 16. The orbiting electrons around atoms are themselves in superposition. One only knows where they probably are as seen on the right in Figure13; the denser the area the more probable you will find the electron in it. For some more complex molecules the computational time to model them approaches infinity unless you have qubits that exponentially increase their computing power. The qubits are quantumized therefore, just like nature, they have no problem keeping up with nature's true exponential complexity, they can simulate our universe.

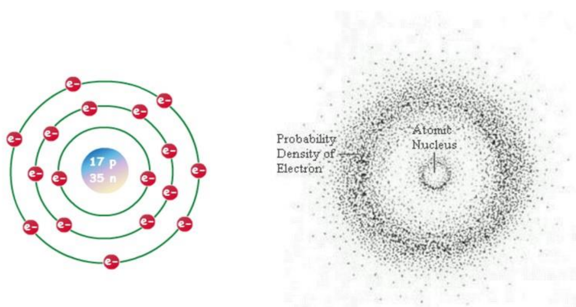

Figure 16: Atomic models

As an example, the input is the number of particles in their starting state while the output is what happens after a given time in modeling of complex molecules. The possibilities of what happens in between that time are almost infinite. When particles increase the number of possibilities increases exponentially with it, i.e. ten electrons would need to track about a thousand possible states. A molecule of just 20 electrons would have to keep track of over a million different probability states. To put it all into context a modern laptop can model 26 electrons, a supercomputer 43 electrons, and as for a 50-electron system, well forget it. That's impossible for any classical computer in the future as for as long as humans will exist.

3.1.3 Quantum Artificial Intelligence Use Case

By 2050, the human population is forecasted to reach 10 billion. With this come great challenges especially in the agricultural department. In Zurich, chemist Teodoro Laino and his team have designed a chemical laboratory that is autonomous, AI controlled and accessible through the cloud. They aim to create enhanced fertilizers by fashioning new catalysts that 'fix' nitrogen, the main ingredient in fertilizers. Undoubtedly, AI can aid by examining the existing literature on catalysts, then in a few years, quantum computers could accurately simulate various nitrogen fixation catalytic processes, thus generating predictive models and identifying new molecules that could ultimately assist in creating the optimum fertilizers for maximum yield to cope with the population boom. All this utilizes only a fraction of energy in comparison with the industrial processes today.

Similarly, molecular modelling can be utilized in the health sector. To develop new drugs, pharmaceutical companies and researchers go through lengthy and costly trials. AI and quantum computing can step in and speed up the processes and may even discover drugs that could cure the incurable. For example, 'Atomwise' (a company that utilizes AI for drug discovery) utilizes super computers with a database of molecular structures, to screen nearly 100 million compounds every day. The company found two drug candidates for treating Ebola virus by probing existing medications and redesigning them in less than one day. What if these search algorithms are further enhanced by quantum computing by looking through all possible molecules at unfathomable speeds? Furthermore, by target testing in silico human tissues and cell models in the shortest amount of time. One may wonder if this would open the gates to curing diseases once believed to be untreatable such as Alzheimer's or even cancer. The prospects seem limitless.

3.2 Quantum Machine Learning

3.2.1 Quantum Machine Learning

Machine learning falls under the umbrella of AI and has become an integral part of computer science with the explosion of data produced on a global scale. Recognizing patterns and learning from such data to deliver correct predictions is the main aim of machine learning. The fields for which machine learning reaps unprecedented benefits are in government analysis, business decisions, medical reports, image recognition, virtual personal assistant, social media, fraud detection and various others. The main question now is how quantum computing can revolutionize the machine learning field.

Quantum machine learning is not simply machine learning but, it's a faster and fundamentally different approach to problem solving. As quantum computing has a significant advantage in multivariable statistical analysis as well as in multi-dimensional systems, this allows for a higher degree reach in modeling and predictive analysis. Opposed to classical systems that are cursed with regular dimensionality, the quantum parallelism effect allows us to avoid this problem. Thus, quantum computational resources are a perfect fit for machine learning problems that more often than not are diverse with a large number of dimensions. The quantum speed-up of an algorithm used in machine learning comes from quantum parallelism, which is to evaluate any function on both possible inputs 0 and 1 at the same time, made possible thanks to the superposition of qubits. Hence, this unique property can aid immensely in hurtling machine learning to new speeds not achieved by classical computer counterparts.

3.2.2 Quantum Neural Networks

One of the most used procedures in machine learning is Neural networks. Quantum Neural Networks is a technique employed in deep supervised learning to train the machine to classify data, and recognize patterns and images. The principle used leverages qubits and rotation gates to operate the network analogous to the neurons and weights as used in a classical neural network to obtain the training parameter that provides a minimum error. Besides enabling the existing AI and machine learning models and techniques, quantum machine learning can lead to entirely new models for training machines, both classical and quantum alike. Machine learning could eventually become a standard component for building quantum computing hardware. Lately, there is more and more evidence that quantum machine learning is evolving from being a subtask of quantum computing to become an approach to quantum computing itself. As per the brief discussion of the above, it is expected that quantum machine learning will disrupt various fields as the progress is very promising.

3.3 Quantum Computing and Brain Computer Interfaces (BCI)

3.3.1 BCI

Can you recall the instant you fell in love for the first time, that invigorating feeling that made everything around you better and more delightful? Well imagine re-enacting that same feeling with just a press of a simple button. How about joining a conference call with a large group of people, with everyone communicating and listening to different conversations at the same time? It does sound far-fetched, however with quantum computing joining forces with AI and brain computer interfaces, humanity and machines can comprehend novel dimensions of the world and effectively enhance our capabilities as individual human beings. In addition, recordings of brain activity not to mention gene analysis which can explore humans and consciousness on a deeper level. As these three fields interact together, we will begin to witness a deeper symbiosis of humans and machines that will shift the fabric of societies. This is a new cognitive era where it is not just outside-in changes that occur as we are used to, but inside-out transformations that unfold directly from our brains.

Let us further explore BCI. BCI signify technologies that can directly connect a human or animal brain with an exterior device for stimulating brain signals or even recording these signals for further analysis. BCI is no longer an uncertainty waiting to be solved as BrainQ, an Israeli startup has already merged neuroscience with machine learning. It is currently about the engineering dilemma where researchers need to construct a bandwidth that can render that connection worthwhile. To elaborate, with speeds up to 20,000 megabits per second computers can communicate with other devices seamlessly on a 5G network. However, till now humans can only communicate with computers by means of typing or speaking which corresponds to a bandwidth of a meager 0.63 megabits per second. Thus, humanity needs to increase the bandwidth of communication between efficient machines and their brains to harvest the full potential of AI powered products and services. This is easier said than done considering the precipitous convolution of the brain's gray matter. In Max-Planck institute in Germany, Mathew Fisher has proposed that utilizing the property of superposition in quantum computing will provide an enhanced understanding of core brain functionalities and their influence.

The brain is an extremely complex organ. BCIs may fail to correctly interpret all our brain signals and the device can get confused on what the owner really wants or needs. There are nearly 100 billion neurons in the brain, a number impossible for a classical computer to even fathom let alone map and calculate based on their activities. This is where quantum computing can intervene. With Quantum machine learning, computers can better understand the structure of the human brain and accurately map brain activities even with the huge number of neurons, which will allow the seamless integration of BCIs with human cognition. This mapping will be achieved by building software that is built on coding that mimics the functions of neurons in the network of the human brain. Each neuron presents a decision-making procedure by receiving an input of various signals and then processes them to produce an output that is either “Yes” or “No”. Each input is weighed on how important it is for the overall decision and, consequently, the weights are adjusted to several test runs to effectively train the network to work better later on.

3.3.2 Real Progress

In 2020 Elon Musk, famed for his ingenious radical ideas, unveiled a pig with a coin-sized computer chip in its brain. Whenever the pig sniffed straw or ate, that activity appeared on a graph composed to track its neural actions. To further elaborate, the chip sends wireless signals that are picked up by computers and then the data is logged. The company behind this is Neuralink and they are hoping to start human trials soon. Creating a device that can communicate and withstand the human brain's complexity is a highly ambitious goal, however if quantum computing is combined with this device, the dream will become a reality. Just imagine one day being able to download information from and to our brains, humans will be capable of learning instantaneously any topic they find interesting, maybe even earn a PhD's worth of information in a mere couple of seconds. Imagine being able to improve your memory ten-fold, improve your attention span, sending messages to another person with the chip telepathically or even restoring a person's ability to talk. Some researchers have even argued that humans will be able to upload their consciousness on computers and if this happens humans may reach immortality. The possibilities are endless, and humans are set to receive an upgrade they never dreamed of. This technology will be available to everyone and very inexpensively once it is widespread globally. No one believed that one day most of the population would have smartphones, but here we are today.

3.4 Quantum Cryptography

3.4.1 Security Versus Quantum Algorithms

Now coming back to the roots of computing again with cryptography where we saw a tremendous amount of progress. The utilization of quantum computing in cryptography for cyber security can be considered a double-edged sword, as it can highly enhance digital security to a point of near perfect breach prevention. On the other hand, it will theoretically be able to render most of the current security techniques obsolete and can easily breach their systems when quantum computing technology is perfected.

The vast majority of used encryption systems depends on keys, which are random large prime numbers that can be employed to encrypt or decrypt data. Current packages for encryption are deployed using symmetric as well as asymmetric keys, both of which would be defenseless if hacked by a quantum computer. Symmetric systems depend on a shared secret key, in order to break this key one would require doubled computing power for each extra bit added. Considering that, as computers became more powerful, people just kept using larger keys to avoid the risks of hacking. However, if one would apply Grover’s algorithm (previously mentioned in the machine learning section), quantum computers could slash the length of the key in half, a considerable reduction in the amount of time required to break a key. Imagine when quantum computing powers are off the charts, no key length would be able to stop such a formidable force.

Asymmetric systems on the other hand utilize both public and private key pairs. Regarding the most commonly spread RSA family of algorithms, their math structure is legitimately complex, however it can be broken if one factors a huge number into the algorithm’s two prime number factors. This can be performed using factoring with Shor’s algorithm (polynomial time algorithm for integer factorization) which quantum computers use to find factors of keys in a fraction of the time.

3.4.2 Quantum Key Distribution

Don’t fret readers as it was mentioned earlier that quantum cryptography is a double-edged sword; quantum properties will come to the rescue and counter its own powers. Quantum Key Distribution (QKD) is a technique that can send encryption keys by employing atypical behaviors of particles that are subatomic in nature. This QKD method is theoretically impenetrable as photons are sent one at a time via fiber optic lines. The most advanced with QKD technology is China with specialized pipes connecting Beijing, Shanghai and other major cities. In the United states, the first commercial QKD network, “Quantum Xchange”, was deployed in the fall of 2019 connecting the financial firms of New York by sending and receiving secure data with QKD techniques.

How does Quantum Cryptography work? QKD uses a series of light particles also known as photons that transmit data over a fiber optic cable. The two endpoints can ascertain the key and the safety of its usage by comparing measurements of the properties of a fraction of the photons in question. If somehow the photon is copied or read by an eavesdropper, the state of the photon will change and the endpoints can detect this alteration, so in other words no one can copy or read the photon without being detected. With the current development of quantum computers world-wide, the risks to information security are high. Thus, as we may fear the quantum computer in this field, we will also need quantum cryptography in order to safeguard information.

Many online security systems from banking to encryption rely on the principle that it is currently almost impossible to take a very large number and figure out the prime factors, like Shor's algorithm. Here input is a single large number and the output is how many sets of prime numbers multiplied together to give that large number. Again, the possibilities here are almost infinite.

3.4 Quantum Computing and Finance

Shifting to the business world, one financial crisis after the other has shifted the world's attention to better understanding clients and to utilize automated trading to alleviate the conundrums caused by market manipulation. For example, Fintech uses computer powered methods that model client behavior, plan and execute trades and automate client dealings. Financial institutions are currently envisioning the future to harness quantum computing potential as this will allow the institutions to better analyze huge unstructured data sets. Also, financial data is usually live streamed with real time equity prices that usually carry high levels of random noise. Quantum computing can aid in this dilemma with optimum results. The COVID-19 pandemic has shown that timely and precise risk assessment remains a grave challenge. Even prior to 2020, the past 20 years have seen various economic and financial disasters that brought about rapid changes in how financial institutions priced risk and assessed. This has led to risk assessment models driven by AI but still based on traditional computing. But with quantum computing on the verge of wide usage, it is a game changer. The time to act is now.

Quantum computers will benefit the finance sector through Shor's algorithm which is diligent in factorization and Grover's algorithm which can quantum search through unstructured databases. It is theoretically proven that quantum computers can solve these faster than a classical computer. As for Shor's algorithm the speed up is exponential, whereas the speed up is quadratic for Grover's algorithm . An application of quantum computing with finance would be modelling of dynamic stock prices. The best-known model for such a task is the Black-Scholes model, which is a model of exponential growth combined with Brownian motion. One can quantumly extend the Black-Scholes model, instead of utilizing the classical functions as it is viable to incorporate quantum functions. This will produce diverse dynamics that have the potential to be more pertinent in a realistic model of stock price movements.

Financial institutions have already started hiring people with quantum skills. In a LinkedIn analysis, it was found that 21 insurance companies and banks hired more than 115 people with quantum set of skills as of June 2020. Wall Street banks are currently showing high interest in quantum computing potential, especially for its run of the algorithms mentioned earlier. Barclays and JPMorgan Chase have been utilizing IBM's quantum computing software since 2017 to test simulations for portfolio optimization. Reportedly, JPMorgan has already initiated a sort of “quantum culture”, and of course many are following suit. One negative consequence of such unprecedented levels of computing powers is the likelihood of financial systems becoming compromised through hacking, but this can be countered as mentioned in the previous section with quantum properties themselves. Thus, quantum computing will entirely transform the financial sector as being able to predict financial models using real-time data in a fraction of the time and will accordingly usher unprecedented levels of operational efficiencies and customer service. Markets will prosper and profits will surge.

3.5 Quantum Computing and Space

3.5.1 Quantum Teleportation

Does quantum computing have aerospace applications? The answer is definitely yes, as space provides an idyllic environment for quantum technology. D-Wave 2 (Figure 17, 18), a commercial quantum computer, was installed by NASA in collaboration with the non-profit universities space research association that helps in simulation and acute modeling of aerodynamic performance which is vital to comprehend various phenomena in space exploration missions. NASA quantum artificial intelligence laboratory contains a 512 qubit D-wave 2, owing to its extremely promising computational potential. NASA aims to utilize the D-Wave 2 for two different missions: first, the Kepler mission which has the sole purpose of uncovering habitable and Earth-sized planets; and second, to validate and identify signals of small planets as they revolve around their host stars, after which huge volumes of data are processed by heuristic algorithms. While some planets may remain in the shadows undiscovered due to the limitations of the computational powers of traditional supercomputers, luckily quantum computers can solve this issue and will leave no stone unturned. As the quantum computer implements rigorous data searches for transiting planets, it provides a distinctive and complementary tactic for this task.

Figure 17: Exterior of D-Wave 2

Figure 18: Exterior of D-Wave 2

David Venturelli, a science operations manager at NASA, has stated that quantum computers are assisting in the research for superior and more secure procedures for space travel overall and sending robots to remote locations. The ultimate objective is to plan out the robot's mission as far in advance as possible as real-time communication with the robot isn't viable considering how deep in space they will be. Here comes in the benefit of quantum communication with quantum teleportation. Yes, it is real! Almost three years ago, a team of Chinese physicists launched a 1400-pound quantum satellite into space. Since then, this satellite has been humming information encoded in entangled photons to and from quantum stations on Earth. In 2019 the project came to fruition when physicists demonstrated quantum teleportation between two computer chips for the first time. They used a single photon to transmit information about its state through the quantum mechanical phenomenon of entanglement. Quantum Teleportation uses entanglement to transfer information instantaneously across vast distances.

3.5.2 Optimization and Plans

With quantum optimization, NASA scientists will grasp new means to predict any incidents on the mission and the best course of action for the robots to complete their mission successfully. The robots have limited lifetime for their batteries when drilling or using infrared thermometers to record temperatures, thus each second counts and precise planning is needed for the tasks to ensure no time is wasted. All of this includes variables that are above the processing level for traditional computers but fit well with quantum computers.

In addition, space mission automated planners which are responsible for scheduling tasks, planning and determining the observation time of a target using radars, can be optimized via quantum computers to improve efficiency and significantly reduce the time required. Venturelli argued that the D-Wave Two is just the tip of the quantum iceberg and extra ground-breaking research is required to enhance quantum services worldwide.

This allows us to even model new arrangements of molecules elucidating the interaction of a collection of particles over time. Simulation applications includes problems in chemistry, materials science, condensed matter, nuclear physics, and high-energy physics. Gaining knowledge in these fields can lead to development of new industrial materials or solving important physics problems. Thus, leading to a plethora of inventions like new batteries, super-strong materials and medicines.

4. Looking forward

4.1 Future Work

4.1.1 Programming Language

Programming languages are the building blocks for any computer-related technologies. Researchers are aiming to generate multiple abstraction layers for programmers to be able to control quantum computer functionalities. One of the tech giants utilizes its Quantum Development Kit which holds Quantum Computer Language (QCL), whose data types and syntax is similar to C programming language. Another approach would be developing a standard to quantum language converter. This facilitates the procedure for current programmers as they do not have to learn a new language from scratch. Quantum Information Software Kit (QISKit) was developed by another tech giant to function as a full-stack library to simulate, write and run the quantum program with quantum algorithms for conducting experiments with simulations, AI and applications of finance. A major feature of QISKit is being an open-source and cloud-based developer tool available for anyone.

Challenges faced for the algorithms programmed would be the quantity of the input data for the proposed implementations and the memory facing quantum dynamics. Yes, quantum algorithms provide major speedups for data processing as mentioned earlier, however they do not provide advantages in data reading. More often than not, the cost of reading data can far exceed the value of quantum algorithms.

4.1.2 Quantum Internet

Instead of 1's and 0's, qubits will be the transmission currency in the quantum internet. First, we need a physical medium, “a quantum channel,” for transmitting qubits. It turns out that we already do this today using fiber cables for our everyday “vanilla” communications. The next will be a means to transmit the qubits over extended distances. Physical mediums are not the best for communication by nature, and so are quantum channels. Hence to reach longer distances, booster nodes called quantum repeaters are necessary. These repeaters are placed along the optical fiber connecting the quantum channel across switches allowing qubits to be transmitted over arbitrarily long distances.

Once quantum internet is normalized, it will make Wi-Fi seem obsolete, the same as dial up internet is for us now. What one might recognize in the experiment are the fiber optic cables which are utilized nearly everywhere in telecommunication technologies nowadays. What is new is that the information travelled across these cables at warp speed with the aid of semi-autonomous systems that supervised it while managing synchronization of the entangled particles. Moreover, the system was able to run for an entire week devoid of human interference. With the teleportation occurring at the speed of light, the supremacy of a quantum computer operating with quantum internet will most likely surpass the speed of the world's existing state-of-the-art supercomputers manifold.

4.1.3 Think Quantumly About Memory

Memory is an integral part of any computer; quantum computers are no exception. Quantum memory management is crucial as the quantum programs (that are composed of sequences of measurements and quantum logic gates) exploit most of the resources from the system, demanding most of the qubits available. Similar to traditional memory managers, the aim of quantum memory managers is to free up space of quantum memory qubits and allocate it efficiently. But in contrast, quantum memory follows these subsequent characteristics:

- Data cannot be copied, with regard to the no-cloning quantum theorem.
- Data will have a limited lifespan, due to the qubits decohering spontaneously.
- Data computations are processed directly in memory and reversing quantum logic gates can be achieved by applying their inverses.
- Noise incoherence on some qubits can alter data in perpetuity and it affects the data on the other qubits entangled with them.
- Data locality is paramount as two-qubit gates are generated by interconnecting operand qubits.

Considering the above, the architecture of quantum computers is heavily influenced by the properties and characteristics of quantum memory. Thus, it complicates the implementation of quantum memory managers, leaving researchers with several dilemmas to solve to perfect the quantum computing race.

4.2 Problems with Quantum Computing

The problem with QCaaS, as with other cloud offerings, is the security concerns that come with cloud in addition to stability in the two-way communication. Another hot topic with quantum computing is that it is not just adding more qubits but creating a good environment as it is very sensitive to noise. Adding one additional qubit to a quantum computer doubles the size of the problem the quantum computer can represent. This increased computational ability comes with the limitations of noisy gates which create significant error rates, meaning will require error correction and substantial shielding from background noise. This general inability to read in data efficiently, and limited ability to measure the system, in turn makes creating effective quantum algorithms difficult.

Another struggle is decoherence; you can only keep it quantum for a small time. This is mainly due to the complexity of building and the practicality of maintaining a quantum environment. Qubits need to be free from all radiation and kept at a temperature just above that of absolute zero. If the particle interacts with anything the quantum effects are scared away. Any slight disturbances such as light particles radiation or even quantum vibrations can snap the particles out of their superposition state, voiding the entire advantage of the machine.

4.3 Cloud Repatriation

We are witnessing a peculiar anomaly in the cloud market due to a huge misconception of the cloud model. The public cloud market is growing. A recent Gartner report cites that the worldwide public cloud service market is expected to grow from $182.4 billion in 2018 to $331.2 billion by 2022, a growth of more than 50%. At the same time, the IDC Cloud and AI Adoption Survey of 2018 indicates that 80% of customers are repatriating workloads from public cloud environments. Cloud repatriation is the shift of workloads from public cloud to local infrastructure environments. This seemingly absurd paradox is due to the initial decision-making around adoption of the cloud together with having the wrong set of expectations. Ideally, Cloud is the correct destination for the correct workload at the correct time with the proper organization and ownership plan, which is rarely applied in today's complex world. QCaaS does not fall short from that as some workloads are just not made to be processed by quantum computers.

Let's break this down. The decision to adopt cloud is not always the correct one. Though IT organizations tend to assume cloud works just like their corporate data center, not every environment can run on the cloud. Moving to cloud is incredibly valuable for the right applications; however, there is work to be done before making the move. What actual value do companies gain through the cost savings they get from cloud, if they afterwards are subject to multiple data hacks to cloud servers?

One cannot expect easy success moving complex systems like IT environments to cloud. Cloud vendors are not always a helping hand while marketing the idea of cloud in terms of how easy and less expensive it is. Therefore, topics like security and performance issues are not considered, not to mention the fact that they are difficult to understand prior to the move to cloud. The cloud can be more expensive and less secure.

The failure to define the business objective of a cloud adoption combined with inadequate planning of the adoption often leads to disappointment. The reality of a cloud adoption is sometimes so far off from what the decision maker is promised that cloud repatriation becomes an escape. On- premises computing will remain at least a part of an organization's IT environment for better control, flexibility and security. As businesses seek to optimize their cloud and on-premises environments, a hybrid of private cloud and repatriation seems to be the reasonable solution. With a more diversified cloud storage strategy, needs are better met.

Most tech giants are already involved in the QCaaS market, but with the types of concerns about cloud mentioned above one can see the opportunity for Dell Technologies, given their leading position in the enterprise computing field. Leveraging this repatriation trend is the ideal entry into the quantum market of IT for QCaaS repatriation. Dell Technologies global chief technology officer, John Roese, has an optimistic view on quantum computing development and call out to developers to experiment with new simulators and programming languages might pave way to enter this market.

5. Conclusion

Today, everything is about availability at a click of a button. The final product of this need is a philosophy and a way to go about life. People want service without the need to own the asset providing the service. 'Anything as a Service' (XaaS) is the new method of moving through life and the heart of the digital transformation. Traditional computing has reached its predestined breaking point and like every technology that grows old, falls apart and crumbles, its successor rises from the rubble, reborn as the new technology. We are now entering the unknown territory of the quantum realm.

Quantum computing has been integrated into this 'as a Service' model. By cleverly exploiting superposition and entanglement in the 'as a Service' model, problems can be solved exponentially more efficient than would ever be possible on a normal computer. Major tech companies, theoretical physicists as well as computer scientists are undertaking rigorous research in the hopes of perfecting this technology to open the door for the quantum age, keeping in mind that it took less than a human lifetime to get from ENIAC to the iPhone.

Right now we don't know what secrets of the universe we might unlock when we start simulating subatomic particles and according to Max Planck, science cannot solve the ultimate mystery of nature because, in the final analysis, we ourselves are a part of the mystery that we are trying to solve. Personally, I am content with leaving it that way while enjoying the benefits of teleportation and quantum internet. Thus, the possible breakthroughs are as unknown as they are exciting, but one thing is certain; quantum computers hold the potential for a radical change in the progress of humanity. We might even discover what is inside black holes or what black matter and dark energy is. We could be looking back and marveling at just how simple our lives once were. There has been a boundary dissolution between thought and reality, where people's imaginations are becoming realities. We gave birth to thought itself manifested into computers, only our imagination will be the limit. To paraphrase J. B. S. Haldane: Our situation as humans may not only be stranger than we suppose; it may be stranger that we can suppose.

Metaphysician and philosopher Terrence McKenna talked about a transcendental object at the end of time that is propelling us into the future and pulling us towards unity and unimaginable possibilities. We might see off our biochemical nature and be uploaded into eternal digital existence in a quantum simulation where we can be programmed to be gods. We are talking here about an entire new world, or even universe, that we, humans, rule over. Results from the Stanford prison experiment make this idea seem worrying to say the least and documentaries like the Social Dilemma are also not very encouraging. This can go in either way: utopia or dystopia, or something entirely new, say a superposition of both. So, I leave you with the ultimate choice: will you choose the red pill or the blue pill?

In any case, I will see you on the other side.

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