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How will quantum computing affect the mainframe environment and its applications?

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Scriptie voorgedragen tot het bekomen van de graad van
professionele bachelor in de toegepaste informatica

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Thesis submitted in partial fulfilment of the requirements for the degree of
professional bachelor of applied computer science

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Preface

There is a certain attraction that comes with learning new things without any proper pre-knowledge and that is precisely the reason that quantum computing has attracted me this much.

The mere fact that the field of quantum computing is developing to a profitable and useful field so rapidly has astonished me from my very first contacts with the environment.

I would like to thank Frank Harkins from IBM for always being available to have a discussion about quantum computing and how it will influence our environments.

But most of all I would like to congratulate the complete research environment around quantum computing on how accepting and supportive they are in helping interested parties, through their open-source communities, forums, Slack-channels and the many freely available research papers.

Samenvatting

Zoals het onderzoek aantoont is het onderzoeksgebied van kwantum computers nog in zijn beginjaren en moeten we kritisch blijven ten opzichte van elke nieuwe uitgave in verband met nieuw onderzoek. Echter is het ook belangrijk dat we buiten het puur theoretische deel ook effectief op zoek gaan naar de praktische toepassingen en/ of inzichten in onze huidige processen met evt. de toepassing van kwantum verwerking.

In het onderzoek proberen we een duidelijk beeld weer te geven aan de lezer, zodat hij/ zij zelfstandig kan nadenken over toepassingen en/ of zelf toevoegingen maken aan de vele open source gemeenschappen op Github. Dit hebben we proberen te bereiken door enkele praktische vergelijkingen te maken met de hulp van het Python-framework Qiskit tussen de uitvoering op een klassiek systeem en een kwantum systeem. De resultaten wijzen inderdaad op een mogelijke versnelling, maar zoals te zien aan de werkelijke uitvoeringen op de echte kwantum computers van IBM is het moeilijk om deze nieuwe technologieën al meteen te gebruiken in bestaande productiesystemen.

We proberen ook alle uitkomsten te relativeren en ervoor te zorgen dat de lezer volledig op de hoogte is van de potentiële valkuilen met kwantum computers en hun toepassingen.

Abstract

As the research shows, the field of quantum computers is still in its early years and we must remain critical of any new publication related to new research. However, it is also important that beyond the purely theoretical part, we also effectively look for practical applications and/or insights into our current processes with the possible application of quantum processing.

In the research we try to present a more clear picture to the reader, so that he or she can independently think about applications and/or make additions to the many open source communities on Github. We have tried to achieve this by making some practical comparisons with the help of the Python framework Qiskit between classical computing and quantum computing. The results indeed point to possible acceleration, but as can be seen from the actual executions on IBM's real quantum computers, it is difficult to use these new technologies in existing production systems at this point in time.

We also try to put all the results into perspective and make sure that the reader is fully aware of the potential pitfalls with quantum computers and their applications.

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1. Introduction

Why does everyone suddenly jump on the subject of quantum computing **(QC)** and why would it concern anyone at this point in time? Well we are rapidly reaching the limits of how small we are able to create the transistors on a chip, Moore's Law may very well be about to end. Currently we are able to create transistors so small that they themselves start being influenced by the quantum world which would undermine the whole point of building smaller and smaller components that are faster than its predecessors.

The quantum field itself is also rapidly expanding due to the practical executions of QC, much in the same way data science has been expanding for the last 2 decades. Only 20 years ago data was something nice to have in a business to gain a possible edge over opponents, now data is the lifeblood for many of those companies. Data is what drives research, competitive advantage and various innovations. QC could offer the way of data handling and processing a surprising speed boost and expansion into regions we just were not able to even understand due to its quantum nature e.g. in sectors like Chemistry, Astronomy, Physics... And this is exactly why the mainframe environment could tie in so nicely into the research towards a classical and quantum computational combined environment. Mainframes drive the big enterprises who in turn drive the smaller ones that our societies are built upon, if QC can aid these big enterprises they would in turn let this information flow into the lower sectors of our global economy. All this is why the paper will try and expose why we should start caring about QC in the very same everyone suddenly started caring about data research with classical computing. (Arute et al., 2019) (Amico et al., 2019)

1.1 Problem Statement

What can QC actually solve as of this very moment, is a question every enterprise is trying to figure out first. The field has shown even in this very early state with the limited amount of computational resources much promise. Inside the fields of data processing there is a clear trend that as we further develop quantum computational expertise the possible business impacts are generated exponentially. Many big enterprises have finally figured out the most lucrative and easy-to-apply ways of capturing important data that could have business value. Now the actual issue that most definitely is worth addressing, is that the processing of the shear amount of data has become unbearable in realistic time schemes.

Business needs all those data results as soon as possible to gain the edge over competitors and industry leaders, quantum could in theory exponentially aid classical computers with the processing of this large amount of data. Mainframes especially are able to generate so much I/O with all sorts of data e.g. credit card spending, production analysis, transport optimization, that the mainframe together with QC could very well become the power couple of the 21st century. With platforms as Qiskit and Cirq everyone is able to contribute towards quantum research even within a mainframe minded environment. (Abraham et al., 2019) and (McClean et al., 2017)

1.2 Research question

The question of "How will QC affect the mainframe environment and its applications?" can be a really useful question to solve because it would allow the highly expertised environment of the mainframe to be able to think of possible applications of the quantum research with their mainframe systems. In this moment of time practical QC has come such a long way that this question could possibly give business value to the mainframe industry and all of their users. Exploring this domain can provide valuable insights in all different kinds of sectors that make use of the mainframe's high-data capabilities.

1.3 Research objective

The paper is designed to allow individuals that are interested in QC and are interested in research to get a better grasp on the real business impacts of the quantum realm. We expect that we can evaluate the real value of QC inside a business, but also we want to find actual value and applications inside the sector as a whole. We also would like to show the practical execution of quantum algorithms and their advantages using Qiskit, which is a python-based framework that is open source to anyone interested in computer science and QC.

1.4 Structure of this bachelor thesis

The paper will consist of the following chapters:

In chapter 2, we will introduce the very basic usage of QC to make sure every reader is able to understand the basic necessary principles to understand this paper.

In chapter 3, we will expose how classical and QC could offer a valuable partnership in their effort to speed up all research.

In chapter 4, we will finally show the real usages of quantum algorithms of the future through simulations or even executions on real devices with Qiskit. This chapter will be designed for computer scientist that want to really understand the technology and want to learn and maybe even contribute themselves towards the many open source options out there surrounding QC.

In chapter 5, there will be an extensive discussion where we take in the results of the practical compartment of this paper. Furthermore we would still like to take a critical look at how QC has its disadvantages and maybe even its flaws.

2. Quantum Essentials

To make sure everyone starts from the same baseline to understand the full potential of this paper, we will introduce a few of the basic quantum principles. This paper is not targeting these specific principles but does use them to explain different practical consequences of the use of them within quantum computation. If there is any further interest regarding these principles, we would refer you to the following papers, Rieffel and Polak (1998) and Shor (2000).

2.0.1 The Qubit and its representations

The foundation of any quantum related paper is and will always be the **qubit**. A qubit is just like a classical computing **bit** the foundational unit of its computer. Whilst a bit can either be on or off, a qubit has a certain statistical measurement to it. To be able to program on a quantum computer you need to think of the issue of computing an equation in a completely different way. A qubit is also not infinite, meaning that any type of computation needs to happen during the time frame of stable qubit without being thrown of its state by decoherence or any other external factors.

One of the biggest issues with qubits is that they can behave unstable when influenced by the slightest of external influences, which also means the influence of an external observer. Once a qubit reaches an unstable state it has lost its quantum advantages and becomes a determined particle, which is not available for calculations any more. Meaning that during the execution of your program you are simply not able to look at the intermediary results as this would affect the final result, which would make the whole computation worthless. This means that debugging and looking at variables whilst you are executing a piece of code simply is not possible, which in turn makes writing actual code for a quantum computer a lot more difficult.

To comprehend the nature of a qubit we need to understand that representing a qubit is only possible in a complex field, which shows of a certain amplitude of the state of the qubit in a point in time. *Felix Bloch* was the individual that came up with the Bloch sphere that we currently use to clearly represent what a qubit is at a certain point in time. So this amplitude refers to the probability of a qubit at a certain point during the execution. These amplitudes can be influenced during execution by quantum gates, external influences and even quantum decoherence.

Another way of demystifying what a qubit exactly means is by representing it through the use of matrices and the Bra-ket notation. By using these matrices and using matrix transformations we can more easily expose the way a qubit can be influenced during execution. This image is mostly preferred by computer scientist because it gives them a clear image of transformation in the same way an ordinary logic gate can influence an electrical signal. The combination of qubit basis states can be achieved by the utilisation of a tensor product. In the formulae below you are able to see how a 2-qubit system is represented through their matrix-representation. So look at the following transformations in much the same way one would look at an electrical signal would flow through a set of gates.

$$|0\rangle = \begin{bmatrix}1\\0\end{bmatrix} \textit{and} \, |1\rangle = \begin{bmatrix}0\\1\end{bmatrix}$$

$$|00\rangle = \begin{bmatrix}1\\0\end{bmatrix} \bigoplus \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}1\\0\\0\\0\end{bmatrix} \quad |01\rangle = \begin{bmatrix}1\\0\end{bmatrix} \bigoplus \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}0\\1\\0\\0\end{bmatrix}$$

$$|10\rangle = \begin{bmatrix}0\\1\end{bmatrix} \bigoplus \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}0\\0\\1\\0\end{bmatrix} \quad |11\rangle = \begin{bmatrix}0\\1\end{bmatrix} \bigoplus \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}0\\0\\0\\1\end{bmatrix}$$

To sum it up a bit can be only be in a state of on or off and this can be checked throughout execution, whilst a qubit is in a uncertain state during execution much like Schrödinger's cat but once observed is just as determined as a normal bit would be. But determining the state during execution will affect the rest of the experiment and will remove the advantage of quantum in much the same way if Schrödinger went on with the experiment after observation that the cat died, he would be certain that cat would still be dead at a later point.

2.0.2 Superposition and entanglement

Superposition is a term a lot of people have heard about and how it could achieve major breakthroughs in the scientific world, but what it exactly represents is the real question.

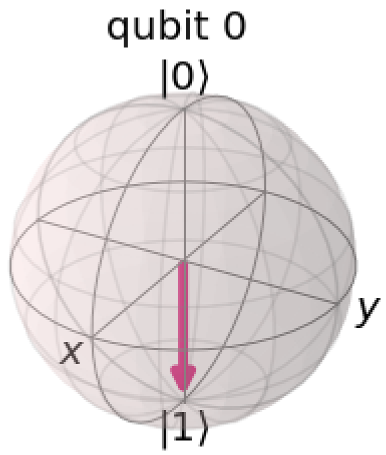

Figure 2.1: A Bloch sphere representation of 1 qubit in the $|1\rangle$ state. The Bloch sphere clearly indicates that the state of a qubit has a certain probabilistic aspect to it.

Quantum advantage is mostly gained from this single quantum principle, where a quantum particle can remain in both states at once whilst it has not been observed. To explain this more clearly from a computer science perspective, a qubit in superposition is during execution behaving as 0 and 1 at the same time. A concept that seems impossible within a classical frame of mind but also very advantageous if you know where to look. E.g. if you are processing a big array of data through your classical processor, your processor will take one item of the array, process, convert and output it before it will take another item of the array and perform the same thing. A quantum processor could go about this process in a similar yet much more ingenious way. It would put an amount of qubits in superposition to represent the full array as input, perform the needed amount of quantum gates and receive the output in a single go instead of needing to loop over the full array. (Draper, 2000)

Entanglement is another interesting principle within the realm of quantum physics. It refers to the correlation between entangled qubits where the state of one qubit influences the state of the correlated qubit in a way that it can be exploited and theoretically infinitely speed up computation. This entanglement can be achieved inside a quantum computer by the use of quantum gates on qubits in a state of superposition. The deterministic result of the qubits at the end of an experiment will show the same correlation in the results, keeping in mind that enough experiments are performed to defend against quantum decoherence mistakes and other external influences. (Brandao et al., 2016)

These two principles are constantly being used by a quantum processor as the one that Google showed of in their latest showcase of their quantum supremacy, Arute et al. (2019). Together they are able to exponentially increase the computing power of a quantum computer, as you add more and more qubits you are exponentially increases the available data items such a processor could handle. For example to be able to simulate the biggest medicine of the 20th century, penicillin you would need 286 functional qubits, which in turn would be able to generate the 2^{286} bits of memory. It would straight up be impossible to get this amount of classical RAM, so it is impossible to simulate this medicine fully. Actually getting to such a stable amount of qubits in itself will still be a scientific miracle.

2.0.3 Quantum gates

Now one might wonder, how do we create calculations with particles that are not observable and not tangible at a point in time. Quantum gates offer the solution to this question, a quantum gate affects one or more qubits during execution so that a programmer is able to perform changes to the state of the qubit but does not create an unstable qubit. From a programmers perspective they function in a similar way that a normal logic gate functions on an electrical signal inside a regular processor. Furthermore we will provide some frequently used quantum gates. One major difference rule that a quantum computer has to listen to when it comes to its gates, is that quantum have to be 100 percent reversible while a classical computer does not have to deal with this limitation. This is clearly shown by the use of matrix representations when a qubit passes through a specific quantum gate and for a classical example, thing of an OR-gate you are able to see the outcome of the signal with an on or an off, but you can not know just from the outcome which initial signal influenced the OR-gate to be activated.

Hadamard gate

The Hadamard gate is single most important gate for creating a quantum computation. This gate is responsible for putting a qubit inside a state of superposition and is also the one to get it out of this state. So in turn without this gate, quantum advantage would not exist. It maps $|0\rangle$ to $\frac{|0\rangle+|1\rangle}{\sqrt{2}}$ and $|1\rangle$ to $\frac{|0\rangle-|1\rangle}{\sqrt{2}}$, which are both superposition states.

$$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

Pauli-X gate

Performs in a similar way a classical NOT-gate performs on an electrical signal or an absence of it. A qubit in $|0\rangle$ state going through a Paul-X gate would go in a $|1\rangle$ state.

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

CNOT gate

This gate works as a flip for a qubit. It is connected to 1 control qubit marked with an X and targets a target qubit marked with a small circle. If the control qubit is in an activated state it will flip the target qubit.

$$CNOT = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Toffoli, CCNOT gate

The Toffoli gate works in the same way as a CNOT gate, but instead it has 2 control qubits. So both of them need to be activated to actually flip the target qubit, which logically requires at least 3 qubits in your system.

$$CCNOT = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

The mathematical forms are there to show that the addition of a gate to your quantum circuit just mathematically transforms the state of your qubit. So if we look at these transformations of our quantum circuit using mathematics we can more easily make the connection with our classical systems that perform in a similar yet different way.

2.0.4 Quantum decoherence

QC is not solely composed of upsides, the biggest downside is that as of now technology has not progressed far enough to actually provide the necessary amount of stable qubits to perform trustworthy calculations with. For example the simulations of penicillin, a system would need 286 qubits that remain stable for a prolonged period, but as of now Google has only been able to keep 53 qubits stable for a prolonged period of time using quantum error correction throughout the calculations. The loss of these quantum aspects during execution is called *quantum decoherence*, it is the phenomenon that describes how a qubit falls in an unstable state after being influenced by external forces or even internal influences from the qubits around it inside the system.

Referring to the image below you are able to see that quantum decoherence is even a measurable phenomenon. The circuit below is specially build to show that quantum decoherence even shows up in the smallest of computations, where a qubit gets thrown in an elevated state of $|1\rangle$ and then gets measured and pictured on a classical bit. If you analyse the results you are able to see that quantum decoherence has occurred and de-elevated the state of the qubit back to $|0\rangle$. In this specific case from the 1024 shots taking on the real quantum device, around 8 percent or 81 of the shots, were worthless due to the quantum decoherence.

The whole field has one giant, non-circumventable that goes with it, the larger our quantum systems become, the more internal decoherence we receive from the higher concentration of qubits near each other. This all could mean that there is a limit to how big we are able to make quantum machines, because at a certain point, without proper error correction, the internal decoherence would make every single calculation useless because of the high probability of faulty data throughout. However if we are able to find a solution to this internal decoherence, the amount of qubits inside a system could be limitless and our data processing with it could also be limitless. (Hartnett, 2019)

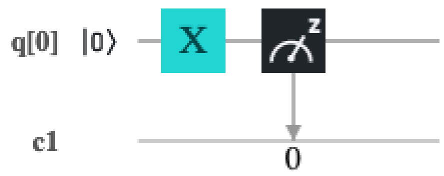

Figure 2.2: This is the quantum circuit that performs a Pauli-X gate followed up with a measurement, to show of how quantum decoherence can influence the results.

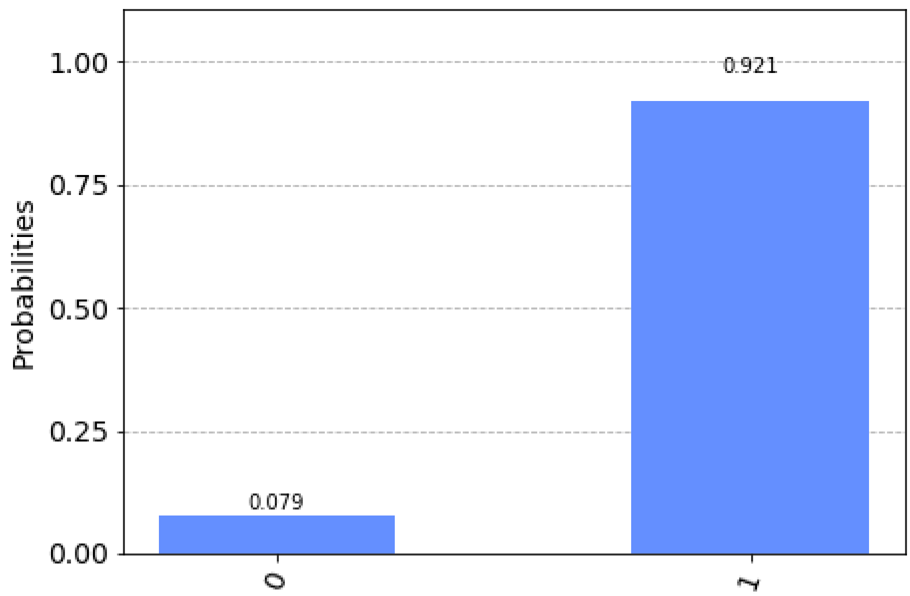

Figure 2.3: These are the results from which it is clearly visible that quantum decoherence has taken place on the initial $|1\rangle$ state to the $|0\rangle$ state.

3. Real-world solutions with Quantum

Once you start looking into quantum theory and everything it could possibly do for your scientific project, you would find yourself in one of the deepest rabbit holes you could ever possibly find. The true value of quantum research is how we can actually use it for real-life solutions. One could easily imagine that being able to simulate an exact medicine within a couple of days instead of the many months it takes at the moment, would save a numerous amount of lives. So keeping this same train of thought throughout, it is of great importance that we actually focus our attention on what current developments could possibly mean for existing projects and research.

3.0.1 Quantum computing and traditional computing

QC is and will never be the sole solution to a problem. This new form of computing is made to be an addition to points where classical computing fails, e.g. searching through an extremely large dataset without having a clear index within a polynomial time frame such as in Terhal and Smolin (1998). QC also has its limits it takes a lot longer to actually set up your computation than it would take on a regular machine, but it could be able to solve a couple of non polynomial problems we are currently facing in computer science like factorization. Some problems have been left NP-complete even with quantum like this paper has tried, Wang et al. (2007).

Classical computing is still great at organising stuff and performing parallel actions on your device, but with the help of QC we would be able to shift the heavy long term calculations over to devices especially made for long term and hard calculations like a quantum processor. Calculating a machine learning model Schuld et al. (2014) or performing an accurate simulation of a new medicine could be exponentially reduced in time, which would in turn return the value of these calculations to the business side in a much faster way and with that would be even more valuable to them if the information is gathered in a proper time frame. (Schuld et al., 2015) (Troyer & Wiese, 2005)

3.0.2 Quantum computing and the mainframe

First of all we need to clarify what a mainframe is and what its main use is in our current business environments. A mainframe is a type of supercomputer that is different from other supercomputers because it is not specialised in solving 1 really hard problem, like simulations or factorisation, it is specialised to have the highest possible throughput for smaller calculations. The mainframe is widely used within the banking, production and logistical sector as it offers the most reliable way of managing your data that is generated by a certain business practice. To clarify let us look at an example where a mainframe computer like the IBM Z15 shines. When millions of users throughout the world want to buy their flight tickets towards France around the end of April, a huge bottleneck is created at the end point of the booking system of the particular airport. A mainframe handles these types of atomic transactions to make sure every single booking will come through with the correct data and if the data is corrupted along the way, the mainframe is able to spot out these irregularities and discard this data so that the user received a proper notification as soon as possible. So look at a mainframe computer as a really good processor of input and output.

IBM has released the new mainframe in 2019, Z15, with a broad future perspective, because as one of the top researchers in quantum technology they have a clear image of how a quantum computer could influence themselves and others within their sector. They are emphasising on 2 very different aspects to make sure their devices are the most likely to take the biggest market share, modernisation and security. With modernisation IBM is trying the incorporate the mainframe in as much areas as possible to keep on attracting new developers so that their devices don't fall behind. And with this modernisation a lot of opportunities are opening up to connect different departments such as quantum research with data engineering etc.

Also emphasising on creating new security measures which focusses more on digital signing than the current RSA factorisation algorithm could secure the mainframe security status indefinitely. Quantum would in the future indeed be able to break these RSA based algorithms and that is why data-security has become such a high importance area at the moment for everyone in computer science.

So now that you are able to view what role the mainframe plays, we can more clearly look at how quantum computers could offer major benefits as a complementary service for solving the harder problems just like a super computer works with the mainframe in much the same way. Nowadays all the data generated from the billions of transactions from the mainframe are preserved so that afterwards a supercomputer would be able to process all this information inside a reasonable time frame to get as most as possible business value out of it. If the quantum computer would be able to help process this data exponentially faster, the business value of this data would also exponentially increase.

3.0.3 Quantum computing and Machine Learning

Another area where QC could majorly impact is the area of Machine Learning **(ML)**. At this moment machine learning is running into a bottleneck where the amount of data has become so intense that ordinary classical computing is not able to process the data in time so that its value can be exploited to its maximum potential. QC could help with this issue in a couple of major aspects, like data model training and data capturing. This would greatly improve the impact of ML on the business side, because the relay of the captured information through the models could indeed be shortened in exponential ways in a purely theoretical way as of now. (Biamonte et al.,)

At this moment research is becoming quite prevalent in ML with a combination of QC-technology. Qiskit has also seen this opportunity opening up and they too try and attract businesses with these advantages. We are able to enhance supervised learning algorithms as well as unsupervised learning, with time series or without. Algorithms such as linear regression, k-means clustering and even neural networks can be enhanced during its training phases with QC. Because due to superposition and entanglement, these algorithms could train a model theoretically through one loop instead of having multiple epochs that contain a certain size batch, which obviously speeds up the models that require a large amount of data to become valuable.

So the utilisation of QC with ML would not aid the accuracy of ML in the short run, but the time frame of processing the complete dataset could be exponentially decreased. Meaning if the relay of critical changes in the flow of data becomes quicker, business will become more valuable in the same manner.

For the practical part of this paper, we will show of how the utilisation of quantum computers can aid ML in promising ways. This does not mean that QC does not have a long way to go, to become superior than classical computing. We will compare the results between classical computing, simulation of quantum computing and the real executions om IBMQ-devices.

4. Practical demonstration with Qiskit

For 2 decades now people have been receiving fully blown quantum mechanics courses where they are able to experiment with the mere thought of quantum experiments in a theoretical type of way, but never were truly interested parties able to perform their experiments in a free and fluid manner. QC is at a point where we are able to effectively experiment with the technology as a broader community. Platforms like Qiskit are excellent in their reach towards interested parties and are more than welcoming towards new developments that could aid the whole community in its research. The service is open source which truly pushes the whole movement of research out of this shroud of high costs and large enterprises. This will obviously influence other branches to follow in the same footsteps as to allow every party that is interested or has a passion to be able to participate in a costless and open manner. To remain objective and fair towards other companies outside of IBM, Google is also participating in the open source community with platforms like Cirq, McClean et al. (2017).

In the following part, we will lay out how interested parties are able to perform their own executions on real devices and start applying what some of them have been learning theoretically for over 20 years. Whilst trying to resolve the main question of this specific paper ‘How will quantum computing affect the mainframe environment and its applications? ‘, a major roadblock has been discovered, which is interesting none the less because it shows were research and engineering has not yet ventured far enough to overcome them.

4.0.1 Grover’s search algorithm in a practical fashion

Grover’s search unstructured database search

Let us start of practical with one of the two most well known quantum algorithms, which is the Grover Search algorithm. If this algorithm were to be applicable on a large scale it could indeed affect the current mainframe environment of DB2 databases in a drastic approach. The whole premise of the algorithm is that we are able to speed up the search time in an unstructured database quadratically. This all meaning when a computer needs to find an item with an unique attribute that differentiates itself from the other items in the list, QC could become the main solution. The whole algorithm uses something called "amplitude amplification" where the algorithm influences the probabilities in such a manner that the correct item has the highest probability after the Quantum computation. (Grover, 1996)

Grover’s search algorithm in an applied form

For the experiment itself, we have chosen for the "Boolean satisfiability problem" which uses Grover’s way of amplitude amplification to find the correct result. This computer science question goes as follows, given a boolean comparison of multiple parts are we able to determine the outcome to get that specific TRUE. Being to solve this comparison in a way that could abuse the fact of superposition could prove useful when we scale out the problem towards thousands or even millions of comparisons for other algorithms. For now the 3-SAT problem has been chosen to be performed using Qiskit to show off the potential of QC for now.

You are able to view the function stated below as the problem that we will try and solve using Quantum technology. The algorithm now needs to find which solutions are possible by interchanging x,y,z with TRUE/FALSE.

$$f(x,y,z) = (\neg x \vee y \vee \neg z) \wedge (x \vee \neg y \vee \neg z) \wedge (x \vee \neg y \vee z) \wedge (\neg x \vee \neg y \vee z) \wedge (x \vee y \vee z)$$

Executing the quantum algorithm

Using a simulation of a quantum computer we are able to show the results in figure 4.1 below. The probabilities have been amplified to where they are the correct results of this boolean expression. The first figure below show the probabilities through the simulation, meaning that these probabilities have not been influenced by quantum decoherence on the real device it is more clearly visible that without any form of quantum error correction QC will run into a brick wall.

If you feel that your algorithm is on point by testing it through the simulator, IBM allows its recreational users to send off their circuits to real devices that have functional qubits to play around with. (At the time of writing the ibmq16Melbourne device had 15 qubits available to mess around with)

The reason for choosing this specific experiment is to show that even problems that just

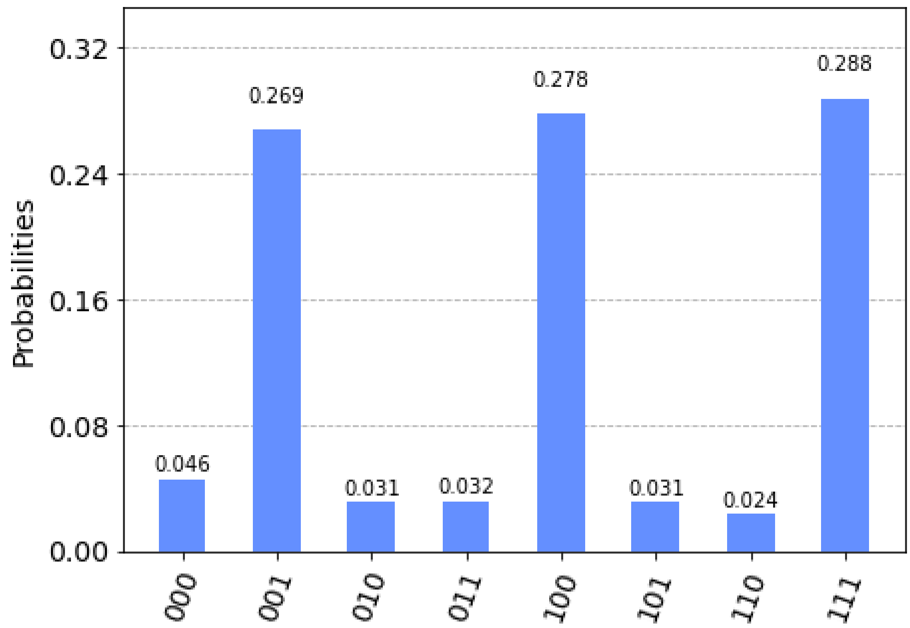

Figure 4.1: These are the results of executing the algorithm for the 3-SAT problem on a **quantum simulator** that comes with Qiskit. The encoding refers to the TRUE/FALSE value of the x,y,z respectively

require us to encode boolean statements we needed 694 quantum gates. IBMQ transpiles the sent-off circuit to the necessary amount of gates needed for this specific calculation. It does not keep in account that having this much gates on a single line of computation invites a multitude of quantum decoherence issues during runtime.

If you have looked closely at the image above (figure 4.2) you are able to see that decoherence for now breaks the probabilities of a computation too much to reliably trust any computation of this size out of a quantum computer. The values become distorted over time by all types of interference even if all the interference from inside the machine is not accounted for the machine can become influenced by a single external interaction like temperature, pressure etc.

$f(x,y,z)$	TRUE/FALSE
0 0 0	FALSE
0 0 1	TRUE
0 1 0	FALSE
0 1 1	FALSE
1 0 0	TRUE
1 0 1	FALSE
1 1 0	FALSE
1 1 1	TRUE

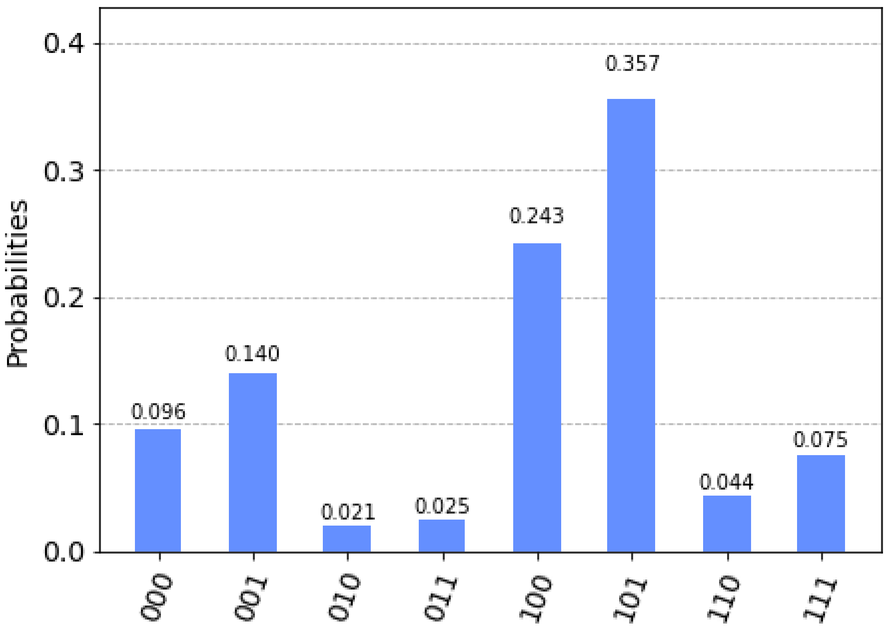

Figure 4.2: These are the results of executing the algorithm for the 3-SAT problem using 15 qubits on a **real quantum device** that comes with Qiskit. The encoding refers to the TRUE/FALSE value of the x,y,z respectively

If we compare the manually gathered results in the table above across the simulated version and the real version, we are clearly able to see that decoherence has played too big of a role to be certain of any output for these types of large computations.

Let us work out a clear example to make sure our probabilities generated by the real quantum device are incorrect. If we take the highest probability of the real execution which is the configuration of 101. Meaning that the quantum computer determined that when X and Z are true the whole boolean expression will result in a returned value of TRUE. This is simply not a valid option for this boolean expression. If we look at the first part of this boolean expression we can see that this configuration would return a FALSE resulting in the whole expression being FALSE because all the parts are connected with a logical AND.

$f(1,0,1) = (0 \vee 0 \vee 0 \vee) \wedge (1 \vee 1 \vee 0) \wedge (1 \vee 1 \vee 1) \wedge (0 \vee 1 \vee 1) \wedge (1 \vee 0 \vee 1)$

Future prospects

As for now we are able to play around with the greater problems of quantum computing but to be able to reliably solve real-world solutions in a beneficial way remains an uncertainty.

So with the current state of engineering, computer scientists will have to wait to fully utilise the system in a reliable fashion. But as engineering develops the power of quantum computing will increase exponentially with each added qubit to the system, which would make algorithms like this extremely valuable for data-crunching. When we find a way to circumvent the interference of quantum decoherence or when we reliably fix the errors it produces, a quantum system could become an essential tool for every sector willing to innovate.

4.0.2 Data-encoding in QC

As the experiment clearly shows there is an actual advantage reachable with quantum computing. Of course quantum decoherence is a main aspect of QC and solving it would be greatly beneficial for the whole sector, but there is also a different problem that arises with defining our classical way of problems in a quantum way. The way we represent data in a quantum circuit quickly becomes overly complicated for any large database structure. Quantum computers are great in predicting what quantum effects will occur and where quantum physics influences specific sectors. The issue lies in the fact that we want to input our classical database into a quantum device and hopefully receive the results in a readable classical solution.

This shows an issue we are facing with the encoding of our classical data to quantum data and back. For the proof-of-concept experiments it does not matter as the encoding time really does not influence the experiment as a whole. But once we start scaling out the issue where we would want to find a specific item through the use of Grover's algorithm, we would run into the issue that the encoding and decoding of the input and output could take up a great amount of computational time. If however QC develops in such a way that we are able to gain the full benefits of qubits in superposition this encoding time could be overcome, but for now it remains a crucial factor in solving the whole feasibility of QC.

4.0.3 Mainframe computing with QC

As the paper has previously stated having QC together with the power of a mainframe could become extremely advantageous for the whole industry to provide the power of data crunching this immense layer of internal data that companies have collected over the years. So we needed to find a circuit that could show of where quantum computing indeed could benefit in the crunching of data in a better/ faster way than classical computing can at the moment. Soon it became clear that simulating anything of a mainframe is impossible for now, we can simulate how a new form of database search could work with Grover. But we are not able to simulate the main advantage of a mainframe device, which is performing quick, stable and secure input and output transformations. And as shown by the experiment it is obvious that having a stable output of a specific input is not one of the main strengths of QC. Then when we take into account the encoding and decoding of classical computations and problems, which would greatly slow down the performance of a mainframe.

So for now there is no clear advantage when we use the current developments of QC with the existing mainframe technology. It does not take away its immense potential when QC is able to process the complete I/O of a mainframe in an exponentially smaller time frame than classical computing processing is able to do now.

Then obviously there remains the issue that quantum processors don't have the capability to actually perform algorithms that require a greater amount of qubits due to decoherence and previously stated problems.

5. Discussion

5.0.1 Quantum computing for now

5.0.2 Quantum computing over the long run

A. Research Proposition

Under this section you are able to view the original proposition for this paper to introduce the subject with schooling officials and technical promotors. This section can also serve as an introduction to this paper for any further interested readers.

To address the whole reason why this paper was created, the subject has become more and more influential in the Computer Science world. We have officialy come at a point where we are able to think of real world utilisations of quantum computers to further our research in various subjects. Quantum has become a buzz word at this point, but not everyone that throws it around has a real grasp on what it exactly means. That is why this paper has been created to aid interested people in the subject to gain a real understanding of what quantum actually is and what it can do.

A.1 Introduction

A.1.1 Situating the subject

There has been a strong believe over the last 30 years that quantum computing can and will influence our sophisticated environment more than we think. In case of the mainframe environment it will maybe be the most influenced sector in *computer science*, because of its immense creation of data. Data will become or has already been the driving factor inside our societies, think of how much our daily lives are already controlled by data (e.g. online shopping, social media etc.). With the usage of mainframes we are able to create a sense of logic in this almost infinite pile of data. Now with *theoretical* utilisation of quantum computing, data can be searched more thoroughly and faster. (Grover, 1996)

If we are able to find and explore quantum applications for our current high-transactional business applications, a new wave of investment in research will open itself up. Which would obviously boost both fields at once. In this paper we will try and find these general applications that can prevail through the use of quantum technology.

A.2 State-of-the-art

A.2.1 Prior knowledge

Inside the paper a couple of physics specific terms will be utilised. If you are not familiar with basic quantum physics notations and or terms, it would be highly recommended to read one or both of the following papers, (Rieffel & Polak, 1998) or (Shor, 2000). For the general quantum notation that are used throughout the field, we refer towards Dirac (1939). It is also possible to read this paper as an informational piece without the implications of the mathematics and physics surrounding the subject. As previously stated the paper will not be going in depth technologically, because the scope is more focused on exposing the practical usages of quantum computing compared to classical computing or the combination of them both.

A.2.2 Recent developments

As of now Google has claimed to have won the *Quantum Supremacy race* (Arute et al., 2019) against IBM. They have realised this through the creation of their 54-Qubit quantum computer (53 functional qubits), that is able to perform a calculation exponentially faster than a classical system could ever hope to perform. In this case the *Sycamore* (Quantum processor) was able to perform a calculation within 200 seconds that could only be performed by a classical computer over 10.000 years (theoretically). Although it most definitely was an experimental calculation that has no real value in the business world, it does however prove the potential of quantum computing. It has been rumoured that IBM will release its counterpart of research in 2020. The fact that these 2 conglomerates are competing so fiercely will only further the technological developments in the realm of quantum mechanics. IBM has not been sitting idly either, they have released a paper regarding quantum algorithms applications. (Amico et al., 2019)

A.3 Methodology

While the field of practical quantum computing is still in its infancy, there are a lot of different possible angles to approach the subject with. First of all we will be introducing the guiding principles of quantum computing, as to all start on the same footing. Then we will explore the realistic potential that quantum computing can offer for economic gain, especially for mainframe development. This will mainly be comprised of an extensive literature study that will set its focus on economic applications of quantum computation and thereby on the mainframe environment. Concretely the paper will use real-life economical batch data and will process this data through the use of quantum algorithms and classical algorithms. If there are any advantages in processing the nightly batch load by using quantum algorithms, it will become provable that quantum computing can also be extremely profitable. There will also be demonstrations of quantum computation software such as Qiskit by IBM (Abraham et al., 2019), Cirq by Google (McClean et al., 2017) and Q Sharp by Microsoft (Svore et al., 2018). Qiskit stands out because it is an IBM Python framework that solely offers the opportunity to actually execute your quantum circuits on real quantum devices as of today. (with limited qubits however)

A.4 Expected results

The paper will try and create a more concrete point of view on the possible features quantum computation can offer. Through the analysis of multiple papers, we are hoping to find certain points of contest. These points indicate the highly debated subjects within quantum computing and are therefore extremely valuable. We will be trying to locate and display the business potential within these points of conflict. Currently IBM has created an extremely stable and performant business environment with its mainframe, Z15 and its older versions. Anything that can/ will affect this stable business platform can form a great threat or opportunity to the way we currently create and process our data. To protect this stable platform, we will be trying to index all the threats and opportunities that come with the introduction of quantum computation in our current computational environment. The second part of the paper will be more software-orientated, where we will be creating an application that processes the typical nightly batch data. This application will be performed on the different quantum platforms an on a classical device. The paper will visualise these probabilistic and timing differences between results of the different software platforms and will try to show attention points with simulating quantum computers compared to effectively executing on one. Through the demonstration of quantum computation we hope that readers are going to be personally inspired to be creative with the new technology and start developing their first 'Hello World' with their quantum circuits.

A.5 Expected conclusions

We are expecting to *debunk* the more absurd ideas of quantum computing. (e.g. destroying all our encryptions and our society) Concretely, we are going to put the whole subject inside a more realistic 'future' vision. This will hopefully offer readers ideas of possible applications of quantum computation inside their departments (e.g. Chemistry, Economics, Astronomy etc.) Also With software being so readily available for the general public, we expect that quantum computing applications will be created exponentially faster than with the dawn of classical computing 70 years ago. With this train of thought, we are hoping that real economical value can be available within the next decade. By processing our example night batch load we hope to find this necessary business value. Frameworks like Qiskit will be developed further and more powerful quantum computers will be made available towards the public to boost the research in the subject. And with these thoughts we can be certain that interest in quantum computers will only increase in the future.

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