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

Lukas Marivoet

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Promotor:
Martijn Saelens
Co-promotor:
Francis Harkins

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Lukas Marivoet

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Promotor:
Martijn Saelens
Co-promotor:
Francis Harkins

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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 the subject and its influences on our societies. But most of all I would like to congratulate the complete research environment around quantum computing on how open and supportive it has been with new developments towards any interested parties, through the open-source communities and the many freely available papers.

Samenvatting

Abstract

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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 in a quantum way 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 Arute et al. (2019), Amico, Saleem, and Kumph (2019, 1), 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 our 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. 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 environment. Mainframes drive the big enterprises who in turn drive the smaller ones that our societies are built upon, if QC can aid the 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.

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 sheer 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 exponentially aid classical computers with the processing of this 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 Abraham et al. (2019) and McClean et al. (2017) everyone is able to contribute towards quantum research even within a mainframe minded environment.

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 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 classical opponent

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.

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.

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.

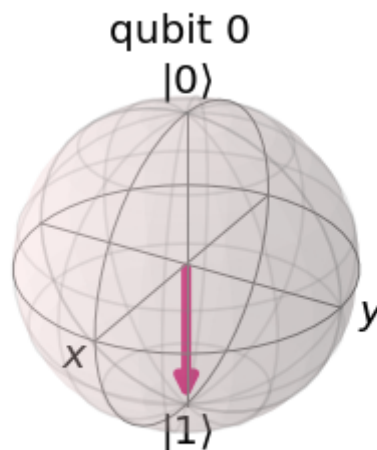


Figure 2.1: A Bloch sphere representation of 1 qubit in the $|1\rangle$ state. The Bloch sphere clearly indicates that the state of a qubit has a certain probabilistic aspect to it.

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 does it exactly represent is the real question. Quantum advantage is mostly gained from this 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 angle, 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. To put it more clearly, e.g. if you are processing a big array of data through your 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 computer could go about this process in a similar yet much more ingenious way. A quantum processor would put an amount of qubits in superposition to represent the 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 major 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 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, Christandl, Harrow, & Walter, 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. This amount of memory is impossible to be able to achieved with a classical amount of bits, while a quantum computer in turn would be able to complete the simulations with theoretically 286 stable qubits. Actually getting to such a stable amount of qubits in itself will still be a scientific miracle.

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 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, 3). QC also will have its limits it takes a lot longer to actually set up your computation than it would 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 computer. Calculating a machine learning model Schuld, Sinayskiy, and Petruccione (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, Sinayskiy, & Petruccione, 2015) (Troyer & Wiese, 2005, 17)

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 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.

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.

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 to 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.

3.0.3 Quantum computing and Machine Learning

Another area where QC could have major 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, Pancotti, Rebentrost, Wiebe, & Lloyd,)

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.

4. Practical demonstration with Qiskit

5. Discussion

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 promoters. 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 officially 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, 1)

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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