Quantum Machine Learning

Image credit: Luana Stockinger-Piamonteze, 7 years old

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Contents

- What is quantum machine learning?
- How do we implement it on a quantum computer?
- How does it perform compared to classical approaches?

Quantum Machine Learning

- Goal:
  - Implement quantum machine learning algorithms on quantum computer
  - Take advantage of superpositions and entanglement
  - We focus on neural networks
- Hope:
  - Quantum machine learning should either be faster or more accurate than classical counterparts
  - Tackle new problems that are not possible with classical approaches

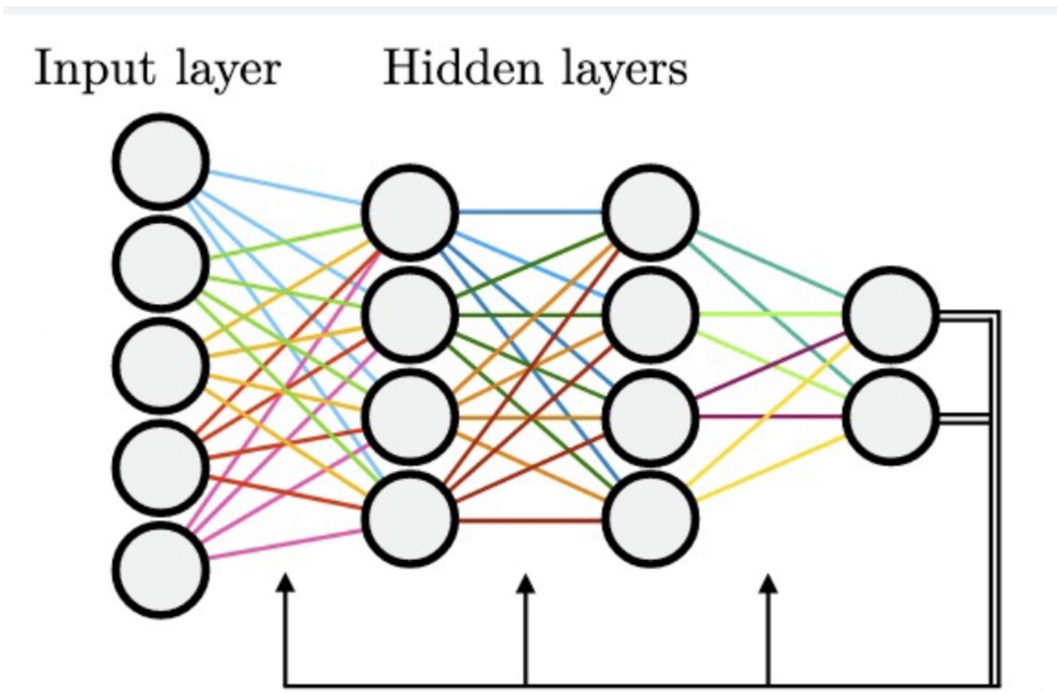
Neural Network in the Brain?

Image credit: Luana Stockinger-Piamonteze, 7 years old

Classical Artificial Neural Network

Input (x)

- Temperature
- Humidity
- Windspeed
- Pressure
- Location



Output (y)

- Rain
- No rain

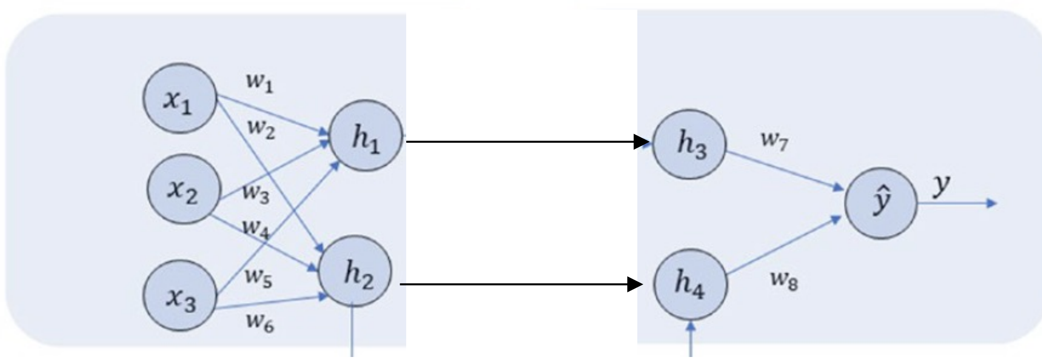
These types of neural networks have been applied successfully in many different areas such as image analysis, natural language processing (Chat-GPT), etc.

Quantum Artificial Neural Networks

- It is not clear how to best implement neural networks on a quantum computer: open research question
- The field is still in its infancy
- Most approaches are theoretical based on experimental quantum hardware
- However, there are promising approaches for small problems

Approach 1:
Hybrid Classical-Quantum Neural Network #1

Classical neural network



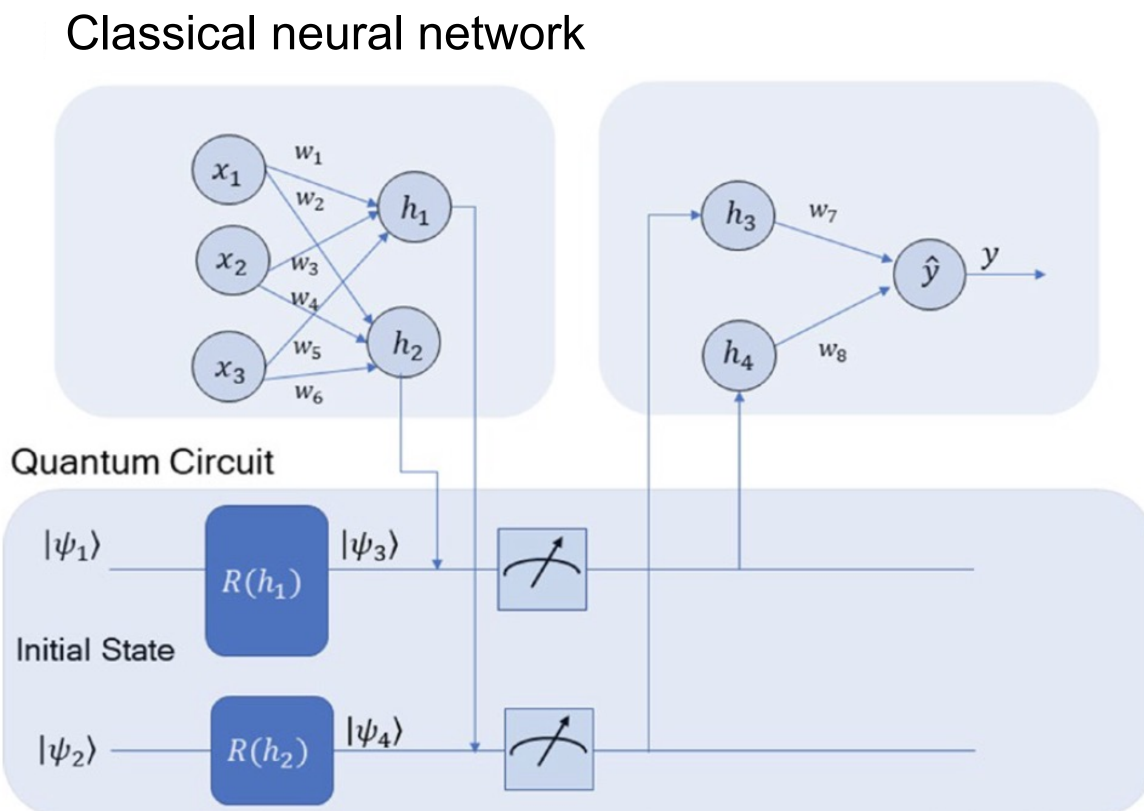
x … input

w … weights

h … hidden layers

y … output

Approach 1:
Hybrid Classical-Quantum Neural Network #2



x … input

w … weights

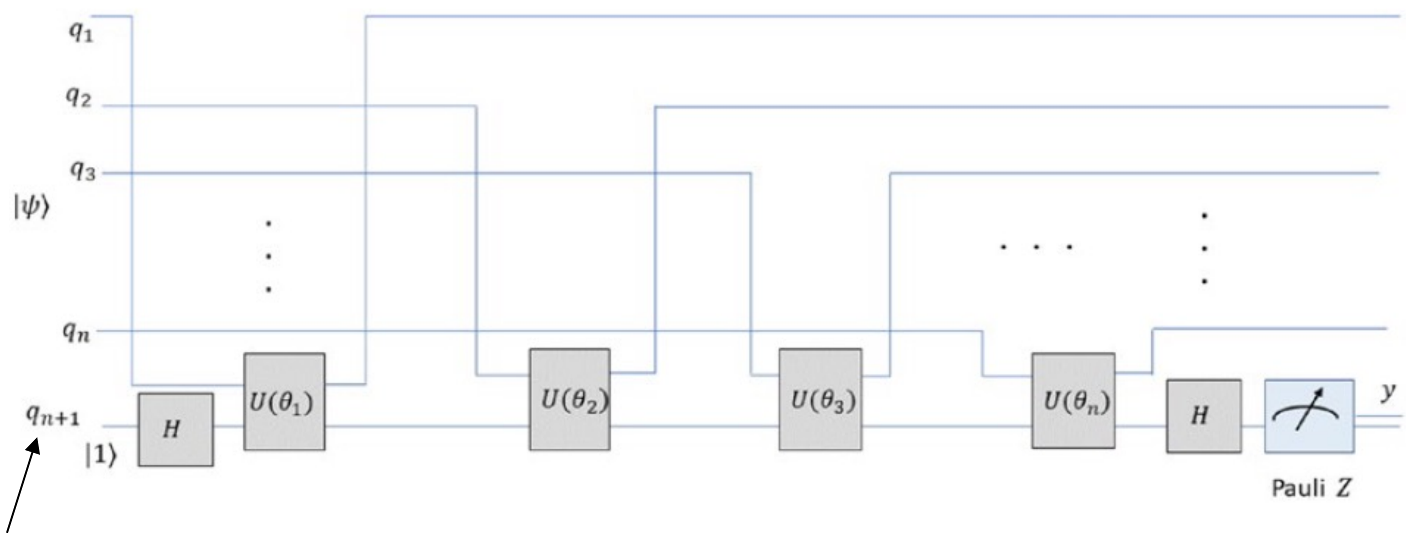
h … hidden layers

y … output

ψ… quantum state

Approach 2:
Quantum Neural Network with Unitary Layers

- The whole network is implemented as a parameterized quantum circuit
- QNN with i layers: $U(\theta) = U_l(\theta_l)U_{l-1}(\theta_{l-1})\ldots U_1(\theta_1)$
  - U ... unitary transformation
  - $\theta = [\theta_L, \theta_{L-1}, \ldots . \theta_1]^T$ set of parameters for the QNN



Readout qubit: After applying i unitary transformations, the state of q_{n+1} should correspond to the real label

How Well do These Approaches Work for Solving real Machine Learning Problems?

Datasets

Dataset	#Features	#Records	#Classes
Iris	4	100	2
Rain	5	100	2
Vlds	5	100	2
Custom	2	100	2
Adhoc	3	100	2

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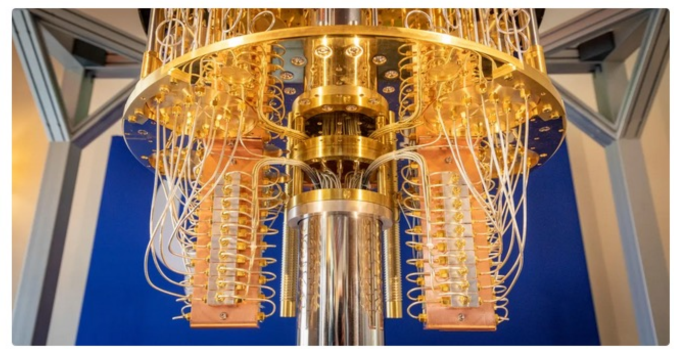
Software and Hardware

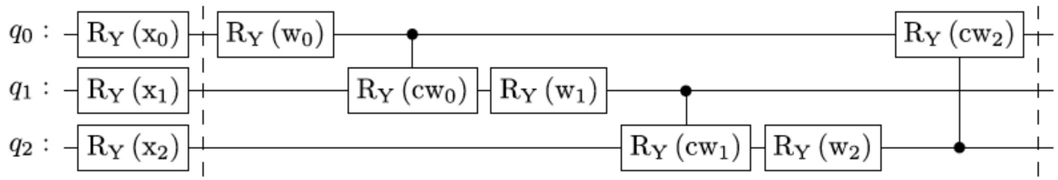
- Qiskit:
  - Python library for quantum computing by IBM
- Quantum simulator:
  - By IBM
  - Can be installed locally or publicly available via cloud
- Quantum computer:
  - By IBM
  - Publicly available via cloud

https://qiskit.org/

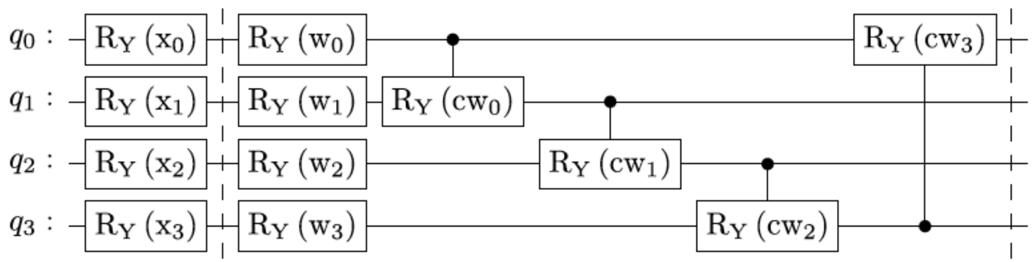


A close-up view of an IBM quantum computer. The processor is in the silver-colored cylinder.
Stephen Shankland/CNET

Evaluation of Different Quantum Neural Networks

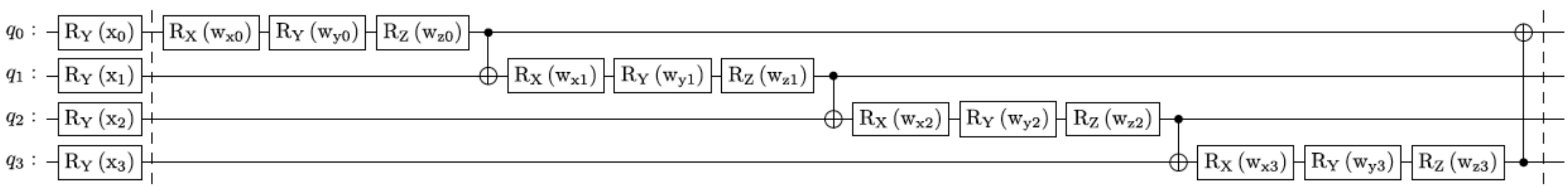


Circuit 1



Circuit 2

Circuit 5



Experimental Results #1

Metric = accuracy (between 0 and 1): higher is better

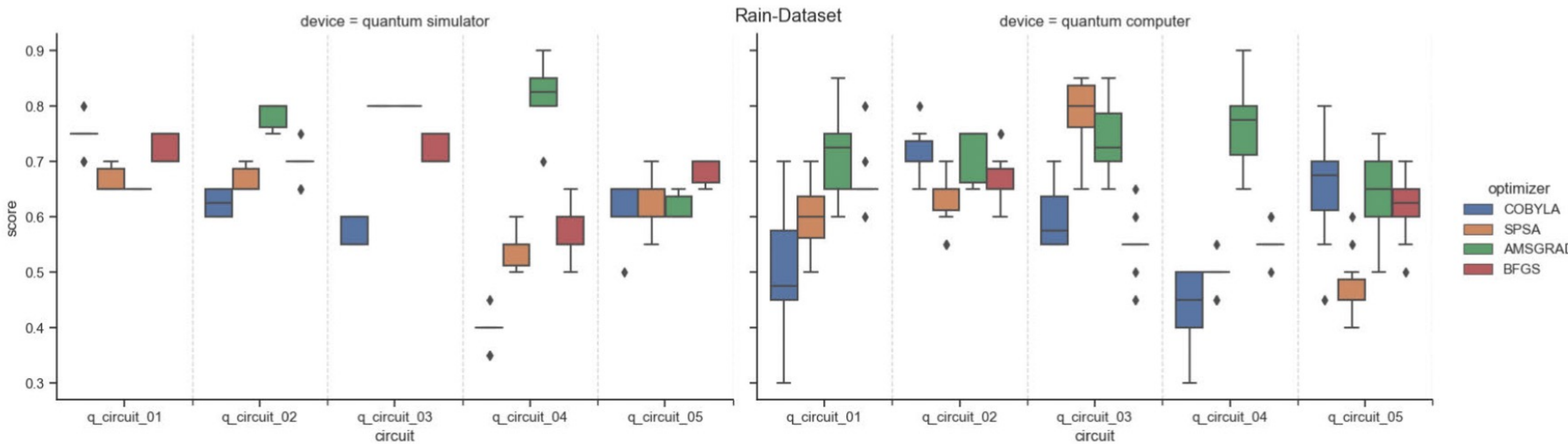
Dataset	Classical NN	QNN (Quantum Simulator)	QNN (Quantum Computer)
Iris	1.00	1.00	1.00
Rain	0.70	0.83	0.79
Vlds	0.94	0.93	0.95
Custom	0.64	0.74	0.75
Adhoc	0.61	0.80	0.75
Average	**0.78**	**0.86**	**0.85**

Quantum neural network (QNN) outperforms classical neural network (NN)
on specific datasets

R. D. M. Simões, P. Huber, N. Meier, N. Smailov, R. M. Füchslin and K. Stockinger, "**Experimental Evaluation of Quantum Machine Learning Algorithms**," in *IEEE Access*, vol. 11, pp. 6197-6208, 2023, doi: 10.1109/ACCESS.2023.3236409.

Experimental Results #2
Details on the Rain Dataset

Comparison of 5 different quantum circuits on
quantum simulator (left) and quantum computer (right)



We can observe a high fluctuation of the results.

score = accuracy (higher is better)

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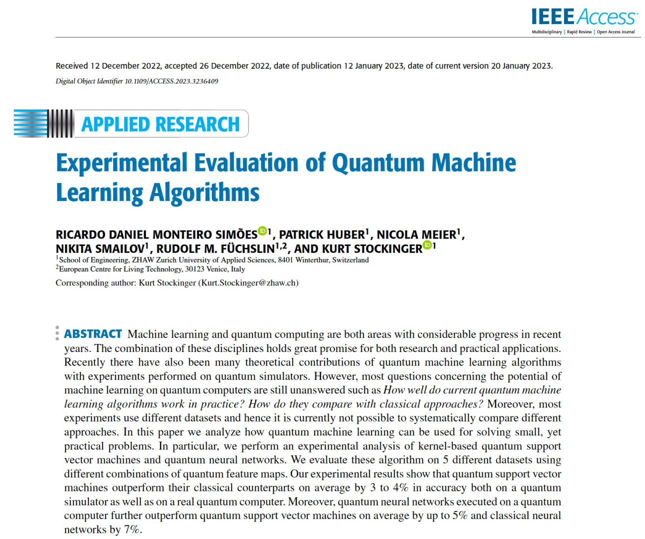
Conclusions

- Quantum machine learning is still in its infancy
- Currently we can only solve small problems
- Quantum hardware needs to mature and become more fault-tolerant
- There is a steep learning curve to get into the topic
- First results are very promising
- Early movers have an advantage



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APPLIED RESEARCH

Experimental Evaluation of Quantum Machine Learning Algorithms

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ABSTRACT Machine learning and quantum computing are both areas with considerable progress in recent years. The combination of these disciplines holds great promise for both research and practical applications. Recently there have also been many theoretical contributions of quantum machine learning algorithms with experiments performed on quantum simulators. However, most questions concerning the potential of machine learning on quantum computers are still unanswered such as *How well do current quantum machine learning algorithms work in practice? How do they compare with classical approaches?* Moreover, most experiments use different datasets and hence it is currently not possible to systematically compare different approaches. In this paper we analyze how quantum machine learning can be used for solving small, yet practical problems. In particular, we perform an experimental analysis of kernel-based quantum support vector machines and quantum neural networks. We evaluate these algorithm on 5 different datasets using different combinations of quantum feature maps. Our experimental results show that quantum support vector machines outperform their classical counterparts on average by 3 to 4% in accuracy both on a quantum simulator as well as on a real quantum computer. Moreover, quantum neural networks executed on a quantum computer further outperform quantum support vector machines on average by up to 5% and classical neural networks by 7%.

https://ieeexplore.ieee.org/document/10015720