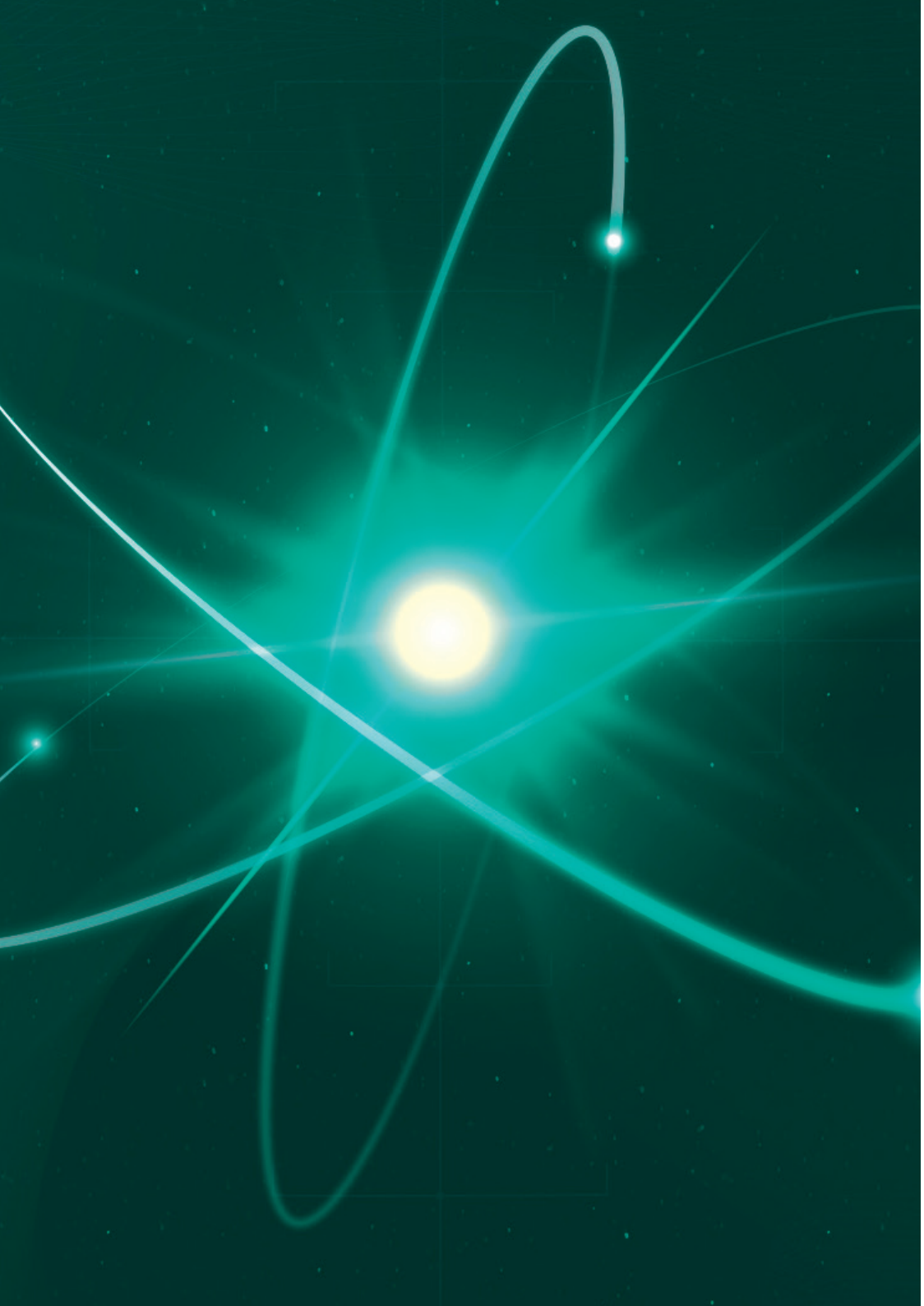
Hybrid Quantum Computing

Business White Paper

How hybrid quantum computing creates business benefits today

By Terra Quantum AG

May, 2022



Why quantum?

Quantum computing will trigger a transformation of almost every industry within the next ten years, with the automotive, logistics, finance, pharma, energy and chemical industries amongst the most positively impacted.

Quantum computing has the potential to help humankind overcome technological limitations in solving our greatest challenges in business and society, including improved energy efficiencies through optimal grid management, rapid acceleration of the drug discovery process, and improved prediction and simulation of complex systems like weather patterns. Hybridisation of quantum and classical high-performance computing technology is rapidly evolving. This enables us to address industrially relevant applications today.

The challenge

At this point in time, we are still facing limitations regarding the capabilities of native quantum hardware. Even though we see rapidly maturing quantum hardware and impressive progress in this space, the purely quantum hardware of today is incapable of solving large-scale industry applications on its own. This results in both science and engineering challenges: best utilising and isolating quantum effects and building systems that can leverage these for computation.

Quantum is now

Hybrid quantum computing is the key to unlocking business benefits, utilising this new technology innovation today. Our approach with the QMware hybrid quantum cloud combined with our proprietary hybrid quantum algorithm libraries, harnesses the best of quantum and classical computing to solve real-world problems.

Following this approach, we have identified 50+ opportunities across industries that will benefit in the areas of optimisation, machine learning and simulation, helping organisations innovate faster, increase profitability and create more efficiency.
Our hybrid approach is modular. Hence, when native QPUs mature sufficiently, we can plug these devices into the back end of the QMware system and seamlessly transition to the latest hardware without needing to make changes to the quantum application.

In this publication, we outline the opportunity for business executives to adopt hybrid quantum computing and create strategic advantages in their industries today. Our hybrid quantum algorithms executed on the hybrid quantum cloud QMware can:

- Generate business advantages by solving real-world problems in the areas of optimisation, machine learning and simulation
- Combine the best of classical and quantum hardware in one integrated platform
- Seamlessly harness the power of improved quantum processors as they mature
- Ensure that our partners and clients do not need to bet on a certain type of quantum hardware or a particular hardware player

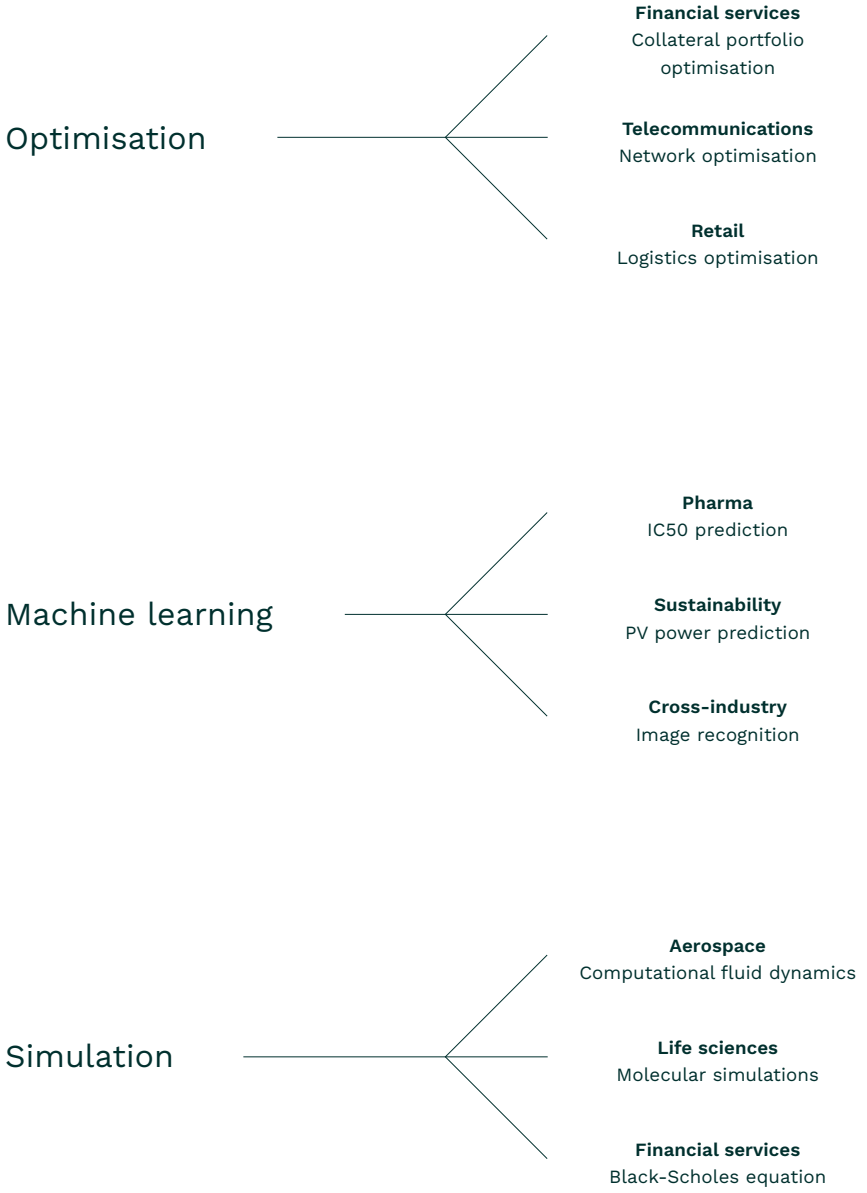
Application areas and industry-specific advantages

We have focused on and identified a use case portfolio of 50+ opportunities across industries that will benefit from hybrid quantum computing today. These industries include financial services, logistics, automotive, life sciences, and logistics.

Using our unique approach, we deliver solutions to clients that outperform their existing approaches to solving their problems. This creates a significant and measurable impact on their business.

Our hybrid quantum approach enables clients to generate business value, but also be perfectly positioned to harness the full power of future quantum computers as they evolve.

To make our areas of capability more tangible, we have broken down our areas of expertise into three categories where we can deliver business advantages for our clients: optimisation, machine learning and simulation.



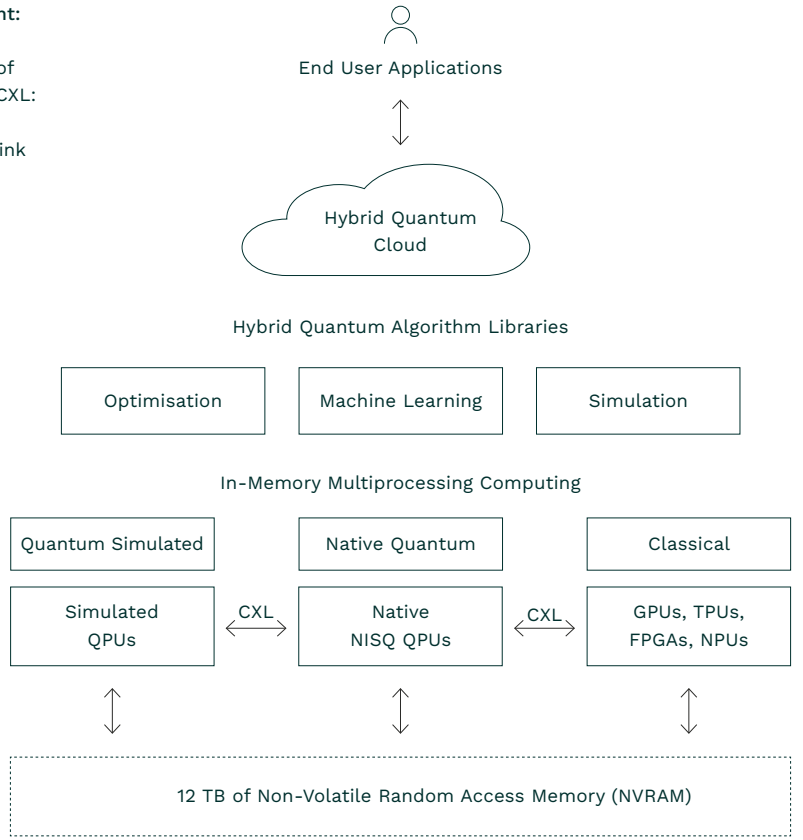
QMware cloud allows hybrid quantum software applications to be executed on a combination of classical and quantum hardware

Terra Quantum leverages the QMware cloud for its hybrid quantum computing approach. The unique architecture provides a clear advantage to competitive solutions, offering a fully integrated platform with a shared memory structure. This means, high-performance and quantum computing processes work – literally - in parallel. Hybrid quantum software applications executed on the QMware cloud are able to access the best classical computing resources (HPC, GPU, etc.), simulated QPUs, emulations of connected physical QPUs for utilising shared memory, as well as various types of native QPUs (e.g. superconducting, trapped ion, etc.) seamlessly, without requiring amendments at the application level.

Parts of the applications will be executed by classical computing systems, while more complex parts will be executed on quantum systems. To address large-scale industrial applications, Terra Quantum also utilises 40 simulated qubits. These qubits are error-free and fully interconnected, enabling a better performance than the marketplace of quantum computing hardware can offer at this point in time.

For customers, the open cloud architecture contains another strategic advantage: the set-up invites third-party vendors to join the platform and integrate their own quantum hardware. In this way, customers are provided with the flexibility and strategic decision to collaborate with a hardware vendor of their choice.
As a result, customers will be able to develop and deploy hybrid quantum applications to solve real-world problems, creating business advantages while also harnessing the best native quantum hardware.

Figure right: High level overview of QMware. CXL: Compute Express Link



Our optimisation algorithms deliver faster and more accurate results

Optimisation problems are ubiquitous across most industries. From portfolio optimisation and optimising the supply chain to inventory management and traffic routing.

Terra Quantum has developed a unique approach that will solve this kind of complex data processing faster than classical approaches and also delivers better – in terms of being globally optimal – answers that classical approaches are not able to find. Terra Quantum's proprietary quantum encoding algorithm can be applied to a wide range of optimisation problems in various industries.

One example is optimising the packing of goods within shipping containers: a logistics company needs to maximise the amount of goods that can be packed, while considering constraints such as weight limitations and placement direction for each package. This is such a complex computing challenge that currently shipping containers are only 65% utilised on average. For a large shipping organisation that transports about 13 million containers a year, each 1% improvement in capacity utilisation will deliver its customers $429 million in annual savings.

In particular, value can be created through:

1. Solving complex optimisation problems faster (enabling faster decision making)

2. Finding improved solutions to complex optimisation problems

The various classes of optimisation problems can be categorised as follows:

- **Discrete optimisation** – finding a configuration of a discrete set of variables such that they optimise an objective function, given a set of constraints

- **Continuous optimisation** – where the variables used in the objective function are chosen from a set of real values between which there are no gaps

- **Black-box optimisation** – problems where the structure of the objective function and / or the allowable constraints are unknown

Technical deep dive

Many discrete optimisation problems in particular are considered NP-hard, which means that the exact solution cannot be found in polynomial time, using classical computing technologies. These types of problems are usually solved using approximation solutions today, which means that there is room for improvement in the solution.

There have been attempts to solve discrete optimisation challenges on noisy intermediate scale quantum (NISQ) computers and quantum annealers. Approaches using these techniques typically require a larger number of high-quality (noise-free) qubits than are available in the systems today, to be able to solve large-scale problems.

Using our unique quantum encoding algorithm we utilise hardware-efficient ansatz and amplitude encoding schemes to enable us to solve large-scale optimisation problems with an exponentially smaller number of qubits. We execute this algorithm on our QMware platform to produce results that are often superior to the high-end commercially used solvers today.

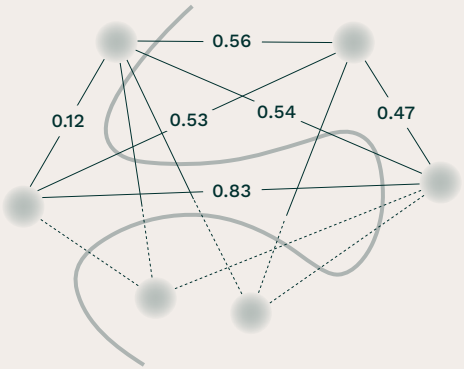
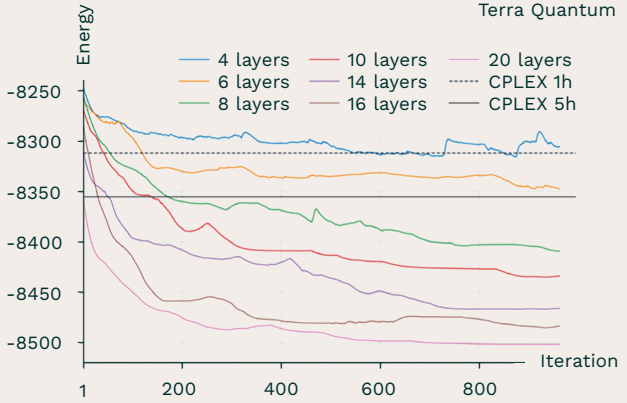
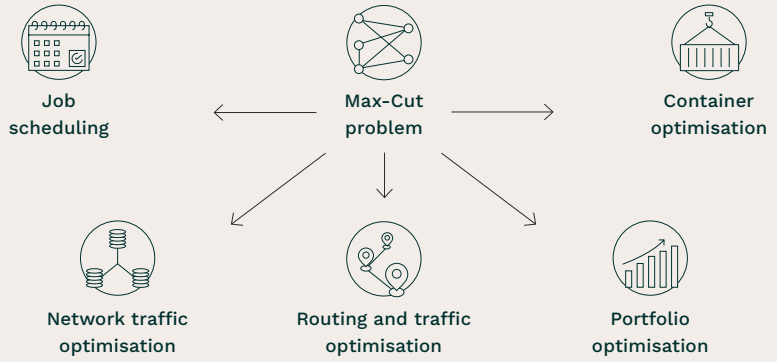


Figure right:
An example of this, applied to the fully connected weighted 256 node Max-Cut problem.

Figure right:
Results for the Max-Cut optimisation problem, compared against a classical solver



In addition to enhancing discrete optimisation, we are also able to enhance continuous and black-box optimisation challenges through our use of tensor networks. More details about our tensor networks approach are given in the simulation section.



Solving the Max-Cut problem allows us to solve real-world challenges. We have the **core algorithm ready for application**, which we can adapt for the specific business needs.

Our machine learning algorithms enable higher efficiency in training and prediction accuracy

Machine learning models represent another complex computing challenge in which hybrid quantum computing excels.

Basically, the task here is to teach a system to predict a certain outcome, in order to enable decision-making. For example, Terra Quantum's machine learning algorithm was utilised to make a prediction of house prices in Boston based on characteristics such as number of rooms, location and owner income. Compared to a classical neural network, there is an improvement in prediction of up to 10%. This helps financial institutions better understand the true value of assets on their balance sheets, like mortgages. The capability improves forecast quality and enables more prudent credit decisions.

Our hybrid quantum-classical techniques have the ability to significantly enhance machine learning applications which have become commonplace in business and society. We can enhance machine learning applications by:

1. Enabling higher efficiency in training (requiring fewer iterations and smaller datasets)

2. Enabling higher prediction accuracy

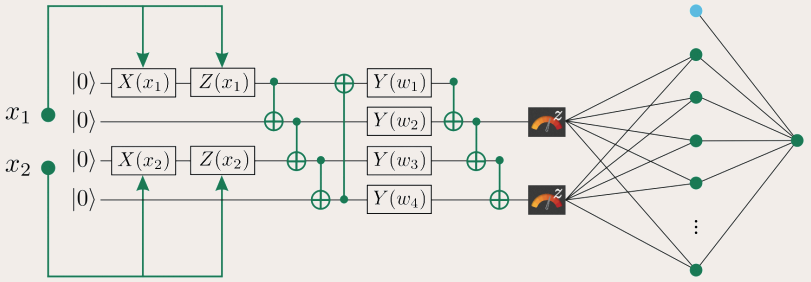
An example of two areas of machine learning where our techniques can have a significant impact:

- **Classification** – predictive modelling problems where a class label (category) is predicted for a given example of input data.

- **Regression** – a technique for investigating the relationship between independent variables or features and a dependent variable or outcome.

Technical deep dive

The crux of our machine learning techniques is to combine quantum layers with classical layers to form hybrid neural networks. In the classification example below, we utilise a hybrid quantum-classical multi-layered perceptron and compare the performance against a purely classical multi-layer perceptron. In the example below, the hybrid quantum-classical approach demonstrated improved classification accuracy and this advantage continued to grow as the dataset decreased in size.



Hybrid quantum-classical multilayer perceptron

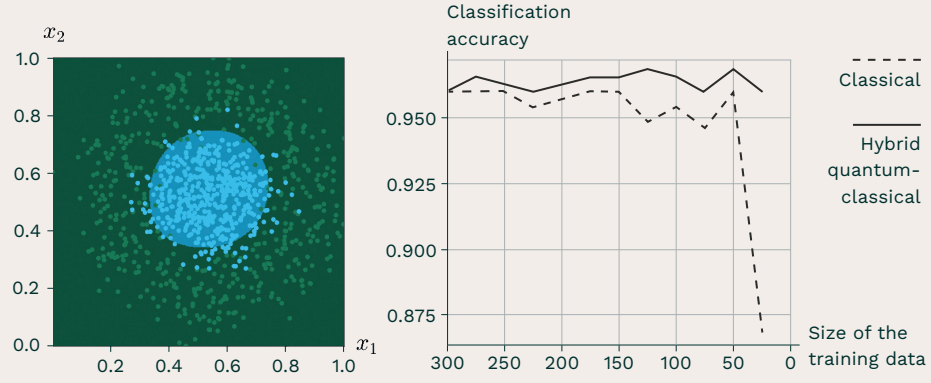
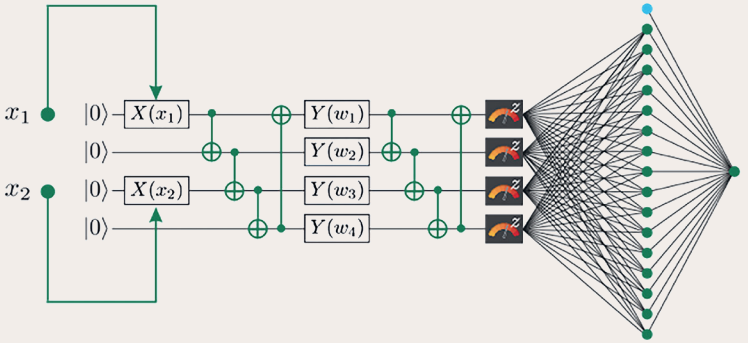


Figure above: Hybrid quantum-classical approach for a classification problem and the results



Hybrid quantum-classical multilayer perceptron

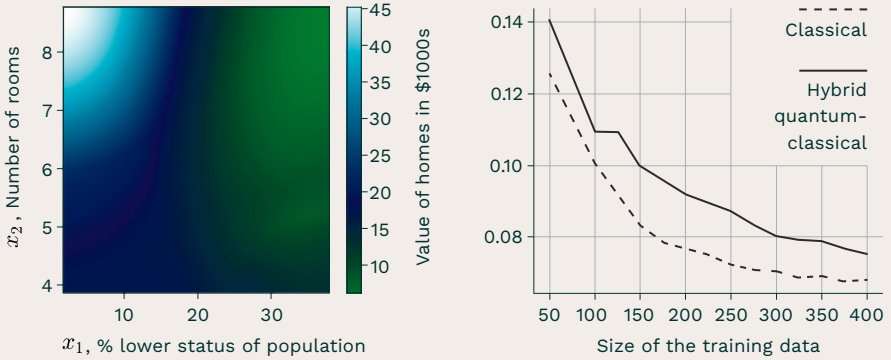


Figure above: Hybrid quantum-classical approach for a regression problem and the results

In the regression example above, we utilised house features to make predictions for house prices. We utilised data from the publicly available Boston House Pricing dataset. In this case, we created a hybrid neural network by replacing the first classical layer with a quantum variational layer. Here, you can see the reduced test losses (which equate to improved prediction). This advantage persists through various sizes of datasets.

Our simulation algorithms create an exponential speed-up using tensor networks

When simulating molecules, quantum computing can address this complex computing challenge in an unprecedented way, being a quantum system itself. Improvements in the speed and accuracy of simulations can yield significant benefits for many industrial applications that assess risk or need to understand the behaviour of complex systems that cannot be easily described through analytical functions: e.g. exploring a new vaccine for life sciences or determining computational fluid dynamics in the aerospace Industry.

Terra Quantum addresses simulation tasks with proprietary quantum simulation algorithms. One of the them utilises quantum-inspired tensor networks, a class of variational wave functions, first introduced in quantum physics for multiparticle system analysis. These tensor networks closely represent the quantum circuits architecture, which makes them an efficient tool for complex simulations such as Monte Carlo analysis. Applying this method, Terra Quantum can unlock an exponential speed-up simulating complex systems. This white paper shows a speed-up of 100 times or more for large problem sizes. Computational fluid dynamics simulati-ons, a computing process to enhance the aerodynamic design of vehicles, currently take days or even weeks.

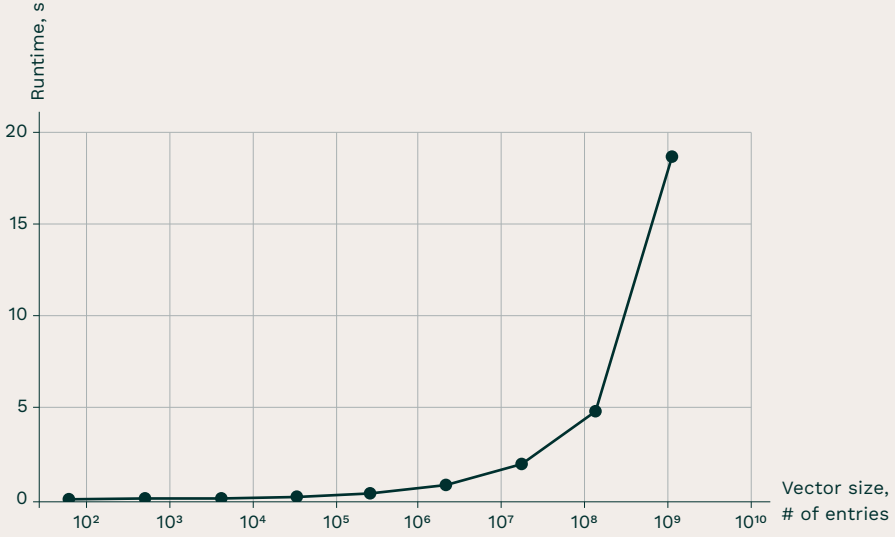
With Terra Quantum’s approach, such simulations can be run in an hour or even less. This can enable very significant reduction in design cycle times and be transformative for the pace of new product and component design.

Technical deep dive

Many of these systems depend on solving partial differential equations. One method we employ for solving partial differential equations is using tensor networks.

Tensor networks were first introduced in quantum physics for multiparticle system analysis. These tensor networks closely represent quantum circuits architecture, which makes them an efficient tool for low-entangled quantum computer virtualisation and simulation of certain physical systems.

In the example below, we compare the tensor networks method of the Poisson equation that is widely used in electromagnetic simulations and heat transfer analysis (a partial differential equation) with the conjugate gradient method. Here, we can see the exponential speed-up that is unlocked through this method.



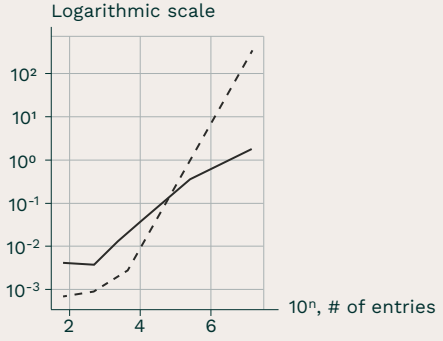
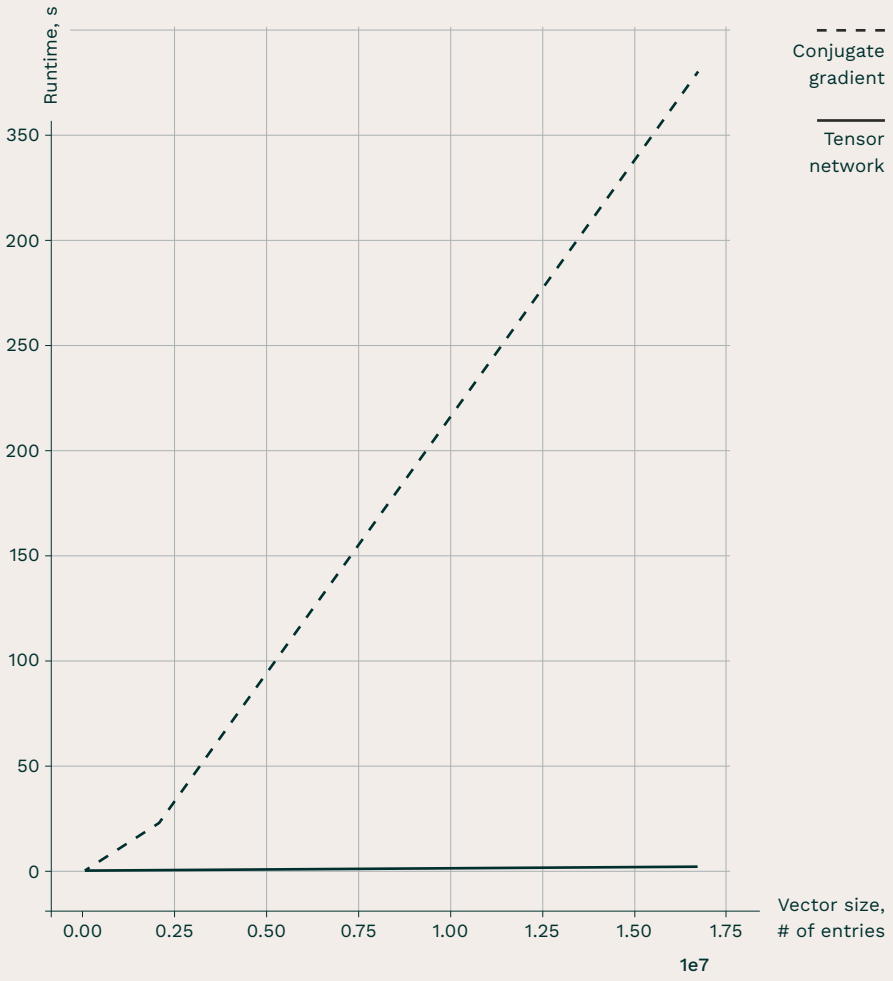


Figure left and above: Exponential speed-up for simulation problems



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