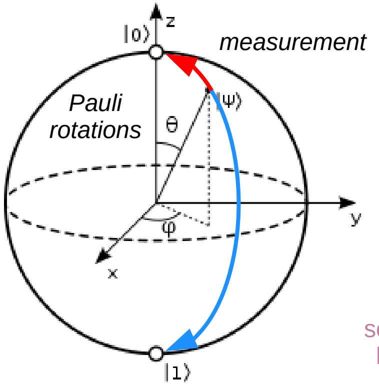
Secrets revealed in this session:

To explore the fundamental principles of quantum tech and its applications

Business Value of Quantum Technology

Harnessing quantum technology to advance business

Jacob L. Cybulski
Enquanted, Australia

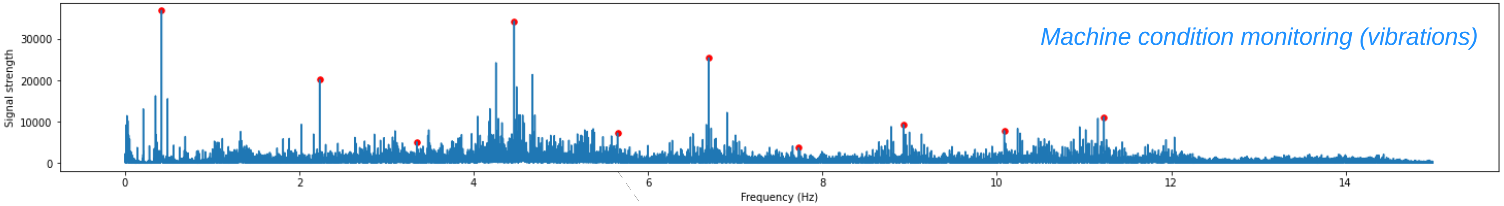


We will assume some knowledge of business analytics

20 January 2025, DISBA, Deakin University

Presenter

Jacob Cybulski
quantum@jacobcybulski.com



Machine condition monitoring (vibrations)

Founder
Researcher
Consultant
Author
at Enquanted

also

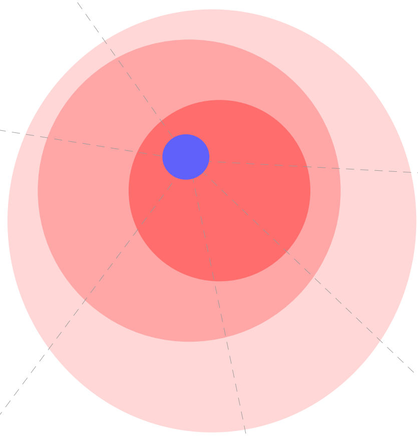
Honorary A/Prof
In Quantum Computing
School of IT, SEBE
Deakin University
Melbourne, Australia

Research

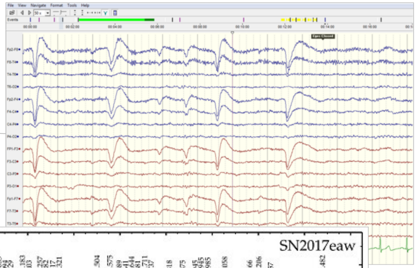
- Quantum computing
- Quantum machine learning
- Quantum time series analysis and anomaly detection
- Classical machine learning
- Data visualisation

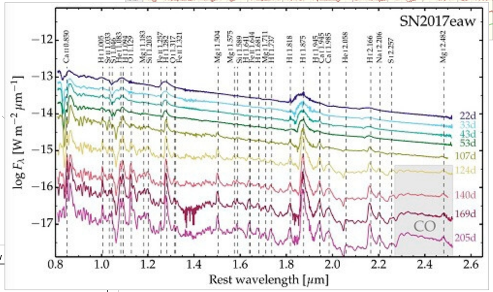
Personal

- Recreational cycling
- Reading science and Sci-Fi
- Quantum challenges and hackathons

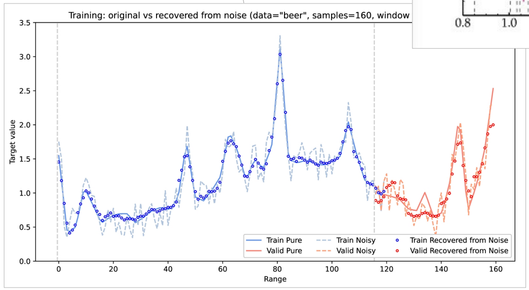


EEG/ECG analysis

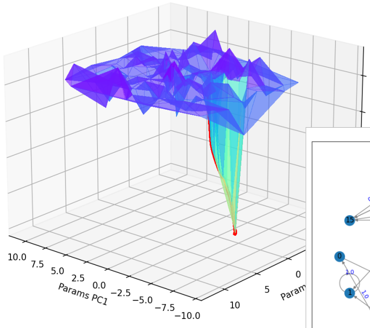




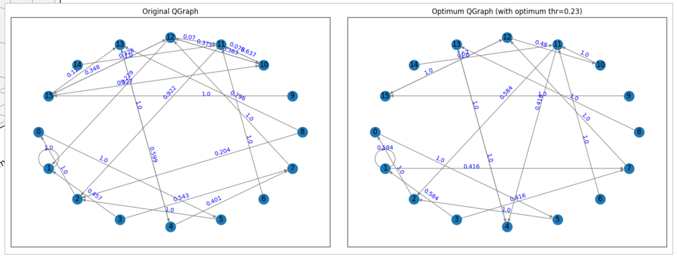
Astronomical observations



Sales forecasting



Model capacity to learn and barren plateaus

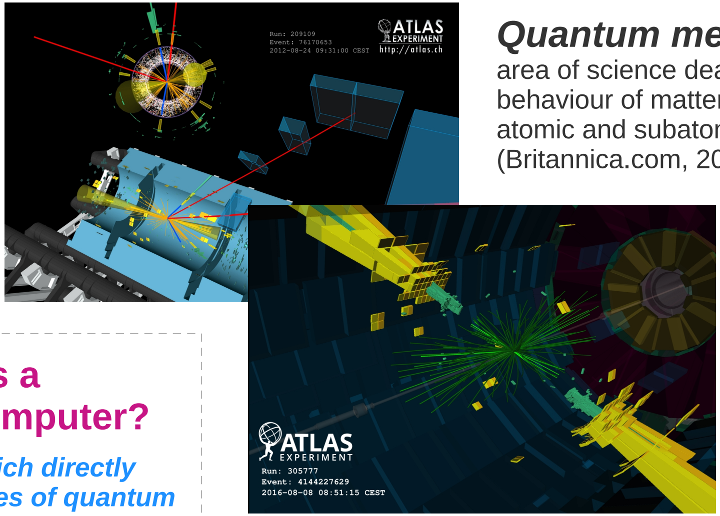


Quantum graphs with community detection

International research collaboration +

supervision of research students in QC + QML

What is
Quantum Technology



Quantum mechanics
area of science dealing with the behaviour of matter and light on the atomic and subatomic scale (Britannica.com, 2020)

CERN
Atlas particle detector
Large Hadron Collider

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

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

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

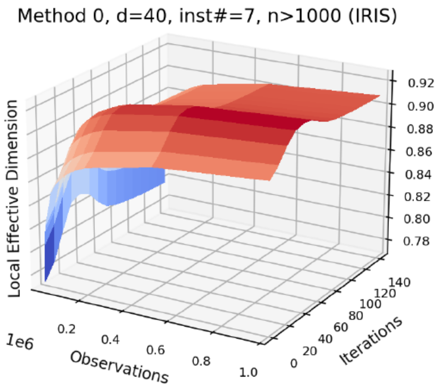
Not an easy path

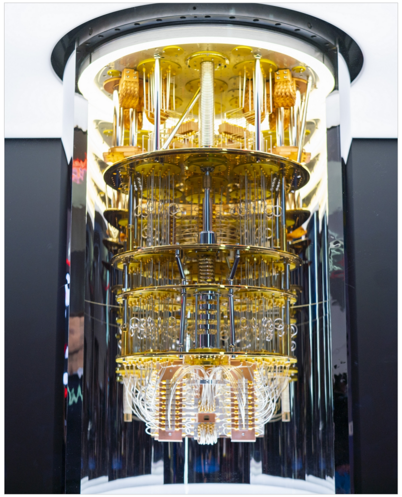
$$V_\Theta = \int_\Theta \mathrm{d}\theta$$

What is a Quantum Computer?

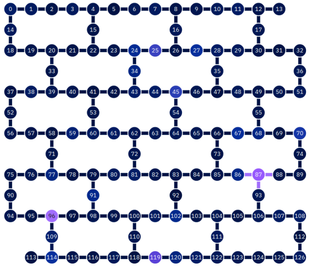
It is a device which directly applies the principles of quantum mechanics to perform computational tasks

There are other quantum technologies e.g. quantum sensing





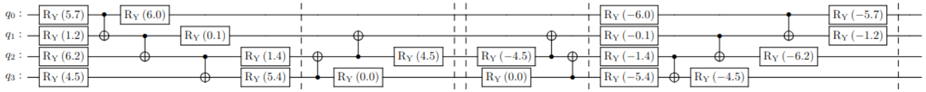
IBM superconducting quantum machine (127 qubits on cloud)



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

Quantum engineering
building quantum devices

Cybulski & Nguyen
Barren Plateaus
in QNNs and VQAs



(2024)

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

SpinQ
(N. Magnetic Resonance)

IQM / VTT
(Superconducting)

IBM (Superconducting)

D-Wave
(Quantum Annealing)

PASQAL
(Neutral Atoms)

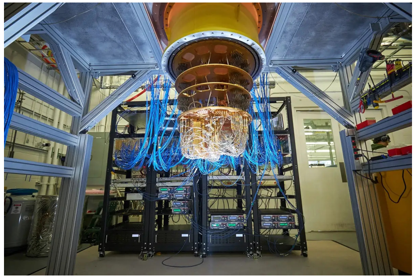
They all use:

Qubits
the fundamental models of quantum information and its processing

Quantum circuits
models of computation, involving qubits and operations on them

Quantum Brilliance
(Diamond)

Xanadu (Photonic)



Google
(Superconducting)

Microsoft Azure Quantum

Providers
- Quantinuum
- IonQ
- QCI
- Rigetti
- Pasqal
- 1QBit
- Microsoft QIO
- Toshiba ...

AWS Braket

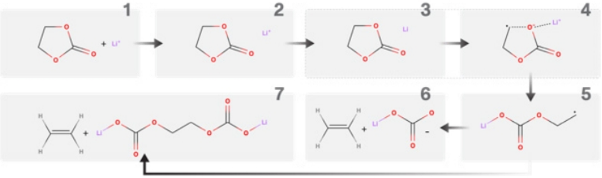
(Platforms)

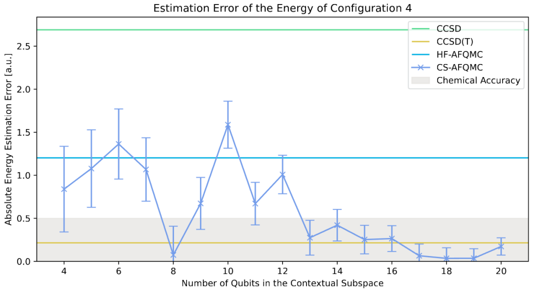
Providers
- IonQ
- Rigetti
- OQC
- Xanadu
- D-Wave
- QuEra ...

Three Selected Applications

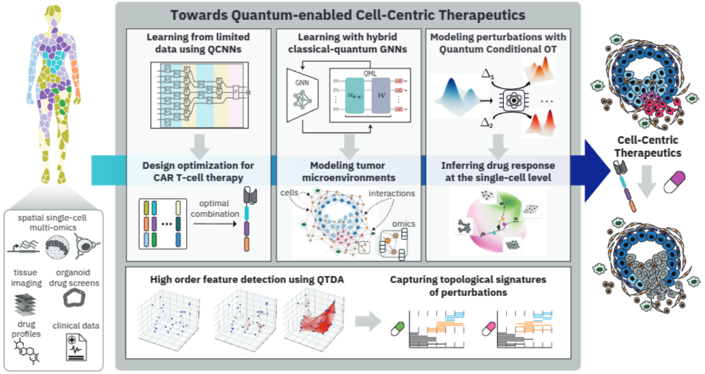
For more recent examples, see:
Olivier Ezratty, 2024. Understanding Quantum Technologies, 7th ed. Le Lab Quantique. URL: https://www.oezratty.net/

- **Chemistry**
- **Company:** IQM and Volkswagen, 2024
- **Platform:** IQM with hybrid quantum-classical QC-AFQMC algorithm
- **Aim:** to develop advanced battery materials to increase their efficiency for use in electric vehicles.
- **Results:** Achieved accurate simulation of critical chemical reactions involving battery chemicals, i.e. ethylene carbonate molecules and lithium ions.

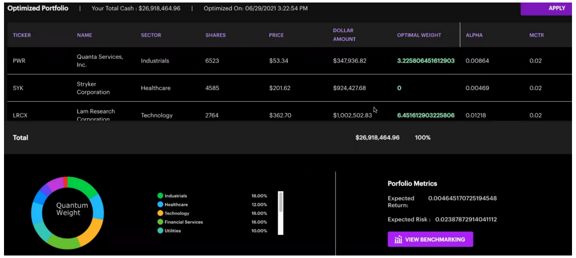


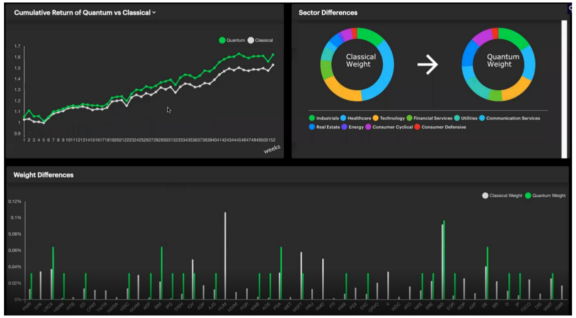


- **Pharmaceutical**
- **Company:** IBM and partners, 2023
- **Platform:** IBM Quantum
- **Aims:** to design and discover new precision medicines based on spatial single-cell technologies to precisely understand the interactions between disease cells and therapies.
- **Results:** Several quantum methods have been developed and tested by IBM and partners to support cell engineering for immunotherapy, modelling tumour microenvironments, inferring single-cell drug perturbations, and bio-topology for cellular behaviour.

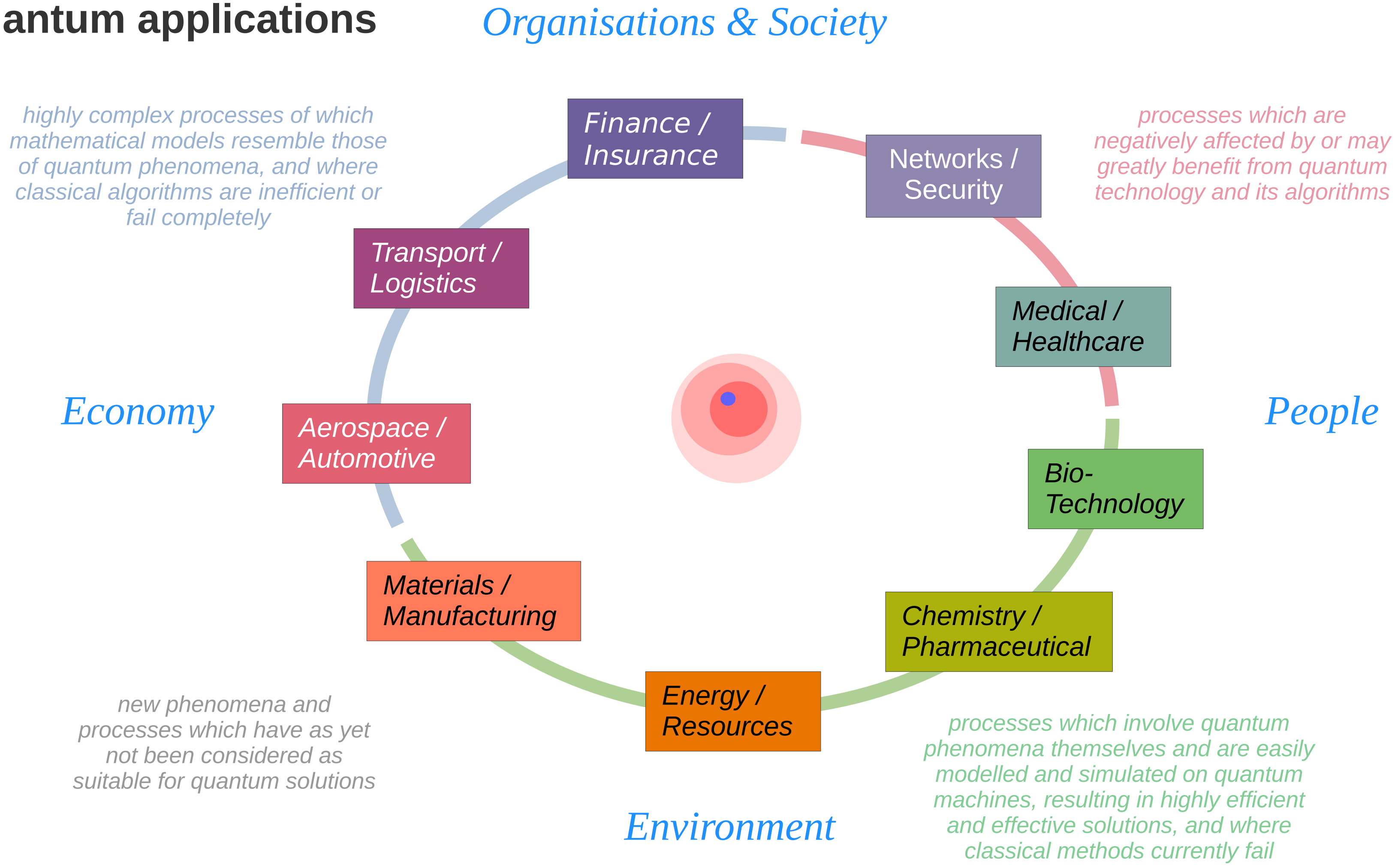


- **Finance**
- **Company:** Accenture, 2021
- **Platform:** D-Wave quantum machine with Leap, via AWS Braket
- **Aim:** to minimise the difference between the target and the final portfolio while maximising the return, using data from Yahoo Finance.
- **Results:** Working portfolio rebalancing system.





The wheel of
Quantum applications

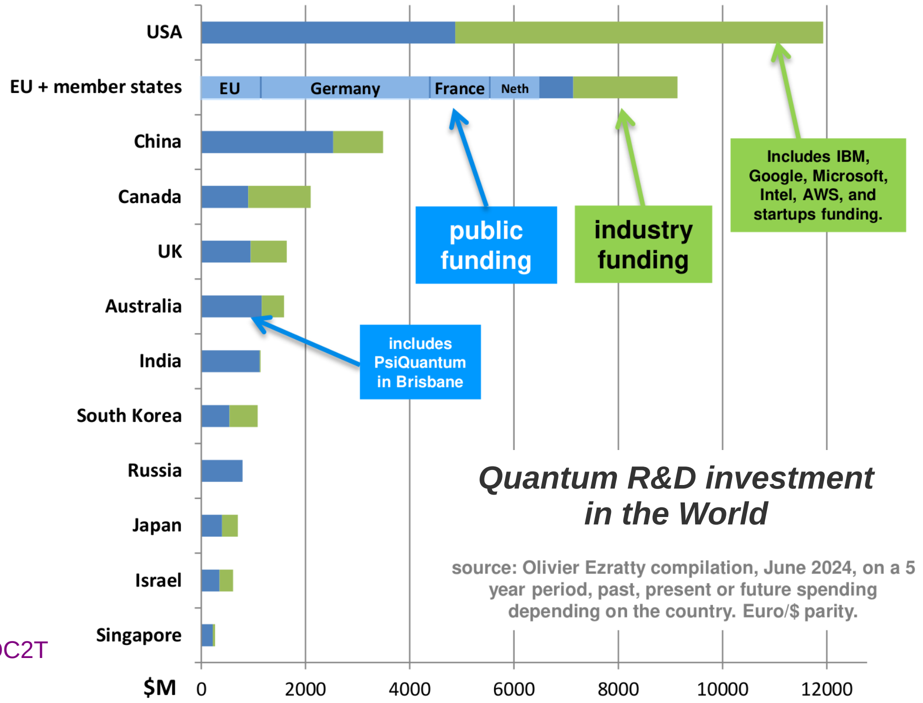


Quantum R&D in Australia

Selected organisations

Business funded
Government funded

- NSW
  - Silicon Quantum Computing (Quantum engineering)
  - Q-CTRL (Quantum computing and sensing)
  - Diraq (Quantum engineering)
  - Archer (Quantum engineering and sensing)
  - h-Bar (Quantum consulting)
  - Sydney Quantum Academy
  - University of Sydney: Quantum Australia
    Quantum Science Group at Sydney / Sydney Nanoscience Hub
  - Macquarie University: MQ Centre for Quantum Engineering (with partners) / frm Macquarie University Research Centre in Quantum Science and Technology
  - UNSW: Fundamental Quantum Technologies Lab / CQC2T
  - UTS: Centre for Quantum Software and Information / CQC2T
- Australian Capital Territory (Canberra)
  - Quantum Brilliance (Quantum engineering)
  - QuintessenceLabs (Quantum cybersecurity)
  - NOMAD (Quantum sensing)
  - ANU: Quantum optics group / CQC2T
- Queensland
  - PsiQuantum Australia (Quantum engineering)
  - Quantum Australia Growth Centre
  - University of Queensland: CoE for Eng Quantum Systems (with PsiQuantum) / CQC2T
  - Griffith: Centre for Quantum Dynamics / CQC2T
- Victoria
  - Enquanted (Quantum applications and consulting)
  - Melbourne Quantum Academy (forming)
  - University of Melbourne: IBM Quantum Hub (with IBM Quantum) / CQC2T
  - Swinburne University of Technology: Swinburne Quantum Technology Centre (with Infleqtion, frm ColdQuanta)
  - RMIT: Quantum Photonics Lab / Research Hub for Diamond Quantum Materials (with QB+LTU) / CQC2T
  - Deakin University: Quantum IT / Distributed Quantum Computing (with CISCO)
  - Monash University: Quantum error correction / Quantum sensors (with QB + L3Harris)
- South Australia
  - QuantX Labs (Quantum sensing)
  - University of Adelaide: Centre for Quantum Materials and Quantum Technologies
- Western Australia
  - University of Western Australia: QISA (Quantum Information, Simulation and Algorithms) Research Centre



Ezratty, O., 2024. Understanding Quantum Technologies, Seventh. ed. Le Lab Quantique.

also see: https://www.industry.gov.au/science-technology-and-innovation/technology/quantum

National Collaboration:
Australian Quantum Alliance
ARC Centre of Excellence for Engineered Quantum Systems (EQUS)
ARC Centre of Excellence for Quantum Computation and Communication Technology (CQC2T)
Australian Quantum Software Network (AQSN)

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

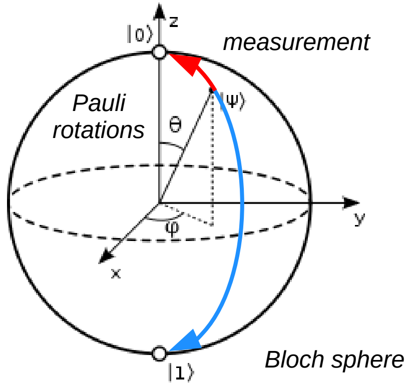
Afterwards, the qubit is in a state of *superposition*, or a combination, of its basis states up and down

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

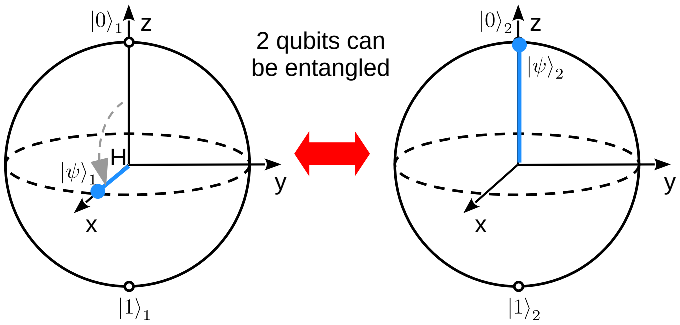
It is impossible to determine the qubit's state without its *measurement*

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?

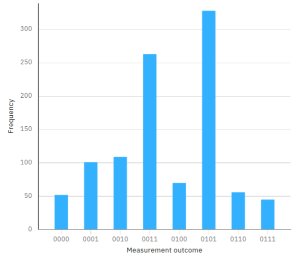
Qubit *superposition* (parallel choices) and *entanglement* (exponential combination of choices and their filtering), as well as *measurement* (collapse of choices and randomness), is what gives quantum computers their immense computational power allowing some problems to be solved in minutes rather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

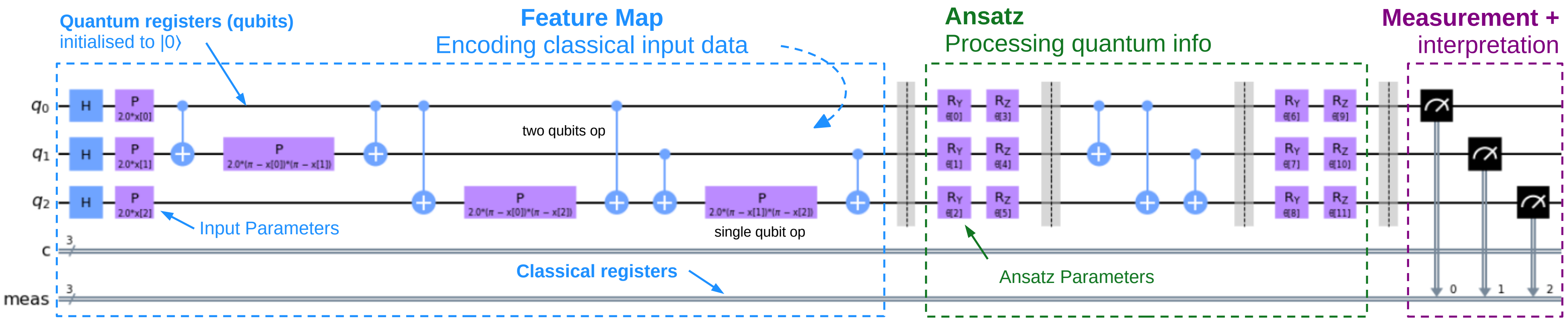
Quantum Algorithms / Models
Parameterised Circuit Templates

- Quantum algorithms are conveniently represented by quantum circuits, which map inputs into outputs, and consist of: *qubits* (or registers) + *operations* (or gates) + *measurements*.
- Circuits are static with all data and operations hard-coded.
- Circuit execution on a quantum machine or a simulator returns a "random" result from a precisely defined statistical distribution.
- When we execute the same circuit multiple times, we need to study distribution of possible results to gain insights.
- When we alter the circuit data, operations, their parameters, or ways to measure the circuit, we need to create a new circuit.
- So we use parameterised circuit "templates" for model training.

- A quantum circuit describes changes to the quantum model's state, and typically consists of three components:
  - ➔ *a feature map* encoding classical input data and preparing the circuit's quantum state
  - ➔ *an ansatz* responsible for quantum state changes, via multi-qubit operations (entanglements + rotations)
  - ➔ *measurements* determining the circuit's quantum state, which can then be interpreted as classical output
- To identify the best quantum model for a sample data, we train its parameters, which relies on pure quantum or hybrid quantum-classical (variational) optimisation.

Results obtained on a NISQ machine





outputs are measured as classical 0 or 1, then interpreted

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

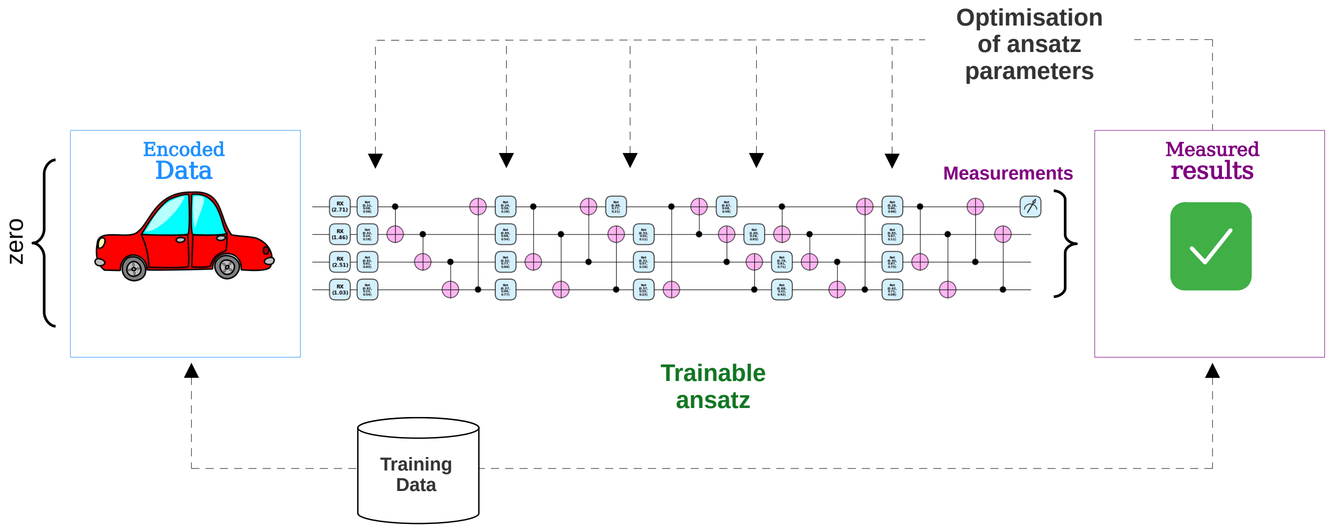
The circuit is executed

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



QC platforms / SDKs

Qiskit, PennyLane, Cirq, Yao, ...

- **Other Platforms / Q-SDKs**
  Classiq / Classiq, Forest / Rigetti, Ocean / D-Wave, Quantum Development Kit with Q# / Microsoft, cuQuantum / Nvidia, t|ket> / CQC, Qrystal / Quantum Brilliance, ...

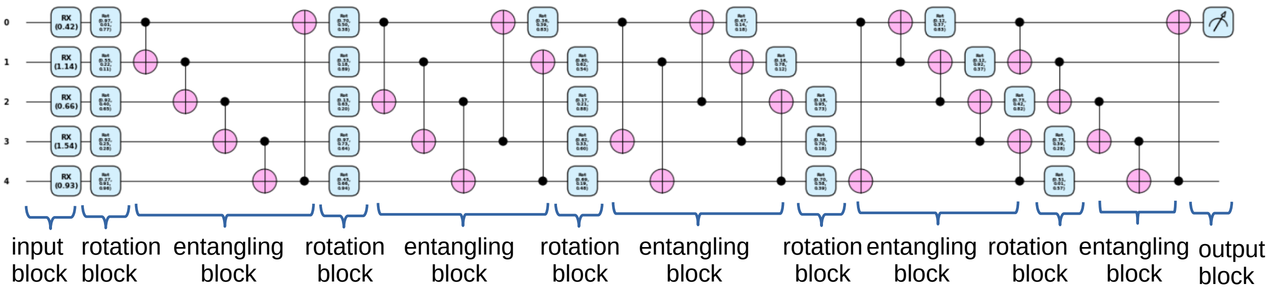
- **Qiskit** (OS)
  - **Location:** USA
  - **Language:** Python
  - **Company:** IBM Research
  - **Backends:** IBM, AQT, IQM, Rigetti, Quantinuum
  - **Models:** VQC, VQR, QNN, QCNN, QSVM, QGAN, Q Kernels, VQE, VQLS, QFT, QAOA
  - **ML SDK:** Scipy, PyTorch, Tensorflow
  - **Apps:** QML, Finance, Optimization, Nature

- **PennyLane** (OS)
  - **Location:** Canada
  - **Language:** Python
  - **Company:** Xanadu
  - **Backends:** Xanadu, AQT, IonQ, Rigetti, Honeywell
  - **Models:** QNN, Q Kernels, QFT, QAOA ...
  - **ML SDK:** PyTorch, Tensorflow
  - **Apps:** QML. Optimization, Chemistry

- **Cirq** (OS)
  - **Location:** USA
  - **Language:** Python
  - **Company:** Google Quantum AI
  - **Backends:** Google, AQT, IonQ, Pasqal, Rigetti
  - **Models:** VQE, QAOA, via TF Quantum (QNN, QCNN, QRNN, QGNN, QGAN, QRL, Q kernels)
  - **ML SDK:** PyTorch, Tensorflow
  - **Apps:** QML, Chem, Materials, Comms, Metrology

- **Yao** (OS)
  - **Location:** China / Taiwan
  - **Language:** Julia
  - **Company:** QuantumBFS
  - **Backends:** Simulators, via Python
  - **Models:** VQE, many others via Julia (Flux)
  - **ML SDK:** via Julia/Python (scipy, sklearn, Tensorflow)
  - **Apps:** Via Julia (QML, AI, Optimization, Physics, Chemistry, Biology, Earth, Finance, Robotics)

Small example:
Estimate diabetes progression one year after baseline



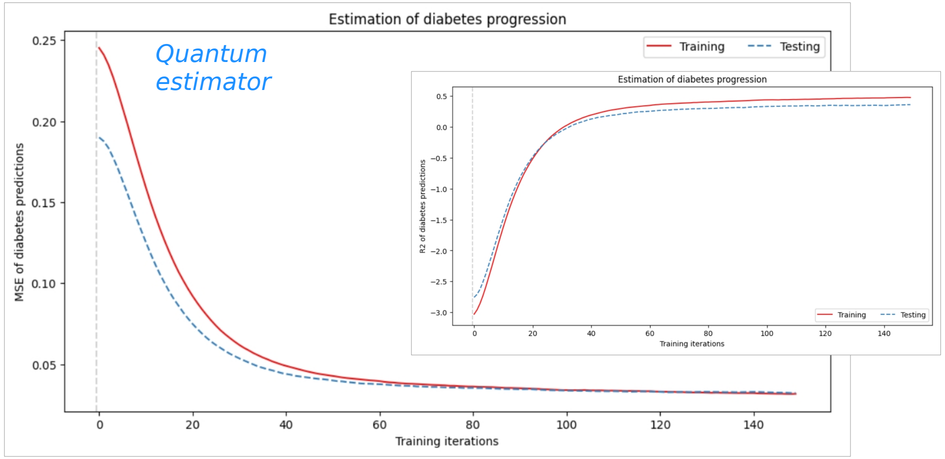
Which estimator is better?
Which could still improve?

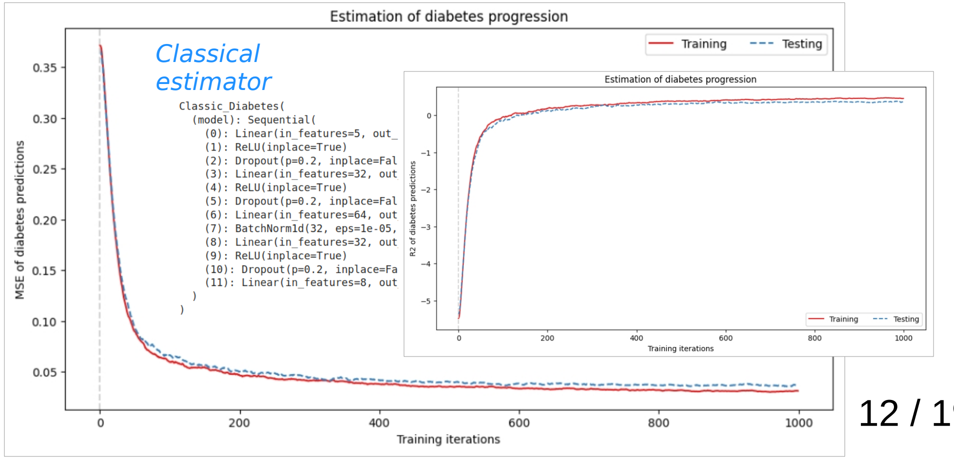
Would this change if we were running the model training on a quantum machine?

```
Model training started

  0 (000024 sec): Loss 0.2452   R2 -3.0295
  7 (000189 sec): Loss 0.0971   R2 -0.5967
 14 (000354 sec): Loss 0.0596   R2 0.0204
 21 (000519 sec): Loss 0.0499   R2 0.1802
 28 (000684 sec): Loss 0.0455   R2 0.2517
 35 (000848 sec): Loss 0.0421   R2 0.3077
 42 (001013 sec): Loss 0.0404   R2 0.3354
 49 (001178 sec): Loss 0.0388   R2 0.3618
 56 (001343 sec): Loss 0.0385   R2 0.3669
 63 (001507 sec): Loss 0.0371   R2 0.3904
 70 (001671 sec): Loss 0.0359   R2 0.4102
 77 (001835 sec): Loss 0.0347   R2 0.4293
 84 (002000 sec): Loss 0.0349   R2 0.4261
 91 (002164 sec): Loss 0.0343   R2 0.4368
 98 (002329 sec): Loss 0.0329   R2 0.4586
105 (002493 sec): Loss 0.0324   R2 0.4673
112 (002657 sec): Loss 0.0333   R2 0.4525
119 (002822 sec): Loss 0.0313   R2 0.4859
126 (002986 sec): Loss 0.0312   R2 0.4870
133 (003151 sec): Loss 0.0316   R2 0.4811
140 (003315 sec): Loss 0.0321   R2 0.4727
147 (003479 sec): Loss 0.0308   R2 0.4935

Total training time: 3526s (00:58:46)
```

```
devices = cpu + lightning.qubit
samples = 296, features = 5, params = 75, epochs = 150
training: cost = 0.0306 @ 0141, r2 = 0.4977 @ 0141
testing:  cost = 0.0309 @ 0148, r2 = 0.3891 @ 0148
elapsed time = 3526sec (00:58:46)
```

```
device = cpu
samples = 296, features = 5, params = 4721, epochs = 1000
training: cost = 0.0278 @ 0852, r2 = 0.5147 @ 0852
testing:  cost = 0.0304 @ 0980, r2 = 0.4708 @ 0980
elapsed time = 3sec (00:00:03)
```





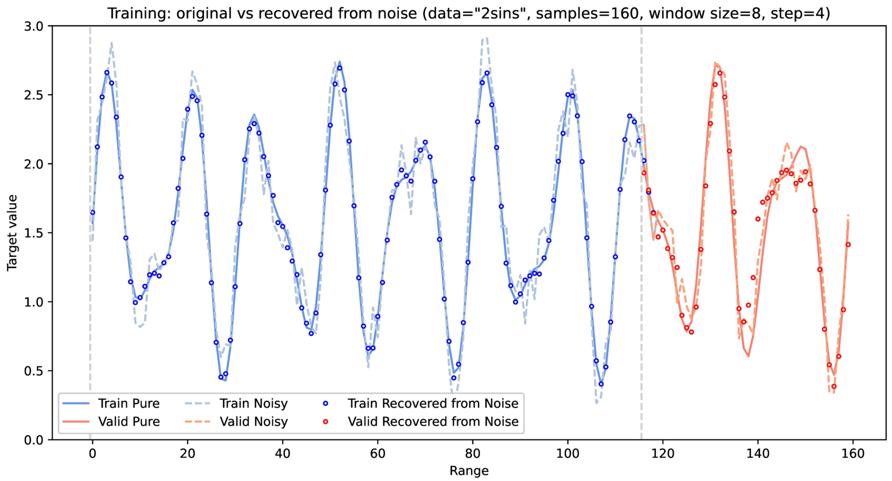
Quantum Autoencoder

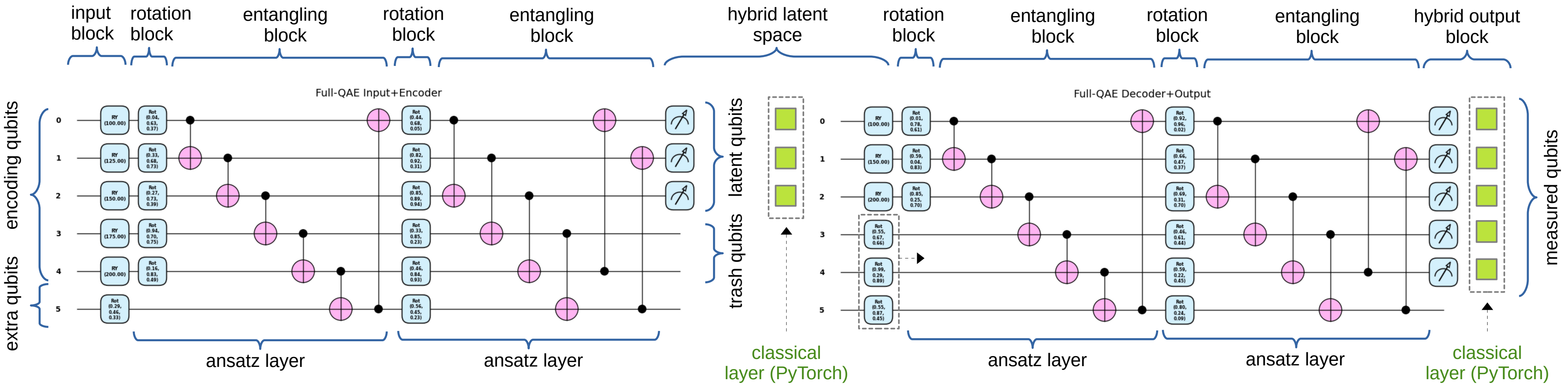
Time Series Analysis with Noise Removal

Simple problems can be solved with pure quantum methods
Complex problems require hybrid quantum-classical methods

One of Jacob's projects is development of complex quantum models (both pure and hybrid), for time series and signal analysis. The models can reduce noise, analyse and forecast temporal data, and detect complex anomaly patterns.

Potential applications and data sets include: machine condition (vibration) monitoring, astronomical observations, marketing and sales, earthquake prediction, EEG or ECG analysis, etc.





Hybrid quantum QAE TSA model for noise reduction

From the lab to the world?

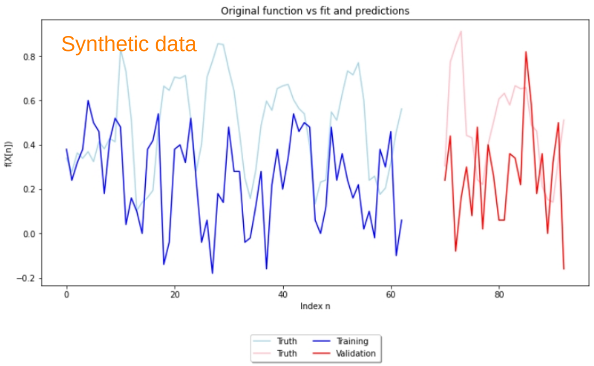
Not so fast and not so simple!

a story of a quantum model development for TS analysis:
predicting sales of beer in USA with QML

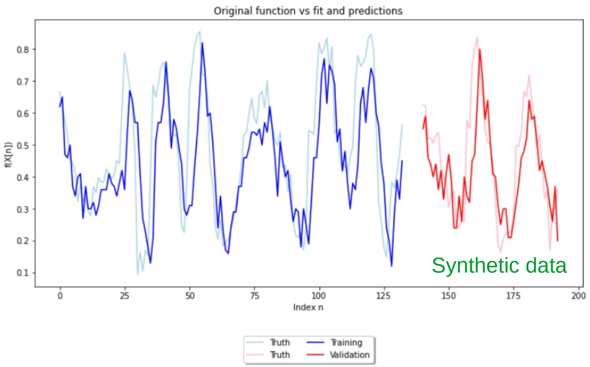
Sliding Window QNN model

Data: Synthetic
Platform: Qiskit

→ worked well for simple data sets



over 100 experiments



Sliding Window Serial Model

Data: Synthetic
Platform: Qiskit

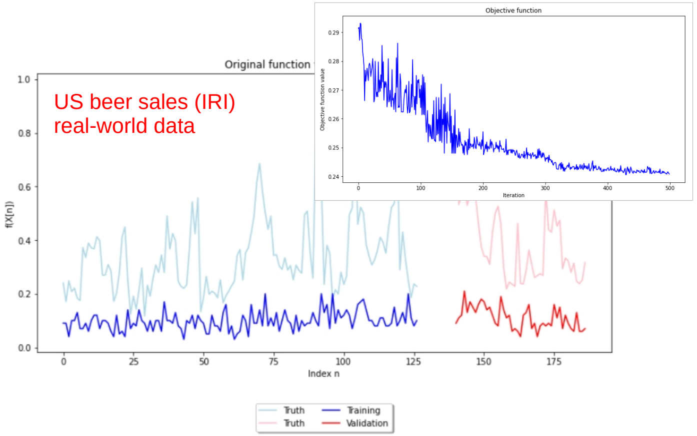
→ good prediction of both seasonality and the signal amplitude.

Ready for the real-world data?

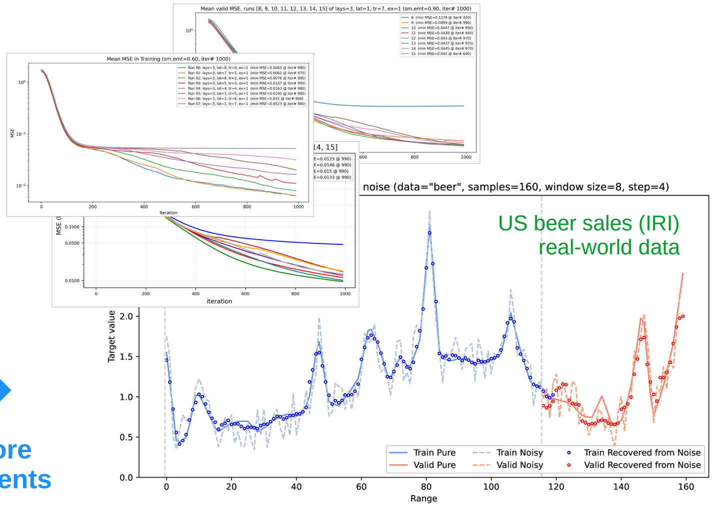
Sliding Window Serial Model

Data: Real-world
Platform: Qiskit

beer sales in USA
→ complete failure!



500 more experiments



Sliding Window Serial Model

Data: Real-world
Platform: PennyLane

500 experiments with varying parameters + changes to the model + cost fun and optimiser + changed the platform →

good prediction + noise elimination

However, all runs were on a noise-free simulator! It would change on a real NISQ machine!

Pros and Cons of

QT, QC, QML, QO, ...

QT has huge potential and its applications are extremely promising!
QT is still in its early stage of research and development.

Benefits	vs.	Challenges
QT is beautiful, as it seamlessly integrates algorithms, maths and physical phenomena	?	QT is difficult, as it is hard to conceptualise, design, develop, execute its solutions, and even understand their results
QT offers “massive parallelism” (via superposition) and “randomness” (via measurement)	?	To produce a solution, QT must remove unlikely alternatives and amplify more promising alternatives (via entanglement)
Quantum algorithms can sometimes demonstrate improvement over similar classical algorithms	?	Quantum advantage can only be demonstrated in niche application areas
There is a lot of free QT learning resources, tutorials, communities, challenges and hackathons	?	There is still an acute shortage of knowledge, skills and expertise in understanding and developing QT solutions
There has been a recent upheaval in quantum education and training of QT skills	?	QT is very complex, so a true QT expertise is still very rare, also, there is the lack of QT dev tools for non-experts
In some disciplines, QT experts have a track record of generating breakthrough applications	?	QT community often displays a “hacker culture”, which lacks discipline of testability, repeatability and quality of results
QT harnesses quantum processes at sub-atomic level to enable very efficient computational tasks	?	There are charlatans hijacking quantum concepts and applying them to non-quantum phenomena, e.g. body, mind and soul

Exercise in finding QT business value

In 5 mins, identify 2+1 examples of the potential business gain from investment in, application of, or changes to quantum technology, justify

educated guesses

two hypotheticals from the mainstream of business activity +
one which is a creative quantum tech business idea

crazy as a coconut

Discuss it with your colleague in 5 mins

Example (think how to explain / justify them)

1. Use QT to determine if a new drug ingredient could destroy AIDS virus
2. Use QT to strengthen a stock portfolio with stock-index futures

3. Place a quantum computer in deep space to save on cooling costs

Getting into Quantum Tech

You can contribute to the quantum field in many different ways, e.g.

- Work on new QT hardware
- Develop new QT algorithms
- Develop new QT software
- Create new UI to QT tools
- Develop new QT applications
- Specialise in a QT area
- Teach / promote QT
- Work in QT recruitment
- Manage a QT team ...

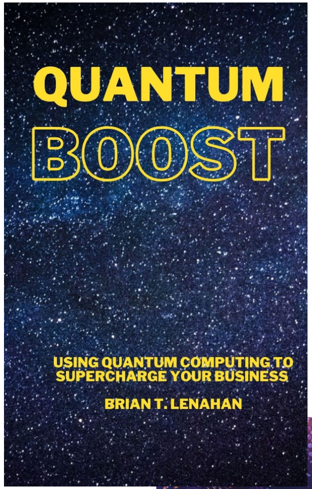
The most important trait of people in quantum tech is their enthusiasm and commitment

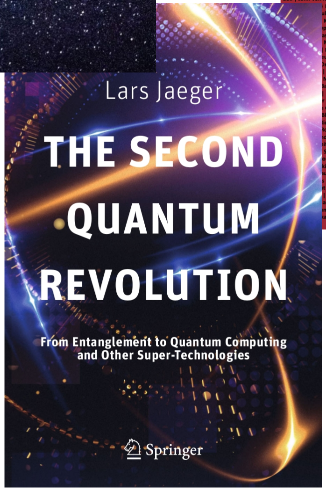
Domain	Skill/Knowledge	Naive Experiments with quantum concepts	Basic Writes simple quantum programs	Medium Takes part in quantum challenges	Advanced Has a technical job in quantum technology	Expert Other people in quantum think they are super
Mathematics	Complex Numbers	✔	✔	✔✔	✔✔	✔✔
	Linear Algebra		✔	✔✔	✔✔	✔✔✔
	Calculus			✔	✔✔	✔✔✔
	Differential Equations				✔	✔✔
	Partial Differential Eqs				✔	✔✔
	Fourier Transforms				✔	✔
	Probability Theory	✔	✔	✔✔	✔✔	✔✔
	Statistics	✔	✔	✔	✔✔	✔✔
Data Science	Programming (Python)		✔	✔✔	✔✔	✔✔
	Optimisation Techniques			✔✔	✔✔	✔✔
	Machine Learning			✔✔	✔✔	✔✔
Quantum Computing	Foundations (Bell State)	✔	✔	✔✔	✔✔✔	✔✔✔
	Circuits, Qubits, Gates, Bloch Sphere	✔	✔	✔✔	✔✔✔	✔✔✔
	Quantum Circuit Simulators	✔	✔	✔	✔✔	✔✔
	Circuit Execution	✔	✔	✔✔	✔✔✔	✔✔✔
	Results Interpretation / Visualisation	✔	✔	✔✔	✔✔✔	✔✔✔
	Algorithms (Grover, Shor, …)		✔	✔✔	✔✔✔	✔✔✔
	Simple Error Mitigation		✔	✔✔	✔✔✔	✔✔✔
Quantum Machine Learning	Variational Quantum Algorithms			✔	✔✔	✔✔✔
	Data Encoding			✔	✔✔	✔✔✔
	Result Interpretation			✔	✔✔	✔✔✔
	Quantum Optimisation			✔	✔✔	✔✔✔
	Quantum Linear Models			✔	✔✔	✔✔✔
	Quantum Neural Networks			✔	✔✔	✔✔✔
	Quantum Kernel Methods			✔	✔✔	✔✔✔
	Quantum Probabilistic Models				✔	✔✔
	Quantum Annealing				✔	✔✔
Quantum Hardware	Configuration				✔	✔✔
	Calibration			✔	✔	✔✔
	Complex Error Mitigation			✔	✔	✔✔

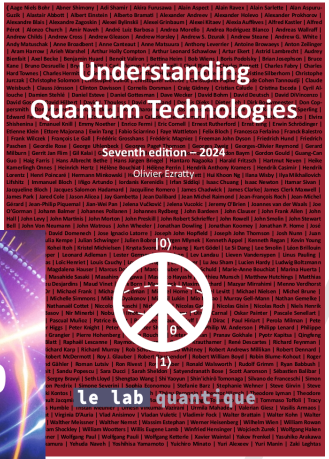
Ready to dive into QT?

→ QC, Quantum Maths, QML and QO

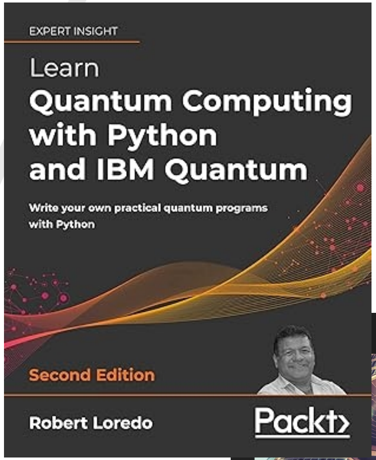
1. Develop some intuition about quantum technology

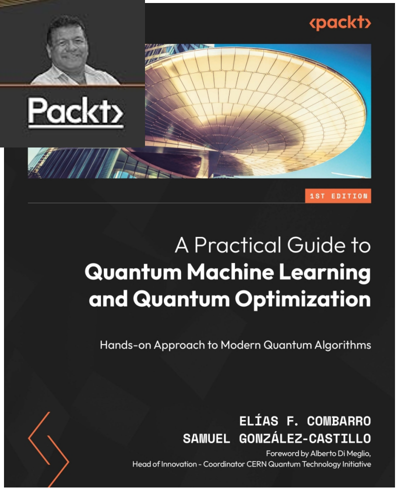




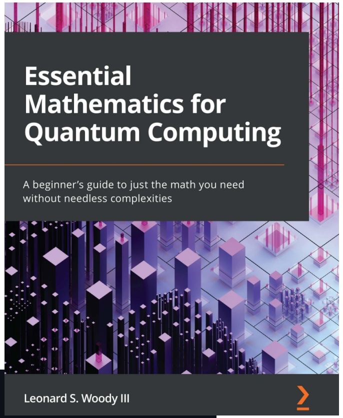


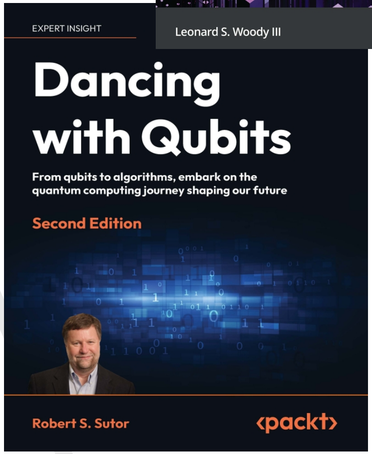
2. Get your hands dirty by using some readily available quantum simulators and machines





3. Understand some mathematics needed to master quantum computing





4. Only then move to more advanced topics and theory, some you would have already glimpsed, e.g. QML and QO

Thank you!

Any questions?

Photos from Unsplash
Enquanted is being somewhere in-between Enchanted and Entangled