Department of Physics, University of Bologna

Quantum Neural Networks for Data-Efficient Image Classification

Francesco Aldo Venturelli, Master student
francesco.venturell3@studio.unibo.it

Dec 15 2023

Table of contents

Quick intro to QML

QML is a new topic of research where people uses quantum models such as Quantum Neural Networks, quantum circuits, qubits...to simulate on a quantum computer to perform predictions and experiment using bunches of data.

Classical **ML** instead is a process (born in 1950) which starting from data goes backward to reveal the logic and the insights between them.

$$\text{From } \textbf{DATA} \xrightarrow{\text{to}} \textbf{RULES}.$$

Basis of ML

There exist three main *way of learning:* Supervised, Unsupervised and Reinforcement learning;

- **Dataset** (and data processing);
- **Model/classifier** (Neural Network, SVM, CNN...);
- **Loss function** (Cross-entropy, MSE...);
- **Metrics and scores** (Precision, Accuracy, F1 score...);

Let's take a closer look

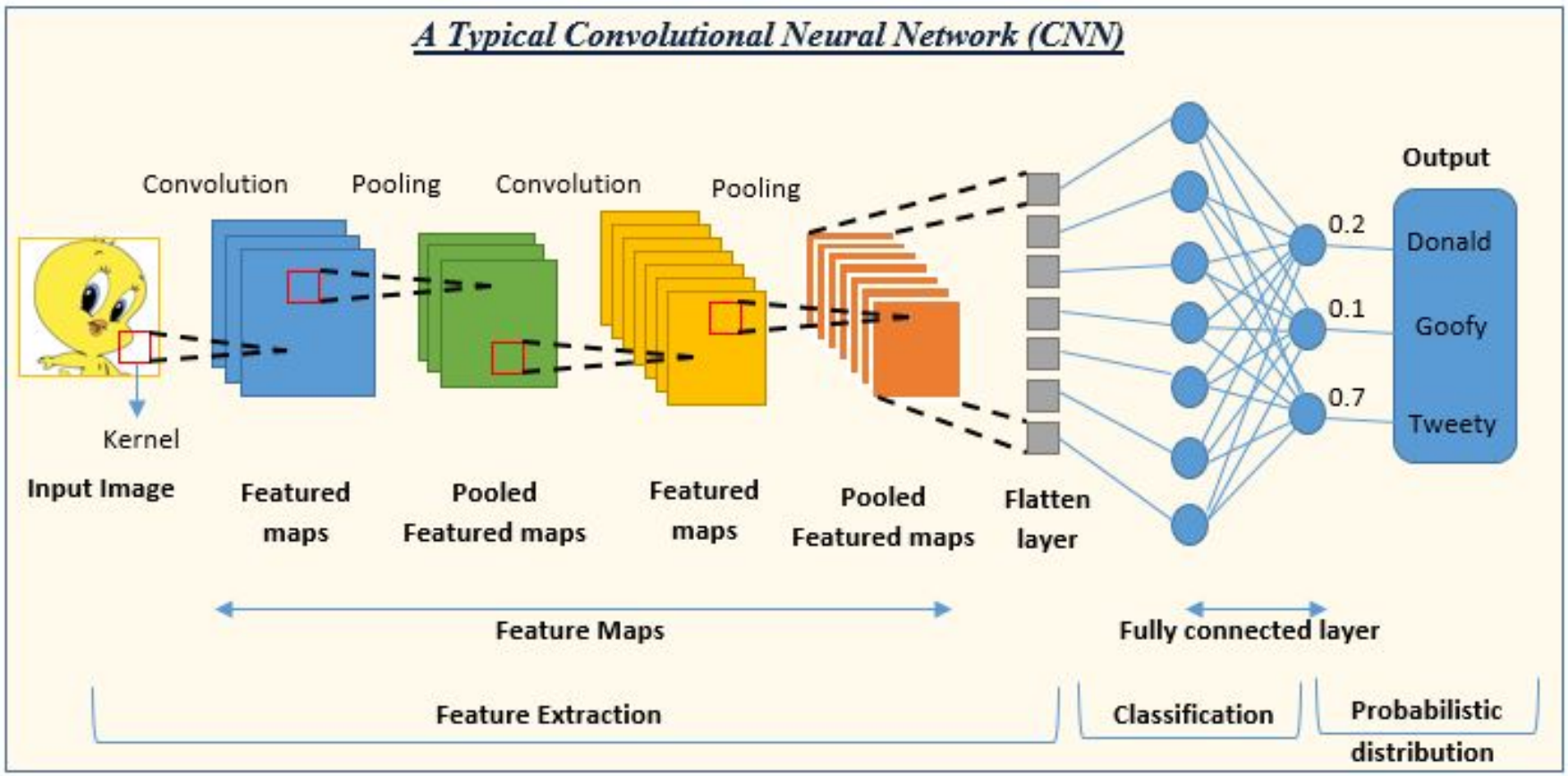


Figure: How a CNN works.

BIG PROBLEM

Question

Why from classical ML do we need Quantum?

Answer

Classical ML models (such as Neural Networks) require enormous quantity of data to reach high accuracy scores!!!

Consequence

This implies too many resources, much memory, more time and energy-consuming processes!

Seeing is believing

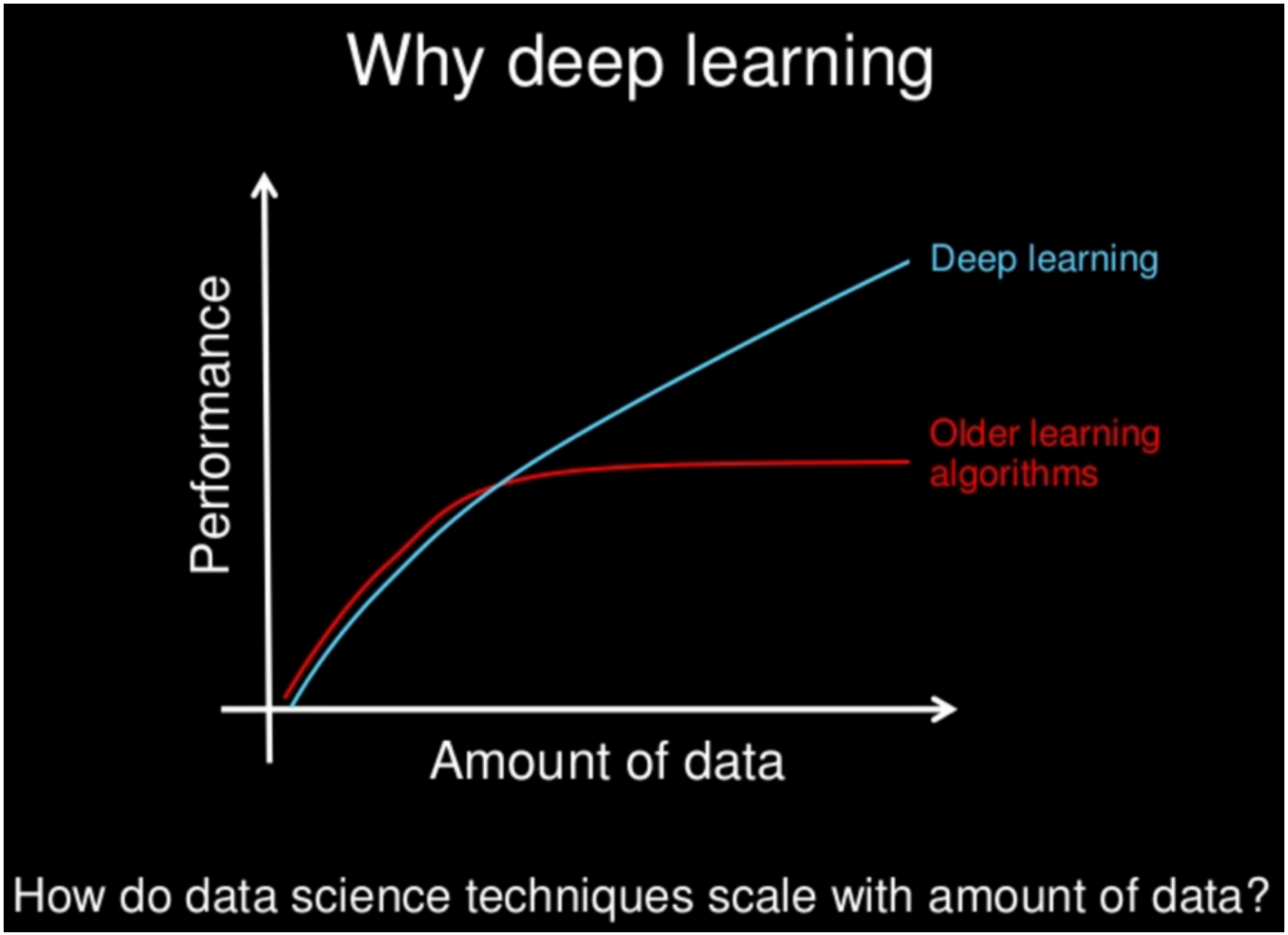


Figure: ML-data scalability.

What does the Quantum model offer?

"In machine learning, power is often referred to as a model's capacity to express different relationships between variables". cit. Abbas, Figalli.

QNNs use quantum effects such as superposition, entanglement, and interference, to do computation.
Some potential advantages of QNNs that come from such intrinsic properties are:

- speed-up in training and faster processing;
- much more functions to fit the data with, since the variety of possible states created by those models is exponentially enlarged thanks to the *Hilber space*.

Few data promising performances

Another tuff advantage brought by QNNs is promoted in the article published in 2022 proves theoretically and with numerical experiments that QML works well with less data during training.

Generalization

The ability of a ML (or QML) model of predicting new unseen data is called **generalization**.

QML models offer the possibility to generalize well using few data $\xrightarrow{solve}$ the starting problem we have mentioned!

Methods

A QNN model is generally composed by three main parts:

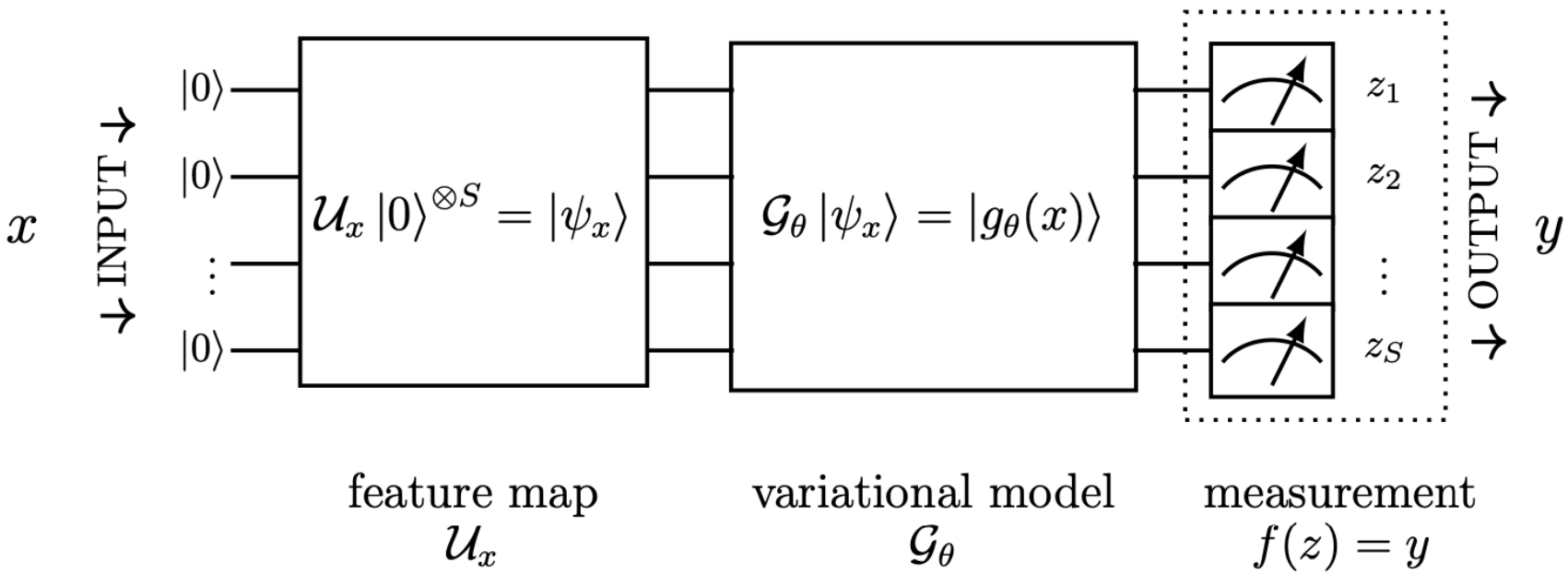


Figure: Theoretical QNN model.

Importance of measurement

Question: why the measurement operation is important?

Answer

It's the operation which we have access to the learned parameters with we compute the loss function.

From

$$|\psi\rangle = F(x)|0\rangle^{\otimes n} \tag{1}$$

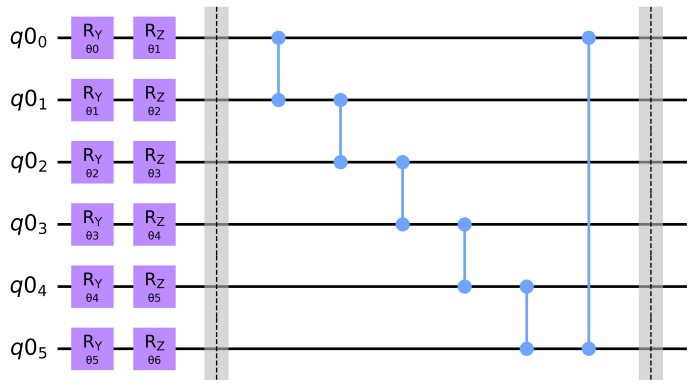
and

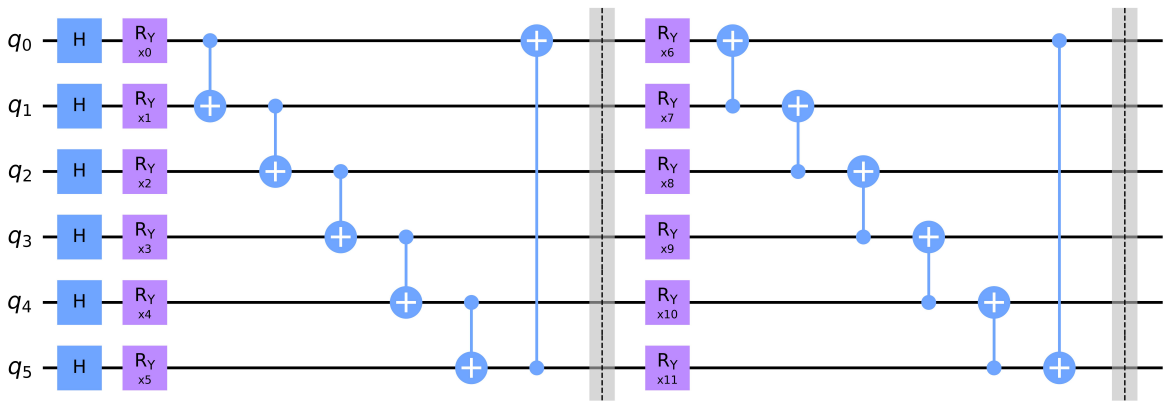
$$|\phi(x,\theta)\rangle = A(\theta)|\psi(x)\rangle \tag{2}$$

we measure

$$f(x,\theta) = \langle\phi(x,\theta)|\hat{O}|\phi(x,\theta)\rangle \tag{3}$$

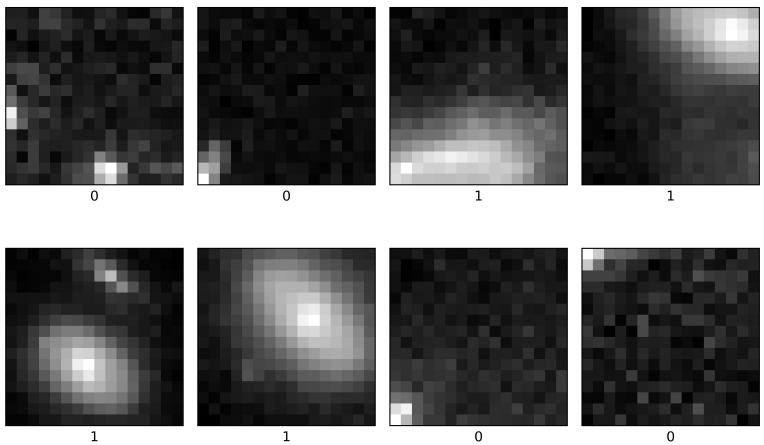
Circuits



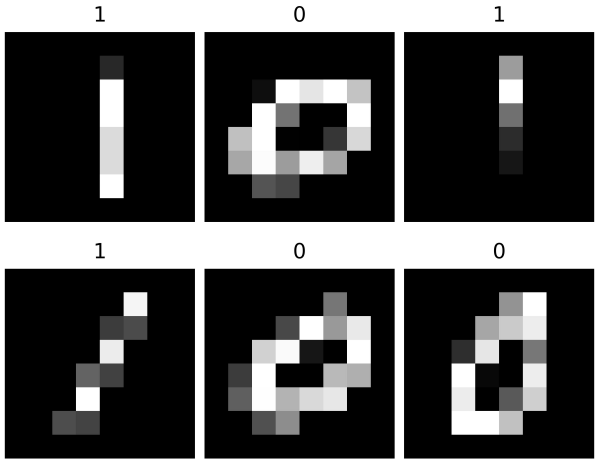


Waterfall and Ring-like feature maps.

Dataset



(a) GALAXY



(b) MNIST 0,1

Figure: Galaxy and Mnist datasets.

Characteristics

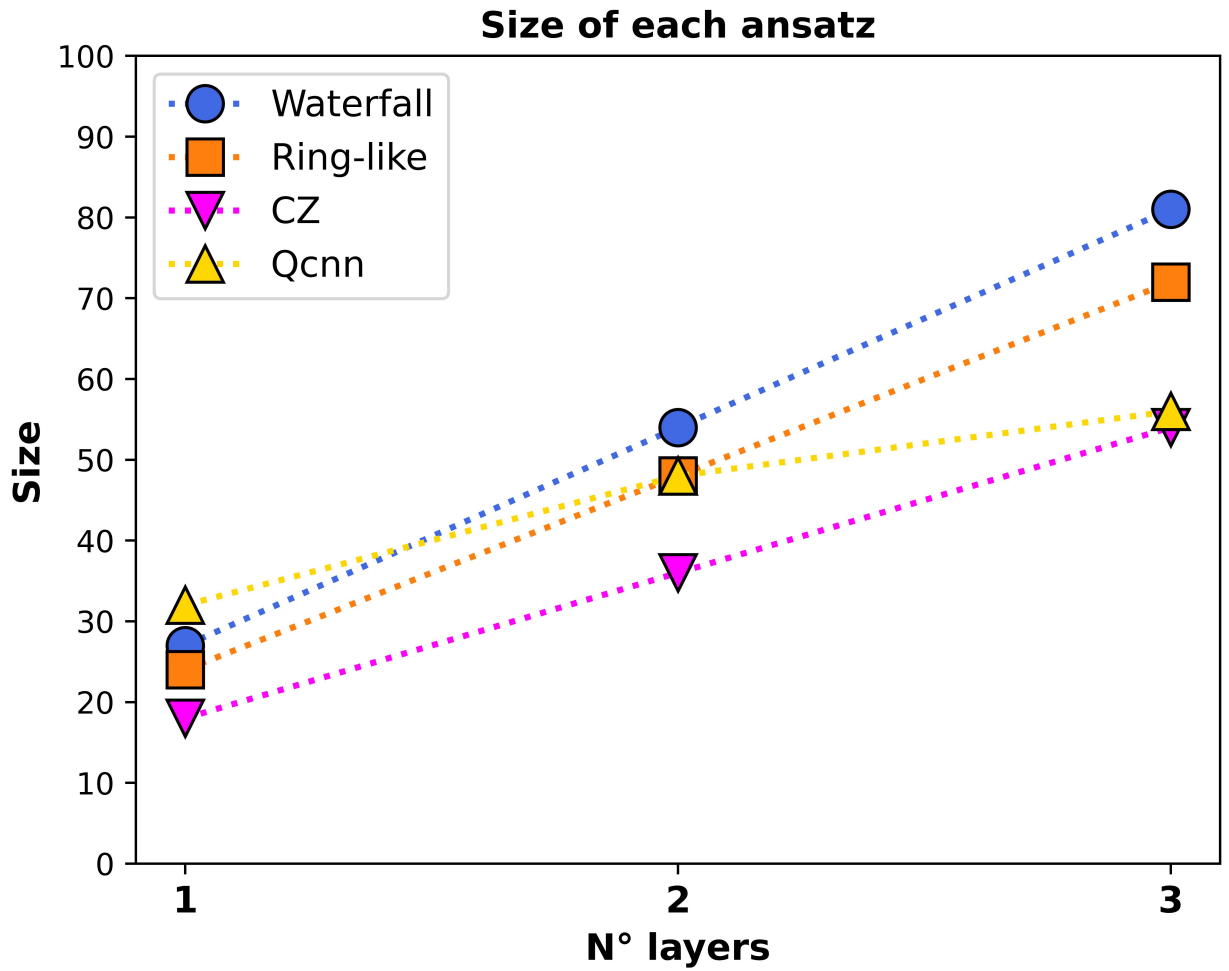


Figure: Circuits' size

Main experiment

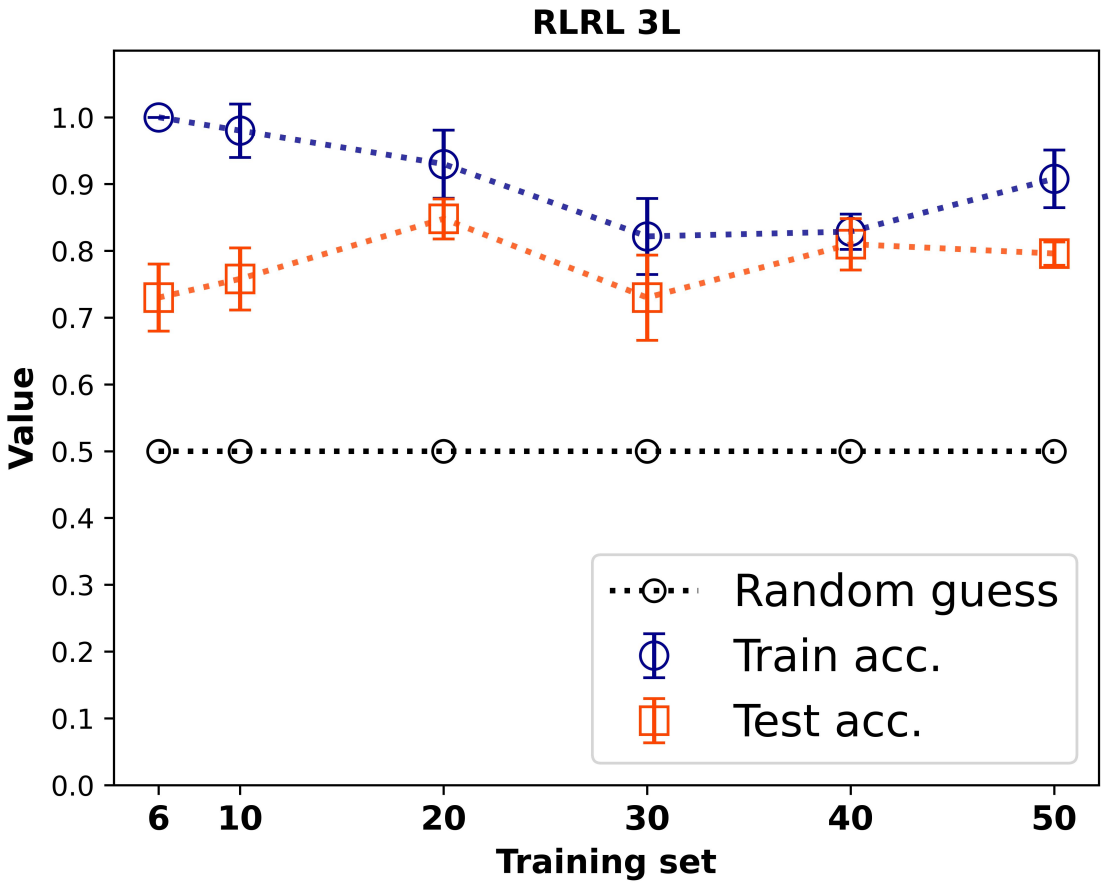


Figure: Generalization performances for RLRL model.

Other experiment

Exp n°2

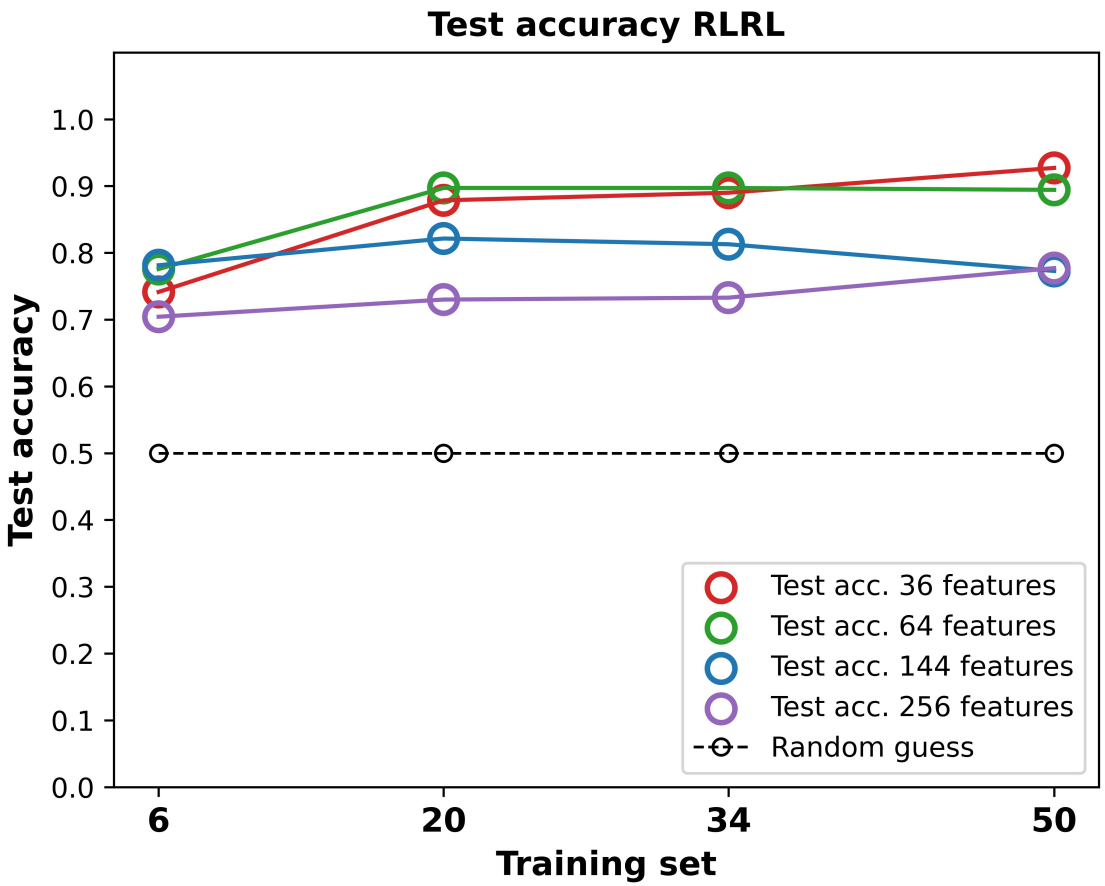


Figure: Test accuracy when less features.

CNN main experiment

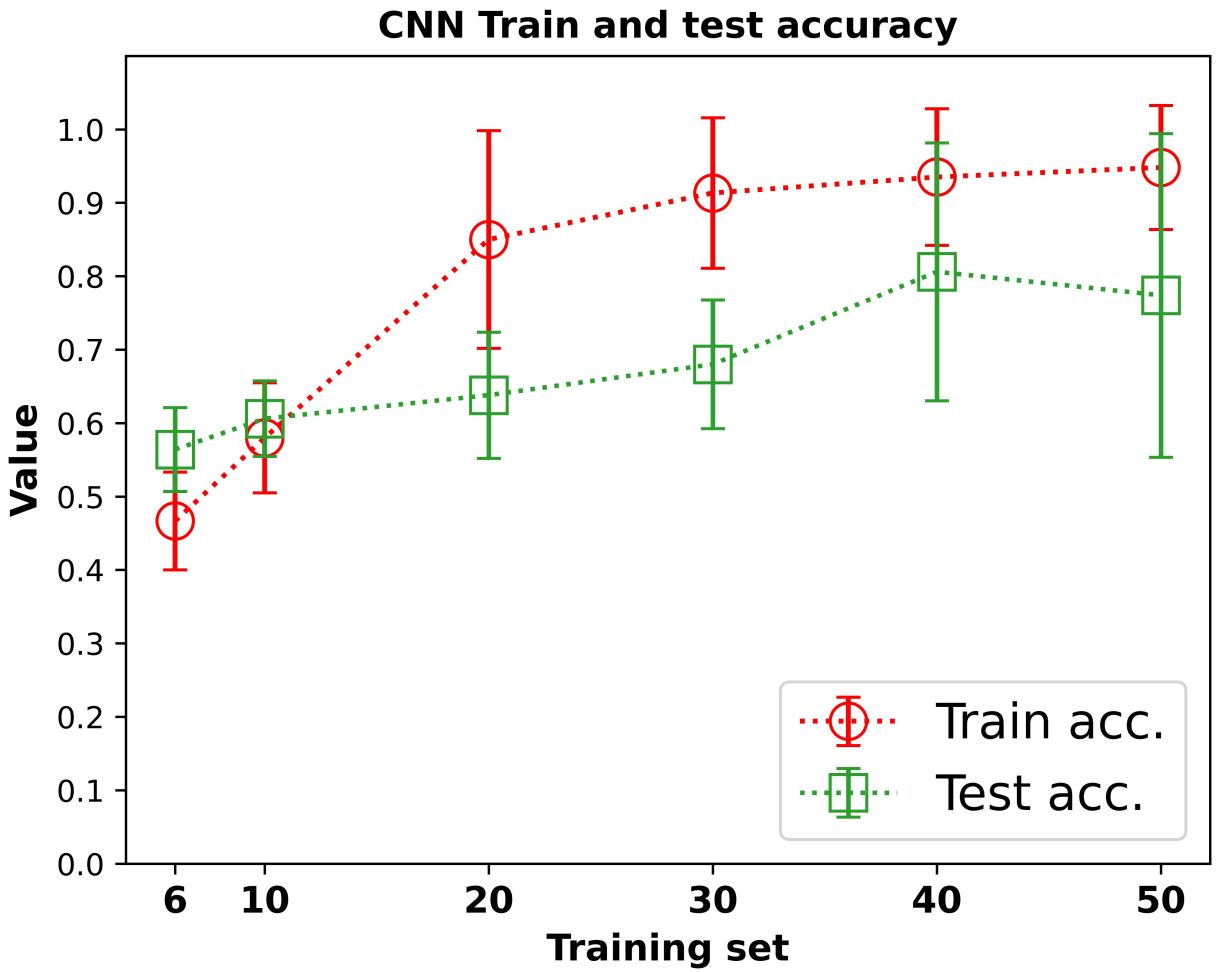


Figure: CNN with Galaxy.

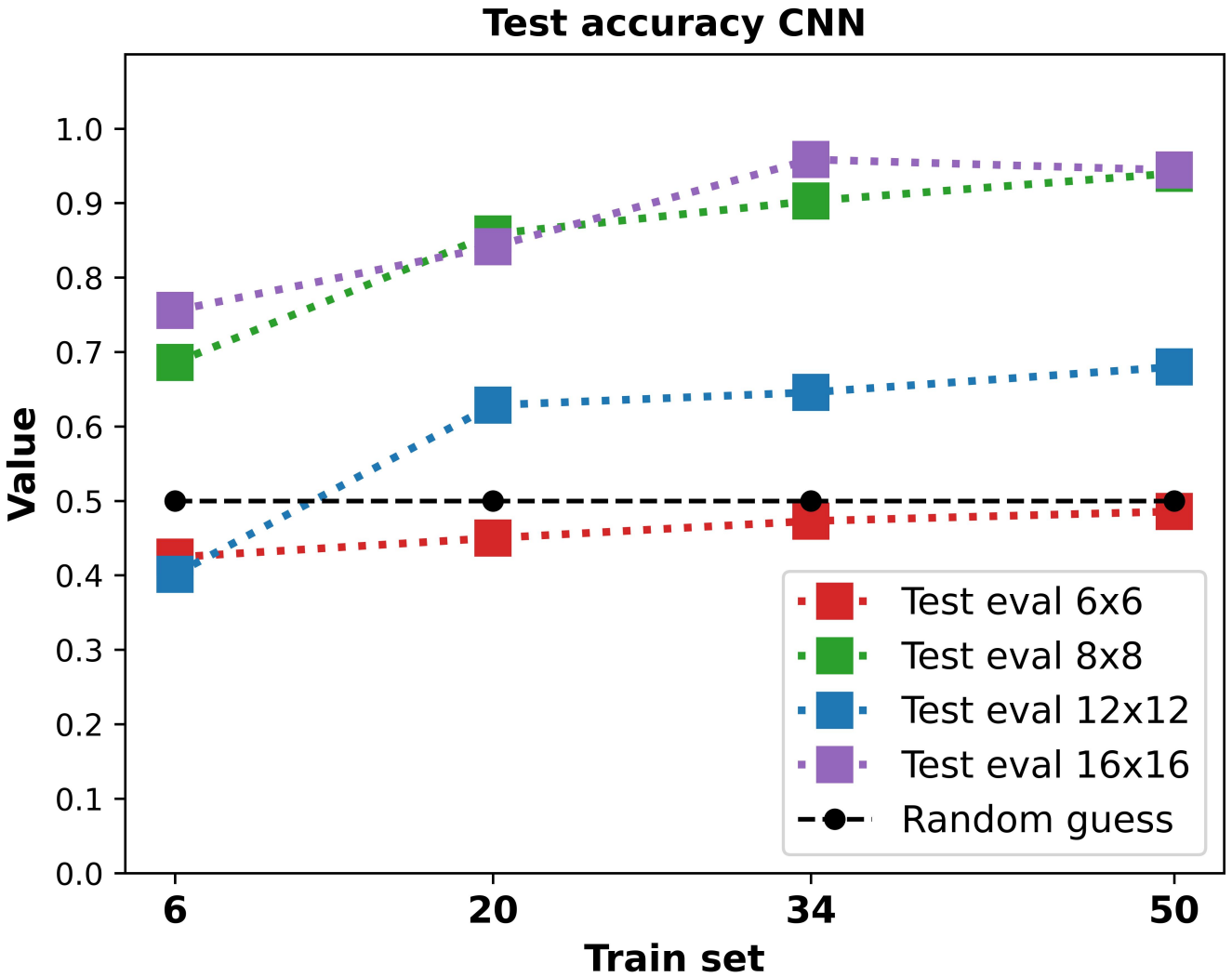


Figure: CNN with less features (Mnist).

Comparison

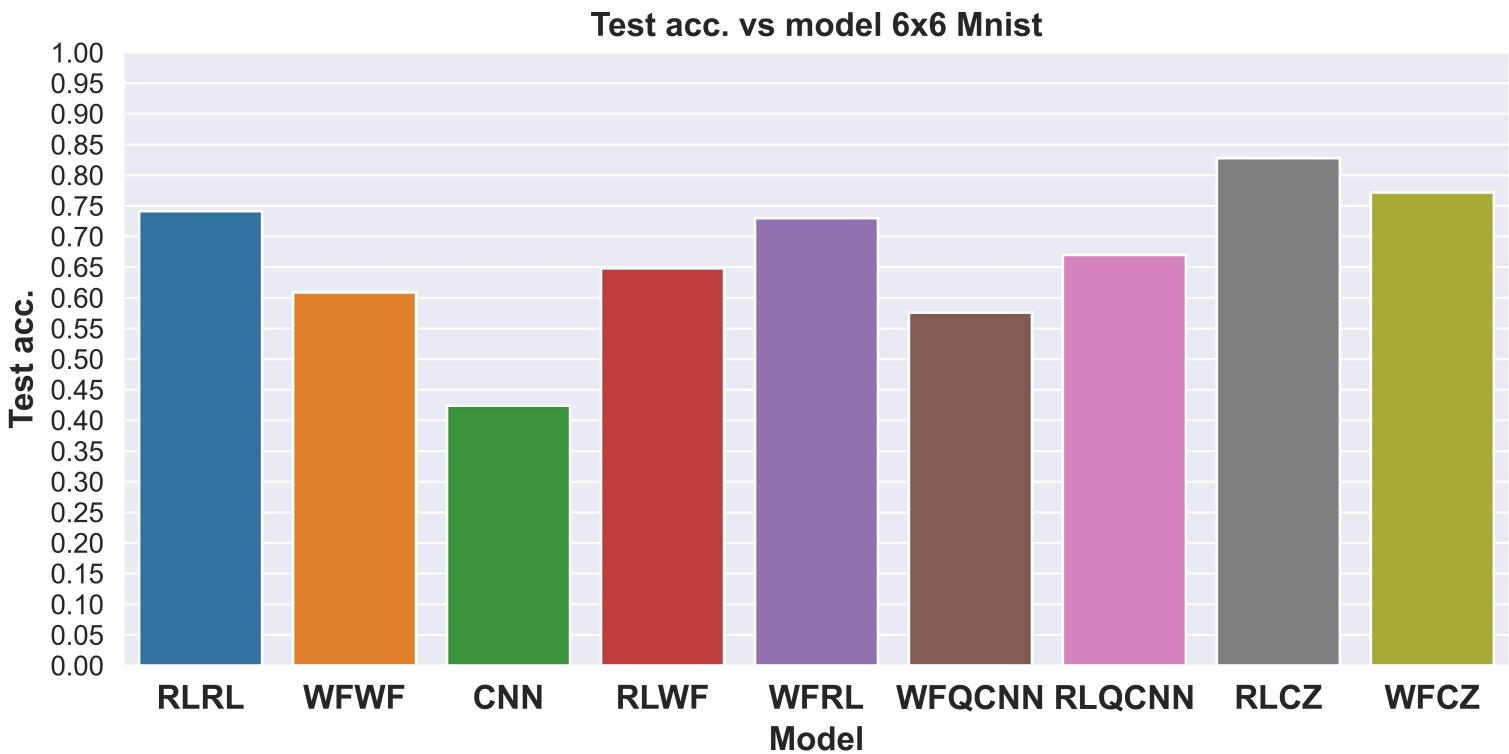


Figure: QNN models vs CNN for 6 training images of Mnist.

Conclusion

The obtained results are not sufficient to prove the advantages of using QNN models with respect to the CNN for many reasons: probably the chosen circuits are not suited for image-recognition, we would have used a non-gradient based optimizer to not to fall down into "Barren plateaus", we should have enlarged the train set..but we have seen that clear advantages could come out when the number of features composing the image dataset is considerably reduced. That's could in principle constitute a point to start investigating the abilities of Quantum Machine Learning models. It's only matter of time, but in the end the truth will be revealed...

Thanks

Thanks for listening and watching!