EVENT CLASSIFICATION FOR HIGGS PARTICLE WITH QUANTUM MACHINE LEARNING IN HIGH-ENERGY PHYSICS

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ABSTRACT

Machine Learning Algorithms like Deep Neural Network (DNN), Binary Decision Tree (BDT), has been used in high energy physics for a long time, specifically in track signal identification and supervised classification tasks. Meanwhile, quantum computing was proposed by Richard Feynman in the early 1980s as a way to performs computations that would be unreachable by classical computers. Over the past 40 years, the noisy intermediate-scale quantum computing devices have been developed and multiple new algorithms are proposed with such device. In this paper, we present the studies of quantum algorithms exploiting machine learning to classify the events of interest from background.

***K*eywords** Quantum Machine Learning · Variational Quantum Circuit · Variational Shadow Quantum Learning · Quantum Kernel Method ·

1 Introduction

In High-Energy Physics experiments, particles created by collisions are observed by layers of high precision detectors. In this field, many early attempts to use quantum computing for HEP exist. For example, the data analysis [3], identification of charged particles[], reconstruction of particles collision points []. ([] indicates adding citation based on those paper) As discussed in many literatures, the quantum machine learning (QML) is considered as one of the QC algorithms that could bring quantum advantages over classical methods[[1], 16].

2 Task description and data construction

Discrimination of events of interests is always the most frequently used ML techniques in HEP data analysis. In this research, we examine the most frequently used variational quantum classider (VQC), Quantum Kernel Methods, Variational Shadow Quantum Learning (VSQL) [2] and Quantum Generative Adversarial Network (Quantum GAN).

Dataset Here we use the dataset from UCI's Machine Learning Repository [Lib].

Task modeling. We approach this task as a regression problem. For every item and shop pair, we need to predict its next month sales(a number).

Construct train and test data. The dataset provided has 28 features, 21 low-level features and 7 high-level features.

2.1 Method 1: Variational Quantum Classifier

2.2 Method 2: Variational Shadow Quantum Learning

2.3 (

Method 3: Variational Shadow Quantum Learning) Suspendisse vel felis. Ut lorem lorem, interdum eu, tincidunt sit amet, laoreet vitae, arcu. Aenean faucibus pede eu ante. Praesent enim elit, rutrum at, molestie non, nonummy vel, nisl. Ut lectus eros, malesuada sit amet, fermentum eu, sodales cursus, magna. Donec eu purus. Quisque vehicula, urna sed ultricies auctor, pede lorem egestas dui, et convallis elit erat sed nulla. Donec luctus. Curabitur et nunc. Aliquam dolor odio, commodo pretium, ultricies non, pharetra in, velit. Integer arcu est, nonummy in, fermentum faucibus, egestas vel, odio.

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3 Examples of citations, figures, tables, references

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Of note is the command `\citet`, which produces citations appropriate for use in inline text. For example,

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produces

> Hasselmo, et al. (1995) investigated...

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3.1 Figures

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3.2 Tables

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[1] Sample of the first footnote.

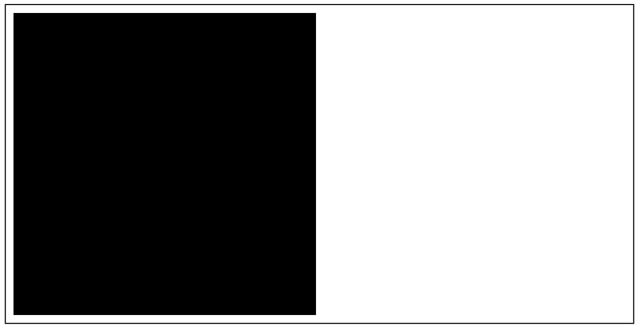

Figure 1: Sample figure caption.

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2	***В ЛУЧАХ СЛАВЫ (UNV) D	2	40
3	***ГОЛУБАЯ ВОЛНА (Univ) D	3	40
4	***КОРОБКА (СТЕКЛО) D	4	40

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3.3 Lists

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4 Application for Tokyo Institute of Technology

In the format easier to read before formal submission.

4.1 Your research topic in Japan: Describe articulately the research you wish to carry out in Japan.

Therefore, firstly based on the existing "Kernel Regression Imputation in Manifolds Via Bi-Linear Modeling: The Dynamic-MRI Case", I do find the proposed problem in the imputation-by-regression Specifically, "KRIM makes explicit use of (non-linear) manifold assumptions and geometry". There is an interesting point mentioned in this paper, where Manifolds learning build on the hypothesis that measured data lie close to a low-dimensional manifold embedded

Table 1: Sample table title

Part		
Name	Description	Size (μm)
Dendrite	Input terminal	$\sim$100
Axon	Output terminal	$\sim$10
Soma	Cell body	up to 10^6

in a high dimensional space. Since I have some familiarity with implementation of geometric approaches. I do believe the enhanced data needs to be implemented.

The length of the program is 5 years in total, therefore, I would like to explore the quantum computing algorithms with the Riemann Manifold in the first two years. I would like to improve the data analysis method in Variational Quantum Circuit Learning, Quantum Kernel Method and Variational Quantum Shadow Learning with the advantages in Professor Slavakis' lab on Riemannian manifold.

To understand the research topic, it is necessary to understand what currently professor Slavakis is working on. The model heavily involves the Manifolds. The kernel regression imputation in manifolds (KRIM).

One question provided to solve: In collected data, "Holes/gaps" or "missing entries" give rise in turn to aliasing and motion blurring in the observed images series. -> Non-parametric approaches.

The other question provided is: "Fast Sequential Clustering in Riemannian manifolds for Dynamic and Time-series-Annotated Multilayer Networks". This work focus on building a sequential-clustering framework able to address a wide variety of clustering tasks in dynamic multilayer (brain) networks via the information extracted from their nodal time-series. There are procedures working step by step:

1. feature extraction from time-series
2. Riemannian Manifolds
3. Problem: state clustering, community detection, subnetwork sequence tracking.

First is the Quantum Kernel Method. The Quantum Kernel Method formation of Reproducing Kernel Hilbert Space (RKHS) with the Fast Sequential Clustering in Riemannian Manifolds. Quantum Kernel Method was proposed as Quantum Machine Learning.

I will do the emulation first on the normal computer, after verification. I hope I could access to D-wave to perform the algorithms on the real quantum computer. If everything works perfectly, I consider my idea could be realized with improvement.

The Top Down Approach: One takes the data and analyze with different method. First I would like to work on the normal signal processing field to study a bit more on classical theory. It is necessary to have a deep understanding of the fundamentals before making great progress in any field.

4.2 Study program in Japan: (Describe in detail and with specifics - particularly concerning the ultimate goal(s) of your research in Japan)

The Bottom Up Approach: The goals of my research in Japan are composed step by step. I would like to enhance the existing algorithms or models for data analysis using Quantum Computing Algorithms as described in last question. I hope to follow up and expand the research shown in previous section and add two or more approaches to build up a relatively complete "Framework" for quantum signal processing.

- Quantum Machine Learning: The Riemannian Manifold Approach
- Quantum Signal Processing: Quantum Computing Encoding Theory Approach
- Quantum Signal Processing: Quantum Fourier Transform Approach

The combination of the work could build up solid foundations of classical signal processing and quantum computing.

Quantum Signal Processing: Quantum Computing Encoding Theory Approach
Specifically, based on Daan Camps' Paper on "Explicit Quantum Circuits for block encodings of certain sparse matrices" and Issac Chuang's paper on "Optimal Hamiltonian Simulation by Quantum Signal Processing". I could see some revolution or breakthrough gradually happen in the field of Signal Processing. The later one shows the way to simulate the physical systems with the quantum signal processing.

Quantum Signal Processing: Quantum Fourier Transform Approach
The structure for the development of Quantum Signal Processing starts from measurement. The wave break down by using Fourier transform's quantum analog part, Quantum Fourier Transform (QFT). The Quantum Fourier transform could particularly decompose into a product of simpler unitary matrices. With Simple decomposition, the discrete Fourier transform on 2^n amplitudes can be implemented as a quantum circuit consisting of $O(n^2)$ Hadamard gates and controlled phase shift gates.

Borrowed from Qiskit's notation, the classical discrete Fourier Transforms act on vector $x = (x_0, x_1, ..., x_n)$ and its mapping to vector $y = (y_0, y_1, ..., y_n)$ according to formula:

$$y_k = \frac{1}{\sqrt{N}} \sum_{j=0}^{N-1} x_j \omega_N^{jk} \tag{1}$$

Where $\omega_N^{jk} = e^{2\pi i \frac{jk}{N}}$. The quantum state $|X\rangle = \sum_{j=0}^{N-1} x_j |j\rangle$ and mapped to $|Y\rangle = \sum_{k=0}^{N-1} y_k |k\rangle$ and the map could therefore be expressed as:

$$|j\rangle = \frac{1}{\sqrt{N}} \sum_{j=0}^{N-1} \omega_N^{jk} |k\rangle \tag{2}$$

Or the unitary matrix:

$$U_{QFT} = \frac{1}{\sqrt{N}} \sum_{j=0}^{N-1} \sum_{k=0}^{N-1} \omega_N^{jk} |k\rangle \langle j| \tag{3}$$

There are already well published paper for quantum Fourier transform. In imaging analysis, Fourier transform is definitely an unavoidable technique. Starting from here, in analog signal processing, I would like to apply quantum Fourier transform, the classical discrete Fourier transform and compare their differences and how quantum Fourier transform could possibly enhance the classical result. Several Goals for working on Quantum Fourier Transform:

1. Forming algorithms could possibly enhance or replace the classical discrete Fourier transform. Such replacement may improve classical algorithms to achieve better performance, like noise filtering and etc.
2. By the theory of Big-O, the quantum Fourier transform is exponentially faster than classical discrete Fourier transform.

The first paper is the more recent one, which introduced the more efficient way to encode the data.

A fundamental method or algorithm in exploring today's hard question in natural science. Not only in biomedical science, neurological science, fMRI, but also in gravitational wave detection, detection of Higgs particles and more. Of course, this could not be simply developed with purely algorithm solutions, collaboration with other teams and more will be necessary.

The Ultimate goal is to explore the Ubiquitous quantum signal processing or quantum machine learning in natural science and more. This is a type of engineering goal which could possibly expand the field of signal processing.

The PhD Thesis by Doctor Yonina Eldar and A.V. Oppenheim.

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