COMP 4560 - Undergraduate Industrial Project Registration Process

Quantum Perceptrons on the IBM Q

Abhishek .
Department of Computer Science, University of Manitoba
Email : abhishek@myumanitoba.ca

Supervisor : Dr. Parimala Thulasiraman
Department of Computer Science, University of Manitoba
Email : thulasir@cs.umanitoba.ca

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Abstract

In the recent years, neural network models have been successfully applied to various machine learning problems such as image recognition and natural language understanding. However, even the current best models suffer from limitations in terms of efficiency such as high training data volume requirements and long training times. Quantum information processing techniques have been shown to provide speedup to many classical machine learning algorithms and many different models of a quantum neural network have been proposed. However, due to the realizations of actual quantum computers currently being under development, the implementations of these models on quantum processors is an area that is yet to be fully explored. In this industrial project, we will first explore the proposed models for the quantum perceptron and then attempt to implement these models on one of the first quantum processing devices available today, the IBM Q. Through this development and testing process, we wish to build an intuitive understanding of the implementation methods of more complex models such as the quantum neural network on near-term quantum information processing devices.

1 Introduction

Quantum computing is use of quantum information processing devices in order to perform sufficiently complex computations. Machine Learning refers to the field of Computer Science in which data-driven and statistical-based learning algorithms are used to improve the performance of a model for a given artificial intelligence task such as face recognition and natural language understanding.

Artificial Neural Networks (ANNs) are one of the primary models in the connectionist approach to machine learning. The earliest known model of an artificial neuron was introduced in [1] which is now known as the McCulloch-Pitts Neuron. This lead to the development of the first model of an ANN. Since then, a plethora of neural network models such as Long-Short Term Memory Recurrent Neural Networks (LSTM-RNNs) and Convulational Neural Networks (CNNs) which consist of different neural units have been successfully developed and applied in many machine learning problems.

The operational parallelism that is inherent in the architecture of ANNs is one of the main reasons of widespread interest in the research and development of these models. In a similar way, Quantum parallelism is an inherent property of quantum information processing devices in the quantum model of computation. The ability and ingenuity to exploit this massive parallelism forms the basis of many well-known quantum algorithms such as Grover's Quantum Search [2] and the Quantum Fourier Transform [3].

One of the earliest work on Quantum Neural Networks is given in [4] in which the author discusses the parallels between the connectionist approach to machine learning, biological information processing and quantum computing. Since then, many different proposals have been developed for models of quantum neural networks. However, in this industrial project, we will limit the scope of the research and implementation to the fundamental units of a neural network i.e. a perceptron.

1.1 Classical Perceptron

The first model of a classical perceptron was published by Frank Rosenblatt in 1958. [5]. The original algorithm was a binary classifier which used a threshold function to compute the output value of the perceptron.

$$f(x) = \begin{cases} 1 & \mathbf{w}.\mathbf{x} + \mathbf{b} > 0 \\ 0 & otherwise \end{cases} \tag{1}$$

where $\mathbf{w}$ is the vector of real-values weights for the connection between the input nodes and the output node, $\mathbf{x}$ is the vector of the input at the input nodes at the single-layer perceptron and $\mathbf{b}$ is the bias at the output node.

The output of the single-layer perceptron indicated whether the input described by the input vector belongs to a binary class or the other.

The single-layer perceptron had the shortcoming that it cannot be used to solve non-linear binary classification problems and hence a multi-layer perceptron i.e. a feed-forward neural network was developed which has the capability of solving non-linear classification problems using non-linear activation functions.

1.2 Quantum Perceptron

The term 'Quantum Perceptron' refers to an implementation of the perceptron which uses techniques from quantum information processing in order to achieve speedup in learning or complexity over classical perceptron algorithms.

Many different models and implementations have been proposed for the quantum perceptron. In the circuit model of quantum computation, the primary challenge is finding the appropriate sequences of transformations and operators to implement non-linear activation functions which form the basis of classical perceptrons. This is also challenging due to the fact that transformations and evolution operators in quantum mechanics are in general, linear therefore non-linear operations such as measurement may have to be potentially used in order to implement the non-linear activation functions.

2 Background Preparation

As a preparation for this project, an Undergraduate Honours Project has been completed in the previous term of Fall 2018 with the thesis "Introduction to Quantum Computing and the Single Pair Shortest Path Problem". In the honours project, we discussed how fundamental concepts and algorithms from Quantum Computing have been applied to graph optimization problems in order to achieve a quantum speedup i.e. a speedup in terms of the query complexity over classical graph optimization algorithms.

In addition to the Undergraduate Honours Project, the following academic courses also allow for background preparation to complete a project in this subject area,

1. **PHYS 3380 : Quantum Physics 2**
   Developed the abstract linear algebraic formalism for quantum mechanical states and operators with classical measurements, found solutions to 1-dimensional and 3-dimensional Schrodinger's equations for the hydrogen atom using mathematical and linear algebraic tools, explored degeneracy in quantum states using quantum mechanical operators.

2. **PHYS 2380 : Quantum Physics 1**
   Learned mathematical methods to derive solutions to differential equations associated with quantum systems. Studied proofs related to observations from quantum systems with no classical counterparts such as quantum entanglement and superposition.

3. **COMP 2080 : Analysis of Algorithms**
   Studied asymptotic algorithm analysis using methods for analyzing the time and space requirements of the algorithms, explored different models of computation and algorithm design using different strategies (e.g. greedy, divide-and-conquer)

3 Related works

In this this industrial project, we would first be reproducing the implementations from the recent work by Tacchino et al.in [6] in which the authors first discuss the unviability of implementing a binary classifier perceptron through successive applications of Sign-flip blocks and then present a quantum subroutine for generating hypergraph states through the application of C^pZ gates between p qubits. Even though, the circuit has exponential gate complexity, it offers a relatively easy introduction to the challenges involved in implementing the quantum perceptron on the IBM Q.

We would then like to research and implement other proposed models of the Quantum Perceptron such as the one discussed in [7] in which Repeat-until-success (RUS) circuits are used as building blocks for implementing the quantum perceptron. We would restrict ourselves to the models proposed for the circuit model of quantum computation in this project, even though there exist proposed models in the adiabatic model of quantum computation through the use of adiabatic processes. This is primarily to restrict the scope of the industrial project in order for a successful completion and secondly due to the fact that universal quantum computer such as the IBM Q have the potential of solving a wider range of problems than adiabatic quantum computers which are primarily restricted to optimization problems.

4 Problem statement

The goal of the industrial project is to explore how can we implement the quantum perceptron on near-term quantum information devices that use the circuit model of quantum computation.

This is relevant especially to industrial and scalable quantum computing since a lot of existing and previous works have focused on researching and developing new approaches and algorithms whereas relatively low amount of information and research exists on the challenges involved on implementing the algorithms on existing and near-term quantum information processing devices.

5 Methodology

The industrial project will be divided into a series of smaller iterative step-projects each of which would have a defined timeline and associated sub-tasks. The table below shows the overview of the step-projects and the expected timeline. The dates may be adjusted in order to allow for a successful completion of the project.

Step project	Step project overview	Expected dates
1	Thorough research and evaluation of the proposed models of the quantum perceptron. Determination of the best model to be implemented on the quantum processors.	January 11, 2019 - January 31, 2019
2	Setup of the development and execution environment for the quantum simulators and quantum processors. Learning of essential programming fundamentals to successfully implement the determined model on the IBMQ5 and IBMQ16 machine.	February 01, 2019 - February 28, 2019
3	Implementation of the models on the quantum simulators and processors available for execution. A theoretical analysis to determine the gate and query complexity of the implemented models.	March 01, 2019 - March 31, 2019
4	Retrospective and compilation of the results from the implementations and the executions of the Quantum Perceptron models.	April 01, 2019 - April 26, 2019

6 Requirements

6.1 Computing Resources

In order to successfully implement and execute the quantum perceptron models on a quantum processors, access to a quantum information processing device is a must. If such an access is not available, we will implement and execute the models on quantum simulators which serve the purpose of simulating actual quantum processors.

IBM Q offers public access to the 5-qubit and 16-qubit quantum computers known as IBMQ5 and IBMQ16. We will be using the cloud access in order to execute the developed programs on the processors.

6.2 Academic Resources

Access to academic articles and journals actively covering the most recent advancements in the field of Quantum Computing and Algorithms is required. This is partially fulfilled through the University of Manitoba Library Resources. In addition, if needed active correspondence to the expert academic resources at the University of Manitoba and experts in the field of Quantum Algorithms and Computation can be achieved through e-mail and other modes of communication.

7 Outcomes and Deliverables

7.1 Outcomes

Through this industrial project, we primarily attempt to accomplish the following :

1. Gain a thorough understanding of the programming principles and fundamental prerequisites for the development and implementation of complex quantum algorithms on near-term quantum processors such as the IBM Q.

2. Explore in detail the current best models for the Quantum Perceptron and through the implementation and testing process, learn about the previously unforeseen challenges in developing scalable quantum algorithms for the Quantum Perceptron.

7.2 Deliverables

At the completion of this industrial project, we wish to deliver the following:

1. Implementation details and results for the execution of the proposed Quantum Perceptron algorithms on the IBM Q Platform's available backends such as the IBMQ5 and IBMQ16.

2. In-depth analysis and potential solutions to the scalability issues of Quantum Perceptron models for near-term quantum information processing devices.

References

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