

# Kwantowe sieci neuronowe

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Seminarium  
Wojskowa Akademia Techniczna

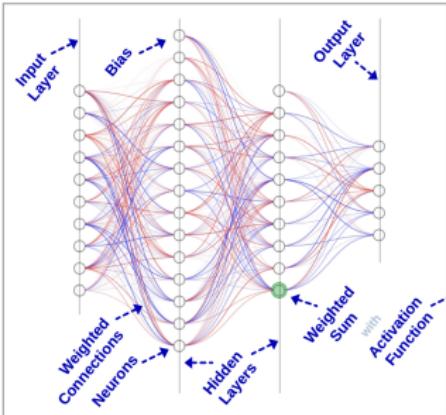
06.03.2025

# Neural Networks

## A class of complex ML models

- Multi-Layer Perceptrons** (MLP) take numerical input and produce numerical output
- MLPs are structured into layers
- Layers** consist of neurons
- Neurons** hold activation - value in range [-1,+1]
- Weighted links** connect neurons of adj. layers
- Activation** is a weighted sum of activations of neurons from the previous layer
- Bias** is a value added to the sum
- Activation function** is applied to the sum to scale the result back to the interval [-1, 1]
- Optimisation** is the process to identify optimum weights and biases, it is commonly iterative
- Optimisation aims** to reduce cost or aggregated loss, a distance between the calculated and expected results

MLP = a simple neural network  
capable of learning any “smooth” function  
learns to associate inputs with outputs



- This process can be accelerated by using specialised hardware, e.g. GPUs or TPUs
- Other NNs: CNN, AE, GAN, LSTM + QNNs

Name	Plot	Function, $g(x)$
Identity		$g(x) = x$
Binary step		$g(x) = \begin{cases} 0 & \text{if } x < 0 \\ 1 & \text{if } x \geq 0 \end{cases}$
Logistic, sigmoid, or soft step		$g(x) = \frac{1}{1 + e^{-x}}$
Hyperbolic tangent (tanh)		$g(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}}$
Rectified linear unit (ReLU)[2]		$g(x) = \begin{cases} 0 & \text{if } x \leq 0 \\ x & \text{if } x > 0 \end{cases} = \max(0, x) = x1_{x>0}$
Cumulative Error Linear Unit (CELU)[3]		$g(x) = \frac{1}{2} x \left( 1 + \operatorname{erf}\left(\frac{x}{\sqrt{2}}\right) \right) = x\Phi(x)$
Silu[4]		$\ln(1 + e^x)$
Exponential linear unit (ELU)[5]		$g(x) = \begin{cases} \alpha(e^x - 1) & \text{if } x \leq 0 \\ x & \text{if } x > 0 \end{cases}$ with parameter $\alpha$
Scaled exponential linear unit (SELU)[6]		$g(x) = \lambda \left( \alpha(e^x - 1) \text{ if } x \leq 0 \atop x \text{ if } x > 0 \right)$ with parameters $\lambda = 1.0507$ and $\alpha = 1.67326$
Leaky rectified linear unit (Leaky ReLU)[7]		$g(x) = \begin{cases} 0.01x & \text{if } x < 0 \\ x & \text{if } x \geq 0 \end{cases}$
Parametric rectified linear unit (PReLU)[8]		$g(x) = \begin{cases} \alpha x & \text{if } x < 0 \\ x & \text{if } x \geq 0 \end{cases}$ with parameter $\alpha$
Signmoid linear unit (SReLU)[9]		$g(x) = \frac{x}{1 + e^{-x}}$
Signmoid shrinkage[10]		$\text{Sigmoid}(x) \cdot (1 - \text{Sigmoid}(x))$
Sigmoid		$e^{-x^2}$
QNN		Wikipedia

# Machine Learning, Deep Learning

## Deep learning algorithm flow

### Model

model with trainable parameters  $f(x; \theta) = \sigma(Wx + b)$  where  $\theta = \{W, b\}$

### Cost function

$$C = \sum_{x,y} (f(x; \theta) - y)^2$$

### Gradient descent

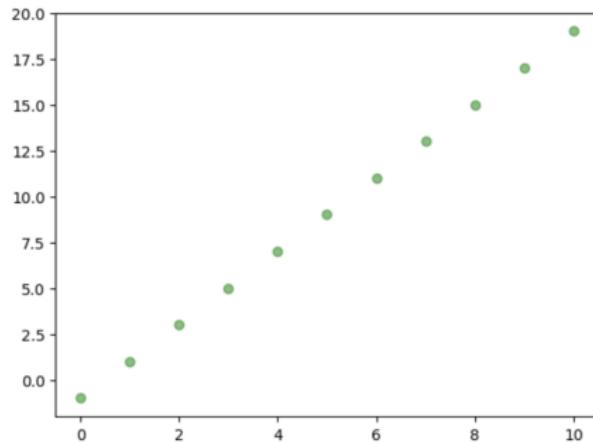
- Compute gradient of cost w.r.t parameters
- Update parameters  $\theta^{t+1} = \theta_t - \eta \nabla_{\theta} C$

# ML models as a special case of NN

Wygenerujemy niezazumione dane na podstawie wzoru  $y = 2x - 1$ . Na podstawie zbioru danych postaramy się oszacować nieznane parametry czyli wyraz przy  $x$  ( $\alpha_1 = 2$ ) i wyraz wolny ( $\alpha_0 = -1$ ).

```
import numpy as np
import matplotlib.pyplot as plt

# zbiór danych
x = range(11)
y = [2*xi - 1 for xi in x]
plt.plot(x, y, 'go', label='True data', alpha=0.5)
```



# ML w kodach

Model regresji liniowej dla jednej zmiennej można zrealizować jako prostą jednowarstwową sieć neuronową. Cały proces można zrealizować za pomocą obiektu `torch.nn.Linear`

```
import torch

class LinearRegression(torch.nn.Module):

    def __init__(self, inputSize, outputSize):
        super(LinearRegression, self).__init__()
        self.layers = torch.nn.Sequential(
            torch.nn.Linear(inputSize, outputSize)
        )

    def forward(self, x):
        return self.layers(x)
```

Aby nasze dane mogłybyć przeliczane przez bibliotekę PyTorch musimy je przetworzyć na tensory - czyli obiekty z biblioteki PyTorch.

```
# dostosowanie do pytorch
x = np.array(x, dtype=np.float32)
y = np.array(y, dtype=np.float32)

X_train = torch.from_numpy(x).view(-1,1)
y_train = torch.from_numpy(y).view(-1,1)
```

Uwaga - ponieważ mamy jedną zmienną zawierającą 10 przypadków - potrzebujemy listy składającej się z 10 list jednoelementowych.

Możemy utworzyć model i wybrać optymalizator z funkcją kosztu.

```
# obiekt liniowej regresji w wersji sieci nn
lr_model = LinearRegression(1,1)

criterion = torch.nn.MSELoss()
optimizer = torch.optim.SGD(lr_model.parameters(), lr=0.01)
```

## Czy zadziała?

# Obliczenia kwantowe

Obliczenia kwantowe to nowy paradymat przetwarzania informacji wykorzystujący własności mechaniki kwantowej - *kubit, superpozycja, splotanie.*

## Modele obliczeń kwantowych

- Quantum Circuits - bramkowy model obliczeń kwantowych
- adiabatyczne obliczenia kwantowe,
- topologiczne komputery kwantowe

## jeszcze jedna zasada

Dekoherencja - oddziaływanie „niszczące” stan kwantowy  
ERA Noisy Intermediate-Scale Quantum (NISQ)

# Quantum technology

## What is Quantum Technology

### Quantum computing and Quantum information science

study of the information processing tasks that can be accomplished using quantum mechanical systems  
(Nielsen and Chuang, 2010)

$$d_{\gamma,n}(\mathcal{M}_{\Theta}) = \frac{2 \log \left( \frac{1}{V_{\Theta}} \int_{\Theta} \sqrt{\det \left( \text{id}_d + \frac{\gamma n}{2\pi \log(n)} \hat{F}(\theta) \right)} d\theta \right)}{\log \left( \frac{\gamma n}{2\pi \log n} \right)}$$

$$\hat{F}_{i,j}(\theta) = d \frac{V_{\Theta}}{\int_{\Theta} \text{tr}(F(\theta)) d\theta} F_{i,j}(\theta),$$

$$V_{\Theta} = \int_{\Theta} d\theta$$

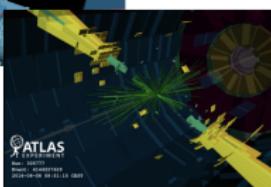
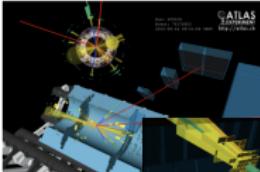
Not an easy path

Quantum finance  
Quantum chemistry  
Quantum optimisation  
Quantum machine learning  
problem-solving with quantum technology



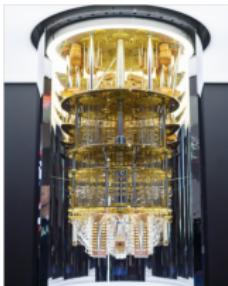
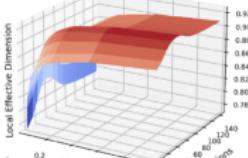
### What is a Quantum Computer?

*It is a device which directly applies the principles of quantum mechanics to perform computational tasks*

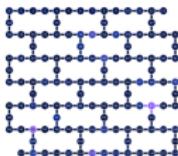


CERN  
Atlas particle detector  
Large Hadron Collider

Method 0, d=40, inst# = 7, n>1000 (RIS)



IBM superconducting quantum machine (127 qubits on cloud)



Quantum engineering  
building quantum devices

# Quantum Machines

Recently in the news ...

## Quantum Machines

Univ of Sci and Tech of China with Shanghai Inst of Microsystem and Info Tech (*Jiuzhang 3 - Photonic*)

Again achieved quantum supremacy  
Gaussian Boson Sampling



D-Wave  
(Quantum Annealing)



PASQAL  
(Neutral Atoms)



Google  
(Superconducting)



Quantum  
Brilliance  
(Diamond)



Xanadu (Photonic)

IQM / VTT  
(Superconducting)



IBM (Superconducting)

Microsoft Azure Quantum

AWS Braket

(Platforms)

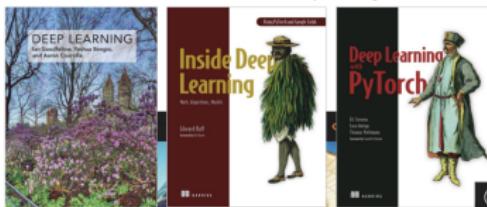
- Providers
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  - IonQ
  - QCI
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- IonQ
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  - OQC
  - Xanadu
  - D-Wave
  - QuEra ...

# Recommended reading 1

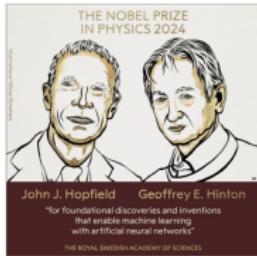
## Recommended reading on QNN + Deep Learning

Classical Neural Networks / Deep Learning



Chapter 10: QNN

Neural Networks  
Fathers



arXiv Cornell University

the generous acknowledge support from the Simons Foundation

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Computer Science > Emerging Technologies

(Submitted on 4 Dec 2022)

**A review of Quantum Neural Networks: Methods, Models, Dilemma**

Hanxin Zhao, Shi Wang

The rapid development of quantum computing technology has led to a massive innovation in the realization of QNNs. In this paper, we introduce higher quantum capacity and computational efficiency compared to classical counterparts. This article will review the development of QNNs in the past six years from three parts: representation methods, quantum circuit models, and applications thereof. Among them, the first part, the representation methods, mainly discusses the classical representation of QNNs and the quantum representation of QNN models, such as VQNN. The second part introduces several quantum circuit models of QNNs, including QFCNN, QCNNs and so on. The third part describes some of the main difficult problems currently encountered. In short, this work is still at the embryonic stage, full of magic and practice experience.

Comments: 14 pages, 10 figures. arXiv admin note: KITP Preprint Series posted on arXiv:2212.01840v1. arXiv admin note: new version: 2302.08706

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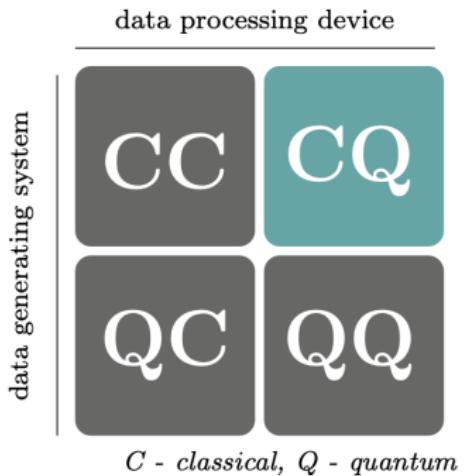
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# Kwantowe uczenie maszynowe

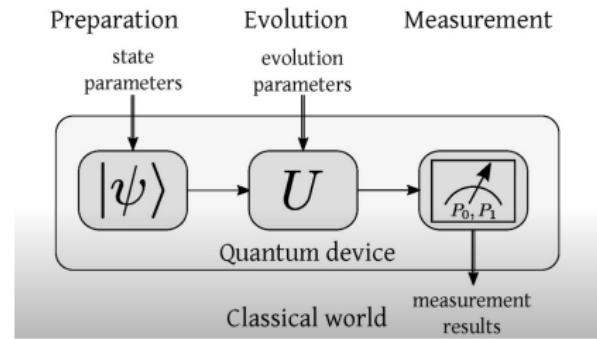
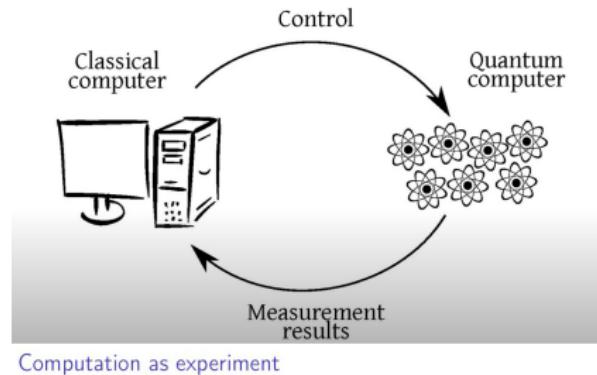


$$|f(x; \theta)\rangle$$

Czy możemy zamienić „model” wykorzystując obliczenia kwantowe?

# Proces obliczeń kwantowych

Quantum computation control loop

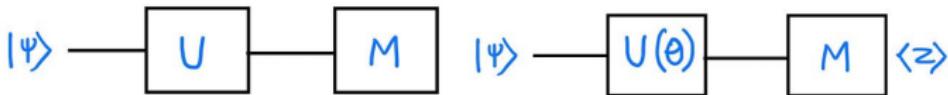


Przykład (deterministyczny): Algorytm Deutsch-Jozsa

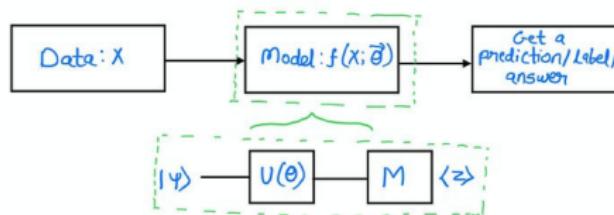
# Wariacyjne modele kwantowe

## Variational Quantum Circuits

Trenujmy nasze komputery kwantowe tak jak robimy to w sieciach neuronowych.



Variational Circuit as Classifier:



Variational quantum eigensolver, Variational quantum classifier, Quantum Support Vector Machine, ...

# Qubits

in scientific terms

In practice qubits involve *elementary particles*, such as *ions*, *photons*, single *atoms*, *electrons*, even *defects in diamonds*; and, their behaviour is governed by Physics (Nature / Universe)

A qubit *represents a state* of such a particle, e.g. an electron spin, which can be *up* or *down*, (written formally as  $| \uparrow \rangle$  and  $| \downarrow \rangle$  or  $| 0 \rangle$  and  $| 1 \rangle$ ), which are called the *basis states*

It is possible to change the state of a qubit with certain predetermined *operations*, such as rotation or reversing the position of the qubit state

Afterwards, the qubit is in a state of *superposition*, or a combination, of its basis states *up* and *down*

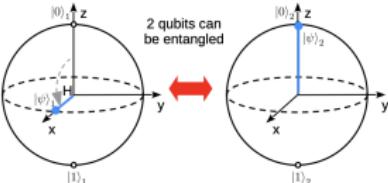
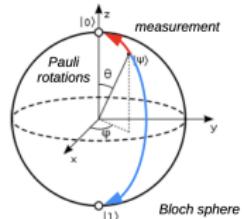
The superposition state is the actual state of elementary particles, not its math description

It is impossible to determine the qubit's state without its *measurement*

Qubit measurement returns only the basis state that is "likely" to be closest to its superposition state, which also destroys the qubit state

The outcome of measurement is precise but probabilistic

Qubits can be *entangled*, then they start behaving as a unit with a common complex state, until they are measured or until some external factor (*noise*) destroys their entanglement

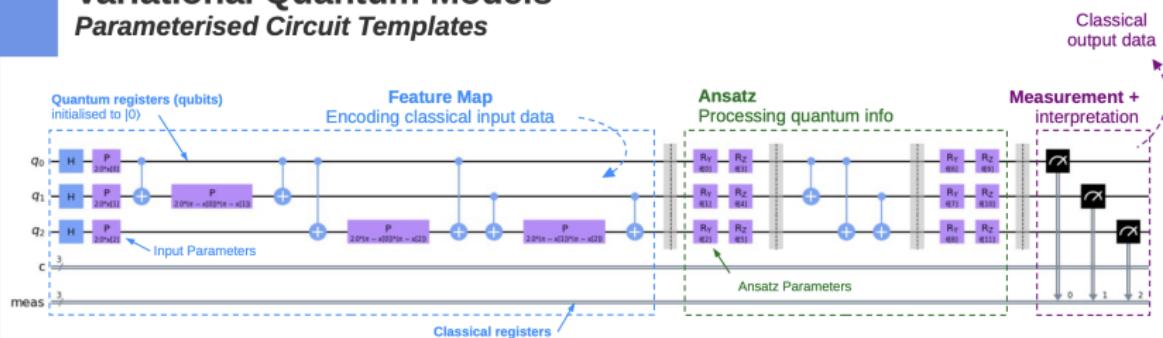


**What makes quantum computers special?**

Qubit *superposition* (parallel choices) and *entanglement* (exponential combination of choices and their filtering), as well as *measurement* (collapse of choices and randomness), is what gives quantum computers their immense computational power allowing some problems to be solved in minutes rather than 1000s of years!

# QNN model

## Variational Quantum Models = Parameterised Circuit Templates



Quantum circuits are static  
Data and operations are hard-coded  
New data / operation params → new circuit

Typically, the circuit consists of three blocks:

- a feature map (input) encodes classical data as circuit state
- an ansatz (processing) alters circuit state
- measurements (output) measures circuit state into classical data

## Variational Quantum Algorithm

VQA is an **iterative process**

VQA uses **cost/loss function** and **optimiser**

VQA has **difficulties**:

- The problem at hand
- Large circuits with many parameters
- Complex measurement strategy
- Unsupervised learning
- Emergence of barren plateaus

### A typical VQA process

The ansatz parameters are initialised to some values, e.g. zero or random

The feature map parameters are bound to the new input data

The parameter values are used to create a new circuit

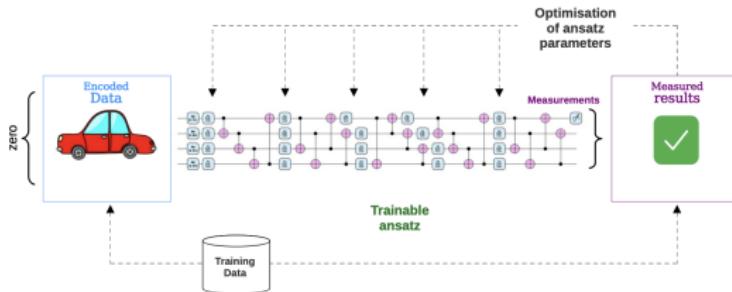
The circuit is executed

The circuit quantum state is then measured

Cost function is applied to measurement results and expected values

The cost of difference is calculated

Based on the difference and previous parameters the new parameters values are proposed



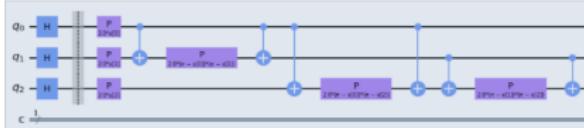
## QNN model

# Quantum Neural Networks

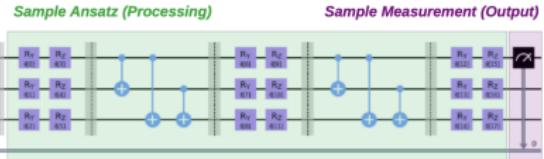
## Specifically Quantum MLPs

- The QNN variational model is typically represented by a quantum circuit of three components, i.e.
    - **feature map** encoding QNN's classical input data and preparing the circuit's quantum state
    - **ansatz** consisting of several layers of trainable parameters (Pauli rotations), responsible for quantum state processing and transformation
    - **measurement** of the circuit's quantum state, which can subsequently be interpreted as QNN's classical output
  - QNNs can be trained with variational quantum algorithms and a wide range of classical optimisers.
  - Pure quantum training strategies are also possible.

### **As per a VOA Model**



### **Sample Feature Map (Input)**



Abbas, Amira, David Sutter, Christa Zoufal, Aurelien Lucchi, Alessio Figalli, and Stefan Woerner. "The Power of Quantum Neural Networks." *Nature Computational Science* 1, no. 6 (June 2021): 403–9.

Reinherz, Amelia. "Quantum Neural Networks for FinTech." *Medium*. May 8, 2020.

QNNs

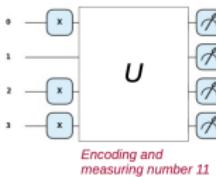
- can deal with highly complex computation (as QM)
  - can deal with large volume of data (as NN)
  - can process entire probabilistic distributions of values (superposition) and utilise parameters space of exponential size (entanglement)
  - require repeated execution to produce output
  - are missing some efficiency of classical NNs (non-linear activations and regularisation strategies)
  - are difficult to process on quantum simulators of limited computational capacity
  - need experimentation and extensive data preparation – there is no magic in quantum tech!

# QNN model

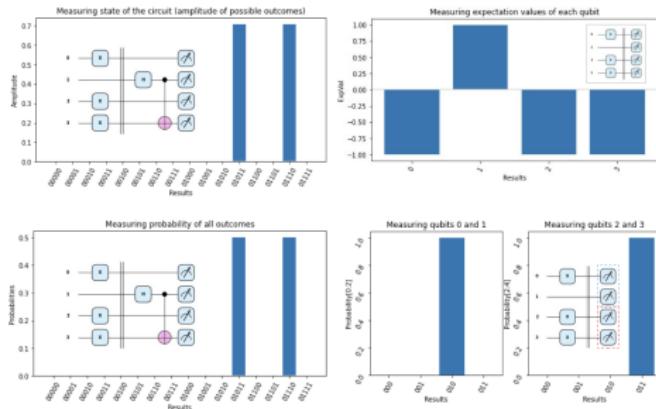
## Data embedding: Basis encoding and decoding

**Basis embedding** is the commonly used strategy for quantum encoding and decoding of integer numbers, where:

- qubits act as bits of the encoded numbers
- circuit state can be interpreted as bits of the numeric value on output
- application needs a single (or very few) integer value on input and output



There are many different approaches to quantum data encoding and decoding that are suitable for QNN, e.g. basis, angle and amplitude embedding.

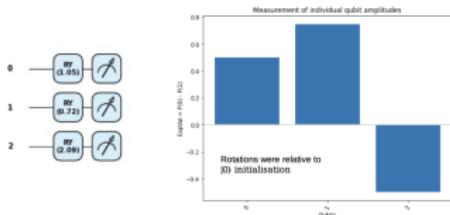


Maria Schuld and Francesco Petruccione.  
*Machine Learning with Quantum Computers*. 2nd ed. Springer, 2021.  
<http://link.springer.com/book/10.1007/978-3-030-83098-4>.

## QNN model

# Data embedding:

## Angle encoding and decoding



Input

Values entered: [np.arccos(0.5), np.arccos(0.75), np.pi-np.arccos(0.5)]  
Ry angles used: [1.047, 0.723, 2.094]

### Measurements

Probabilities: [[0.25, 0.75], [0.562, 0.438], [0.25, 0.75]]  
Amplitudes: [0.5, 0.75, -0.5]

**Angle embedding** represents numeric values as properties of qubit state rotation (angle, amplitude or probability)

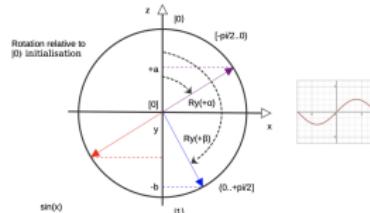
The rotation operators are the basic quantum operation

Encoding rotations are performed around x, y, z axes of the Bloch sphere (multiple values per qubit are possible)

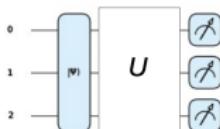
Rotations are relative to a specific qubit state, e.g.  $|0\rangle$

Input encoding can be repeated across the circuit, called reuploading, which improves the model performance

As training will place qubit states in areas  $x < 0$  and around the z axis, measurements may not distinguish these states from "pure"  $x > 0$  and  $z = 0$ .



## Data embedding: Amplitude encoding and decoding

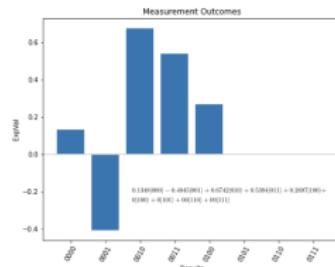


*Amplitude embedding* is one of the most useful encoding / decoding strategies

Unless supported by the quantum platform, it is considered the most difficult (see Sutor 2024)

In amplitude encoding, each data point is encoded as expectation value of multi-qubit measurement of all qubits' states

This way, we can embed  $2^{\text{qubits}}$  numbers into a circuit!



Consider a vector:

$$\mathbf{v} = [0.1, -0.3, 0.5, 0.4, 0.2],$$

which needs to be normalised by the vector length:

$$\sqrt{0.1^2 + (-0.3)^2 + 0.5^2 + 0.4^2 + 0.2^2},$$

which results in a new vector (approximately):

$$\mathbf{v}' \approx [0.13484 - 0.40452 \ 0.6742 \ 0.53936 \ 0.26968].$$

To encode 5 amplitudes in a quantum circuit, we need at least 3 qubits. Thus, resulting in the following encoding:

$$0.1348|000\rangle - 0.4045|001\rangle + 0.6742|010\rangle + 0.5394|011\rangle + 0.2697|100\rangle + 0|101\rangle + 0|110\rangle + 0|111\rangle$$

We will rely on PennyLane and Qiskit to generate quantum gates for this circuit ...

There are many other methods of data encoding, e.g. QRAM, time-evolution, or dense-angle, or Hamiltonian encoding.

Many of these methods are offered as ready-made feature maps.

Qiskit feature maps include:

- FeatureMap
- ZZFeatureMap
- PauliFeatureMap

## Commonly used measurements and interpretation

There are many ways of obtaining the outcome of a circuit execution, e.g. we can measure:

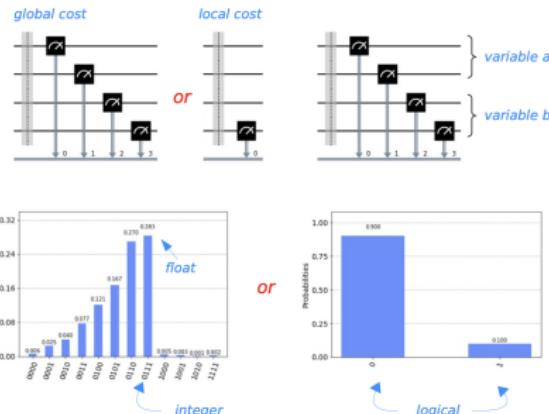
- all qubits (global cost)
- a few qubits (local cost)
- groups of qubits
- as counts of repeated measurements
- as probabilities of  $|0\rangle$  and  $|1\rangle$
- as expectation values,  $P(0)-P(1)$
- as variance, etc.

Repeated circuit measurement can be interpreted as outcomes of different types, e.g.

- as a binary outcome:  
single qubit measurement
- as an integer:  
multi-qubit measurement
- as a continuous variable:  
expectation value of a specific outcome

Circuit state measurement has an impact on the calculation of the loss/cost function

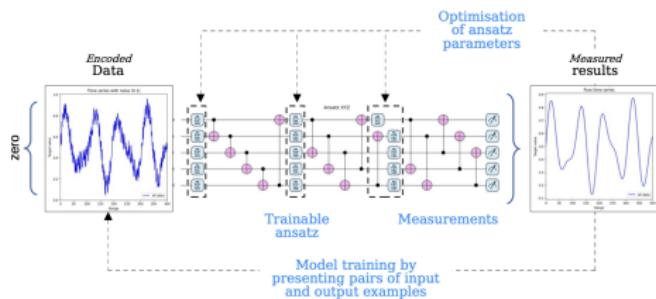
Model measurement and interpretation of results share their fundamental concepts and methods with data encoding.



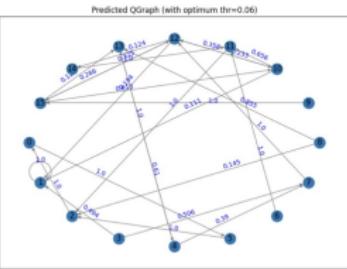
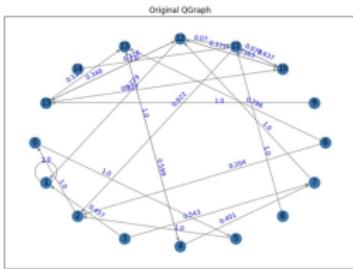
Probability distribution of measurements can be further interpreted, e.g. we could check parity of the probability kets (e.g.  $|110\rangle$  is even, while  $|111\rangle$  is odd), add all even and odd probabilities respectively, and treat the result as a logical measurement.

## Training of Quantum Neural Networks

- QNN training needs a loss / cost function and an optimiser of the model parameters
- The loss function and optimiser can either be pure quantum or hybrid
- Pure quantum approach often relies on quantum adiabatic or quantum annealing optimisation, and Grover-like amplitude amplification
- A hybrid approach uses variational quantum algorithms (VQA), and relies on the QNN execution on a quantum machine, and its parameters optimisation conducted on a classical machine
- Hybrid training of QNNs is identical to training classical NN models

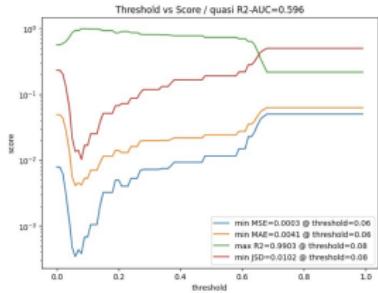


## Current Work



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Quantum states in circuits chained—  
Truth blooms, unrestrained.

Quantum Haiku by DeepSeek

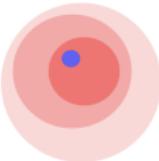


### Quantum Graphs

Development of concepts and formalisms related to  
"quantisation" of classical data structures, such as time  
series, signals and graphs.

Quantum graphs for instance will assist highly efficient  
representation and processing of very large interconnected  
structures, e.g. when assisting management of social  
networks, identification of sub-graph communities and  
detection of anomalies in graphs.

Enchanted is being somewhere in-between Enchanted and Entangled



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# Summary

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