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(Some) efforts towards application-driven benchmarks in Germany

PD Dr. habil. Jeanette Miriam Lorenz
11.05.2023

Airbus Quantum Computing Challenge

Bringing flight physics into the Quantum Era

ZEIT ONLINE

Suche

Politik Gesellschaft Wirtschaft Kultur Wissen Gesundheit **Digital** Campus Arbeit Sport ZEITmagazin mehr

Technologie

Bund investiert zwei Milliarden Euro für Quantencomputer

Innerhalb von fünf Jahren soll in Deutschland ein Quantencomputer entstehen. Mithilfe von Qubits erzielt die Technologie weit höhere Leistungen als herkömmliche Rechner.

11. Mai 2021, 11:29 Uhr / Quelle: ZEIT ONLINE, dpa, kzi /

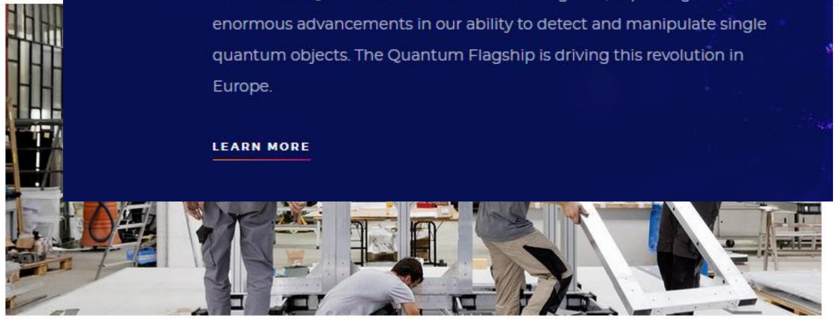
QUANTUM FLAGSHIP

Discover

The future is Quantum.

The Second Quantum Revolution is unfolding now, exploiting the enormous advancements in our ability to detect and manipulate single quantum objects. The Quantum Flagship is driving this revolution in Europe.

LEARN MORE



Computertechnologie

Ein Quantensprung für Deutschland?

Stand: 15.06.2021 18:25 Uhr

In Ehningen bei Stuttgart wurde Europas erster Quantencomputer eingeweiht. Der ultraschnelle Rechner der Firma IBM soll der Wirtschaft helfen, im Wettstreit mit China und den USA zu bestehen.

Von Michael Herr, SWR

Das "Wunderwerk der Technologie", wie Angela Merkel es nannte, ist wuchtig: Immerhin eine Grundfläche von drei mal drei Metern bei einer Höhe von drei Metern soll der Quantencomputer haben, den IBM zusammen mit der Fraunhofer-Gesellschaft am Dienstag in der Deutschland-Zentrale des IT-Konzerns in Ehningen bei Stuttgart der Öffentlichkeit präsentiert hat. Der laut IBM "leistungsstärkste Quantencomputer im industriellen Umfeld

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Emerging technology:
Quantum computing

Quantum computing (QC) has the potential to lead to disruptive changes in many industrial areas:

- **Simulation** of quantum mechanical systems
  - (Development of new drugs, chemical sector with battery development,…)
- **Optimization** problems (Logistics, production, pharma,…)
- **Quantum machine learning** (Computer vision, mobility,…)

But for which applications will QC really offer an advantage in practise?

→ Application-driven benchmarking procedure required!

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One example: Hybrid QCCNN for radiological classification tasks

Bay QS

Gefördert durch
Bayerisches Staatsministerium für Wirtschaft, Landesentwicklung und Energie

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Reliable QC-assisted AI for medical classification tasks

Context: Artificial intelligence increases in importance in the medical diagnosis process (e.g. in imaging).

Challenges: Image data is expensive, complex and only available in small numbers (10^2 -10^3),

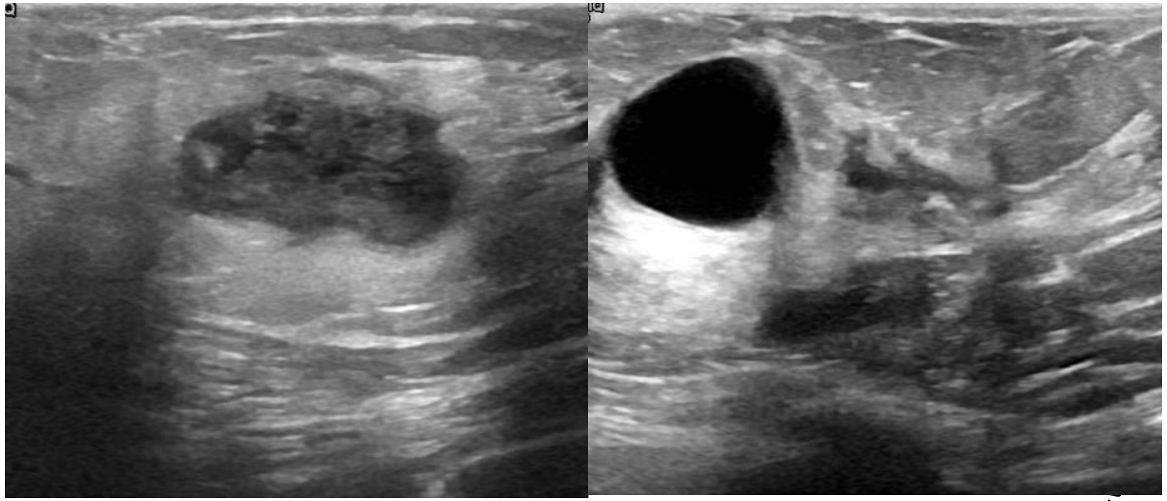
The decision process needs to be comprehensible and reliable.

→ Classical methods need large training datasets.

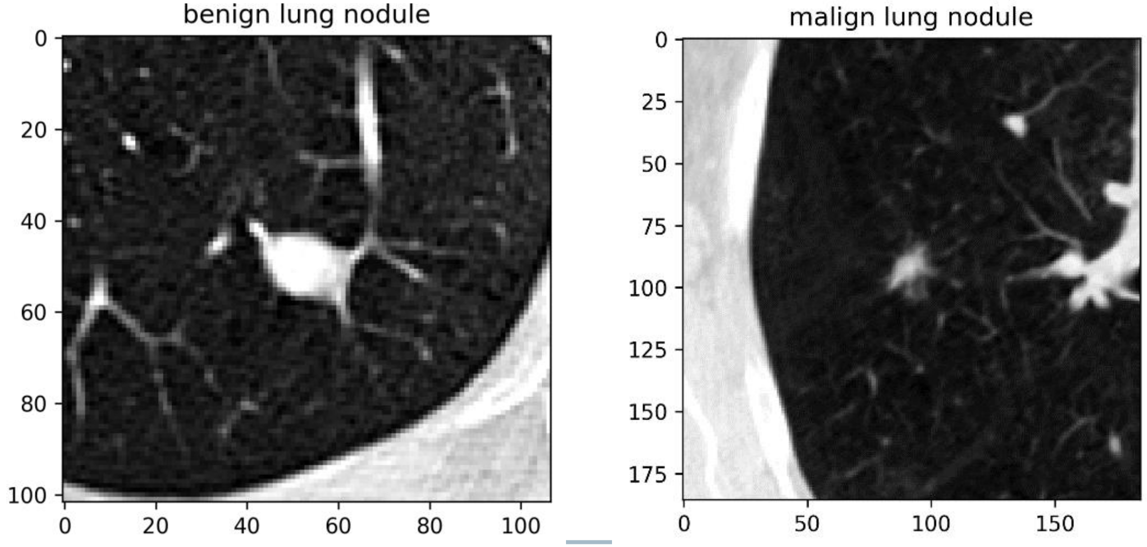
Target: Improvement of the medical classification tasks via hybrid, quantum computing-assisted machine learning methods.

Expected improvement: QC-assisted methods might result into a faster training of the algorithms - in particular in situations with little training data

Malign breast lesion **Benign breast lesion**



Source: W. Al-Dhabyani, et al, "Dataset of breast ultrasound images". Data Brief, vol 28, pp 104863, 2020



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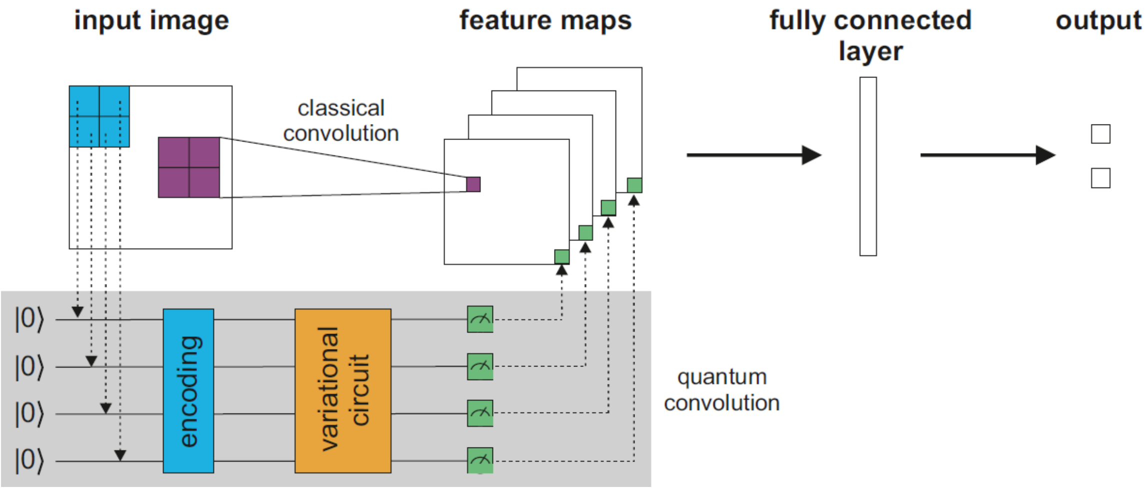
Hybrid quantum-classical convolutional neural networks

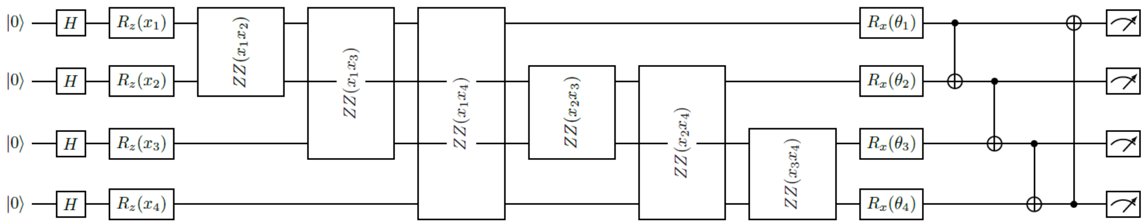
Convolutional neural networks very successful in image classification tasks.

Improvement: Hybrid quantum(-classical) convolutional neural networks promise to be better suited for situations with little training data, potentially leading to a more precise and faster training convergence.

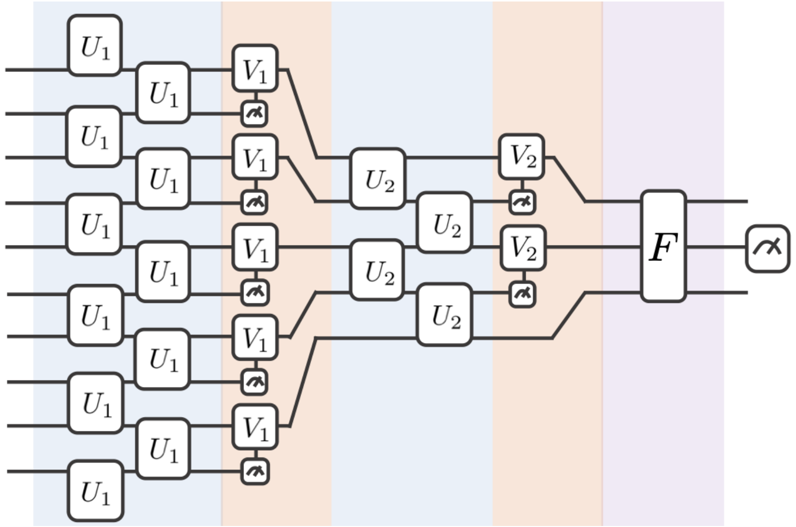
Idea: Replace some of the classical convolutional layers by quantum convolutional layers – also replacement of pooling layers would be possible.

Hybrid ansatz, since only a few classical layers replaced → also possible to execute on the current or soon-available NISQ quantum computers.





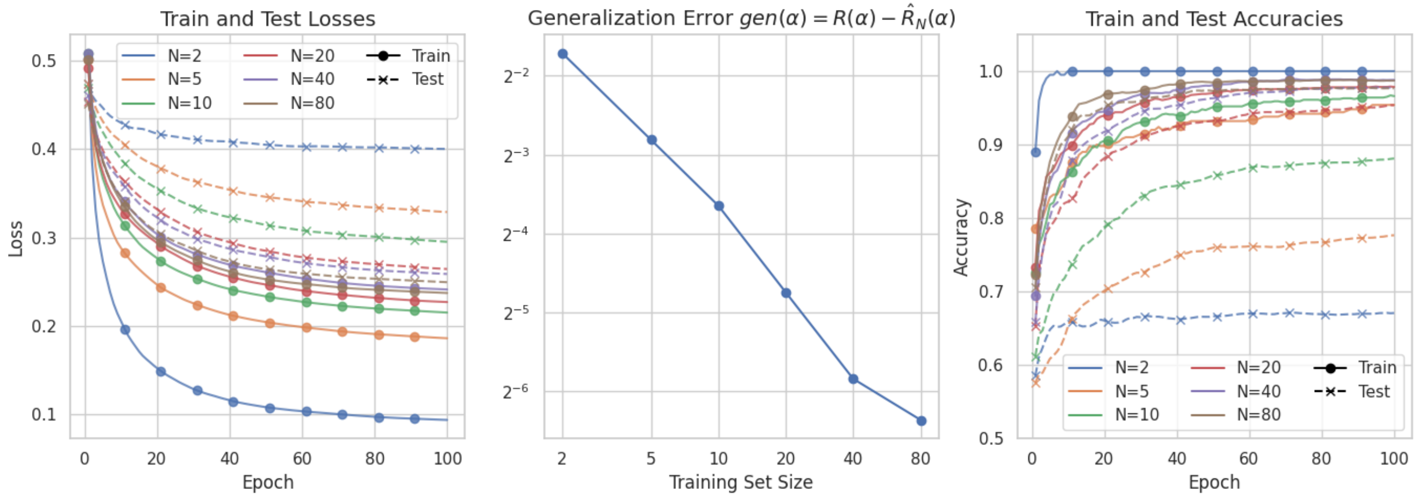
Generalization with less data



The **generalization error** is given by the difference between the expected true loss of a (Q)ML model and the average loss over the training dataset: $gen(\alpha) = R(\alpha) - \hat{R}_S(\alpha)$

Specifically for QCNN particularly favorable: $gen(\alpha) \sim O\left(\sqrt{\frac{T \log MT}{N}}\right)$

for T parametrized local quantum channels, M gates and N the training set size



Sources:

- Iris Cong, Soonwon Choi, Mikhail D. Lukin. "Quantum Convolutional Neural Networks" arxiv:1810.03787, 2018.
- Matthias C. Caro, Hsin-Yuan Huang, M. Cerezo, Kunal Sharma, Andrew Sornborger, Lukasz Cincio, Patrick J. Coles. "Generalization in quantum machine learning from few training data" arxiv:2111.05292, 2021.
- Korbinian Kottmann, Luis Mantilla Calderon, Maurice Weber, Generalization in QML from few training data, Pennylane demonstration, https://pennylane.ai/qml/demos/tutorial_learning_few_data.html

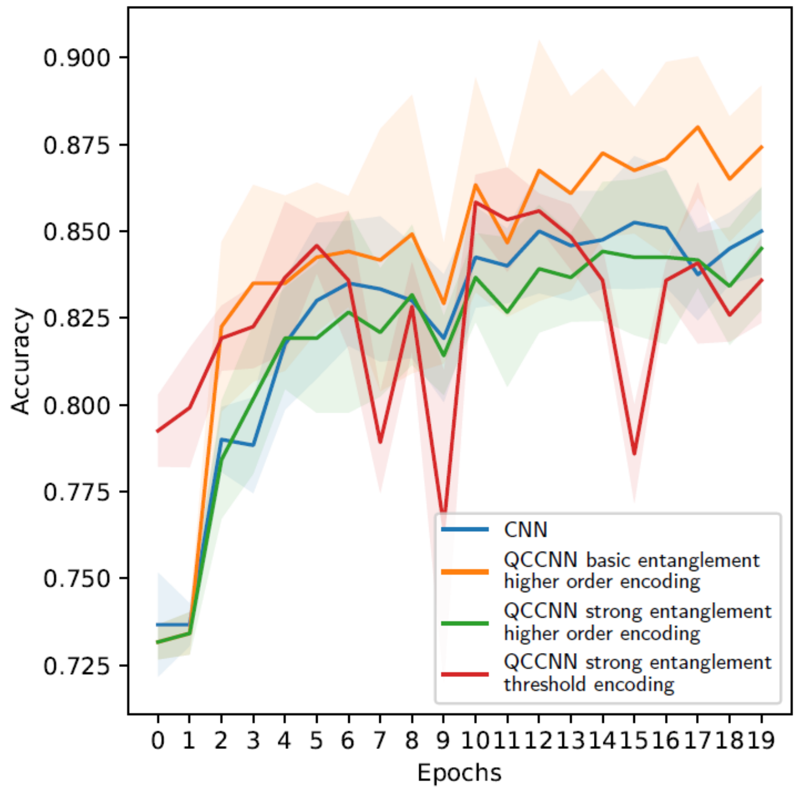
QCCNN: Results and benefits

‚Faster' training convergence:
In comparison to classical CNNs, QCCNNs may reach a better or similar performance while using less training parameters and/or training iterations

Less training data required
Theoretical findings indicate that general QCCNs are able to reach a good performance also when only small training data is available – situations in which classical methods might fail

A QCCNN is a hybrid algorithm
The algorithm consists on parts running on classical computers and of parts running on quantum computers in an interaction between both systems → current small quantum computers are already (almost) able to run these algorithms

Only small parts of the input data is processed at the same time
Data encoding into quantum computers is already possible with present quantum hardware



Paper: A. Matic, M. Monnet, J. M. Lorenz, B. Schachtner, T. Messerer, Quantum-classical convolutional neural networks in radiological image classification, arXiv:2204.12390 [quant-ph], https://ieeexplore.ieee.org/document/9951255

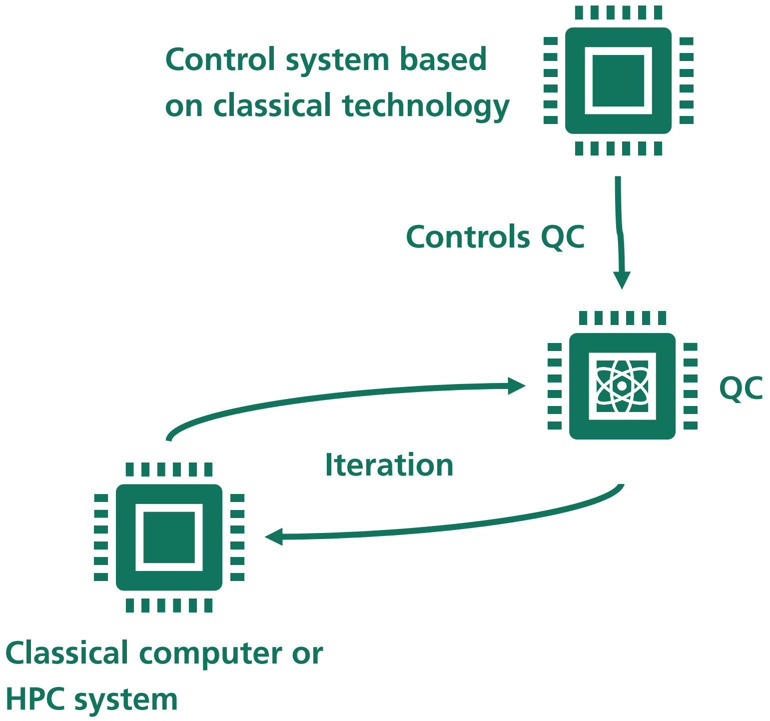
Considerations for QC hardware and software

Current QC hardware limited in size, connectivity and affected by noise:

- Only small QML architectures possible (small number of qubits, small depth) – not full QCNN
- Smaller architectures can (theoretically) be processed by current hardware
- In practise for the specified 2D architecture required:
  ~ 1000 images (28x28) -> 1000 * 14 * 14 circuits = 196000 circuits
  * Shots
  * Number of training iterations
  = ~ 3.9 billions circuit evaluations
  + backpropagation procedure

- Without runtime environments: execution time is a couple of months
- With runtime, further downscaling of images, and a couple of tricks
  ~ hours – days

Improvements in runtime environments and excution times needed!



Fraunhofer Competence Network Quantum Computing

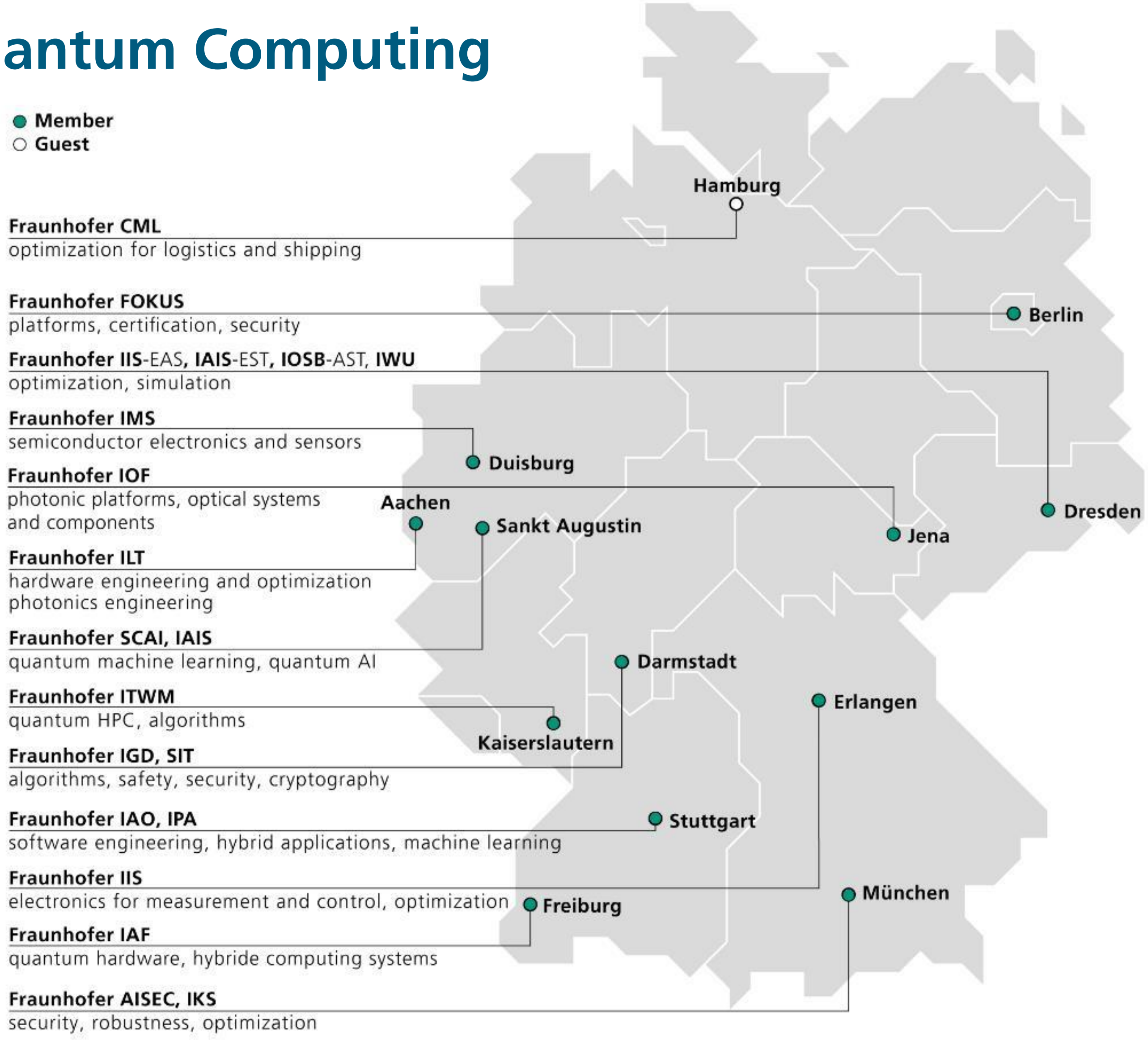
Fraunhofer IKS

Fraunhofer Competence Network Quantum Computing

One Stop Solution for Research and Industry

- **8 regional Competence Centers,** consisting of Fraunhofer Institutes, each with its own research focus
- Wide range of **fields of application**: logistics, chemical and pharmaceutical industry, finance and energy sector, materials science, IT security technologies and much more
- Exclusive access to **research platform** around an **IBM Quantum System One** installed in Ehningen, Germany
- Multi-level **training and education program**
- Strategic development by **Board of Directors** and **Industry Advisory Board**

Speaker: Prof. Manfred Hauswirth (FOKUS)
Deputy: Prof. Anita Schöbel (ITWM)



Fraunhofer IKS

Competency in Safe Intelligence

- Application-oriented research for reliable software technologies
- Expertise on cognitive systems, AI and modern software architectures in safety-critical applications
- Combining safety and intelligence: Safe Intelligence

Quick Facts
Founded in 2019 in Munich
100 employees
3 research areas

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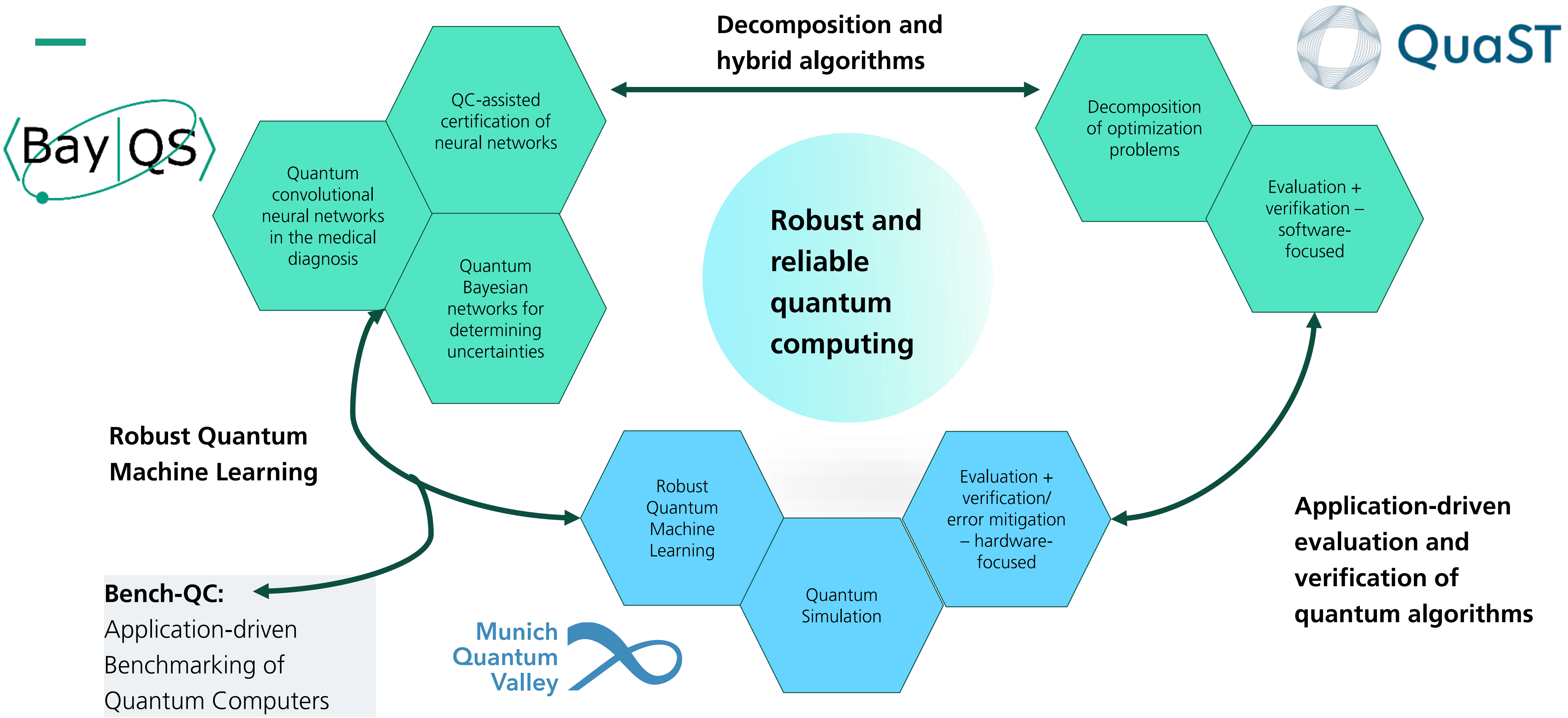
Fraunhofer IKS – Quantum Computing



Munich Quantum Valley

Munich Quantum Valley

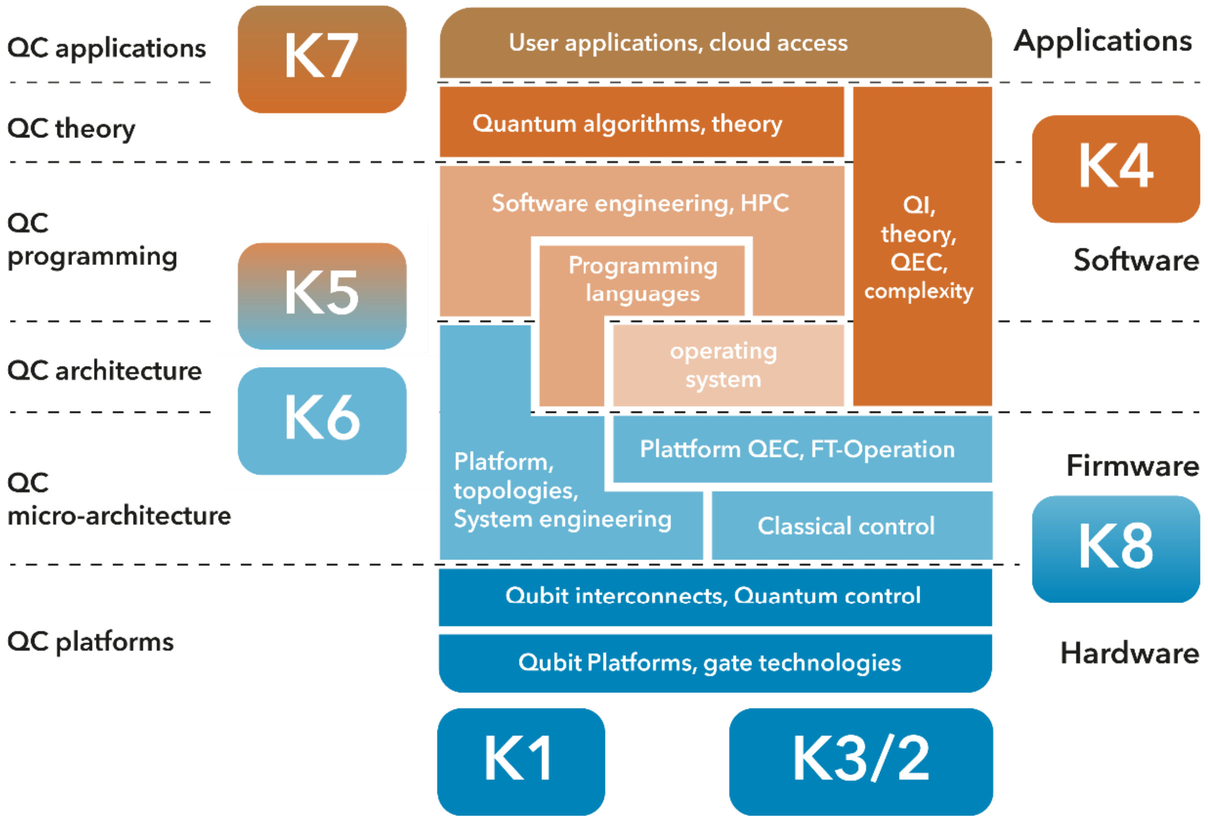
Konsortium 7: „Quantum Algorithms for Application, Cloud & Industry"

Munich Quantum Valley

MQV is an ambitious Bavarian initiate that aims to realize full-stack quantum computing infrastructure for three different hardware architectures. It is a combined effort of multiple partners and 300 Million Euro in funding.

Consortium 7:
„Quantum Algorithms for Application, Cloud & Industry"

1. **QC Application Algorithms for Industry Use-Cases**
   - Find quantum algorithms for **complex industry use-cases**, focus on **NISQ compatible** algorithms
   - **Benchmark** against hardware platforms, **optimize** for most suitable hardware platform
   - **Benchmark** against classical algorithms / heuristics, estimate for **type, scope** and **scale of potential quantum advantage**
2. **Supporting Software Tools and Processes**
3. **Infrastructure Access & User Support**

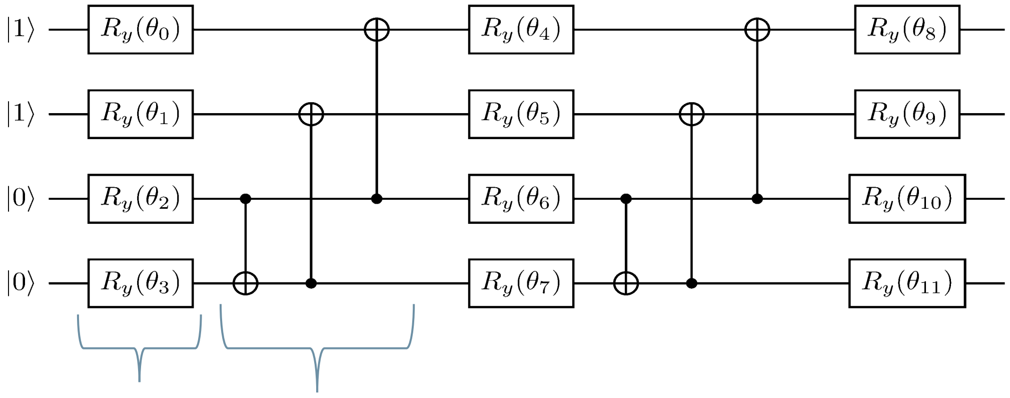


Example application

Simulation of the ground state of the hydrogen molecule

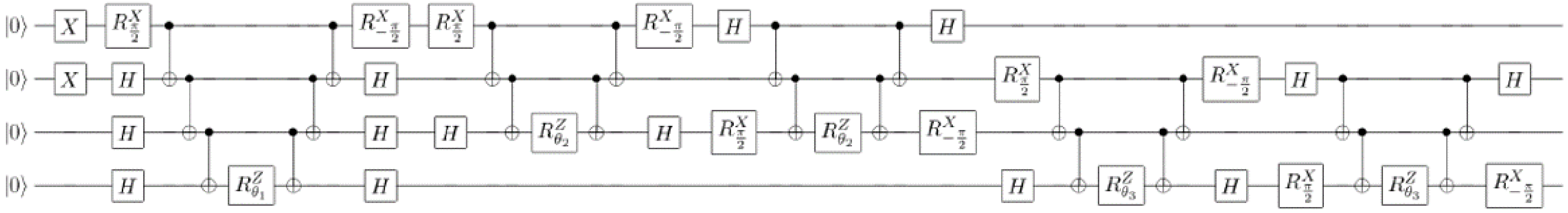
Advantages:

- Energy of ground state precisely known
- Can be used as calibration for hardware and interplay between classical and quantum parts of algorithms



Ansatzes:

- Hardware-efficient (low-depth, but generic)
- Chemically-inspired (coming from the physics/chemistry problem, but deep circuit)



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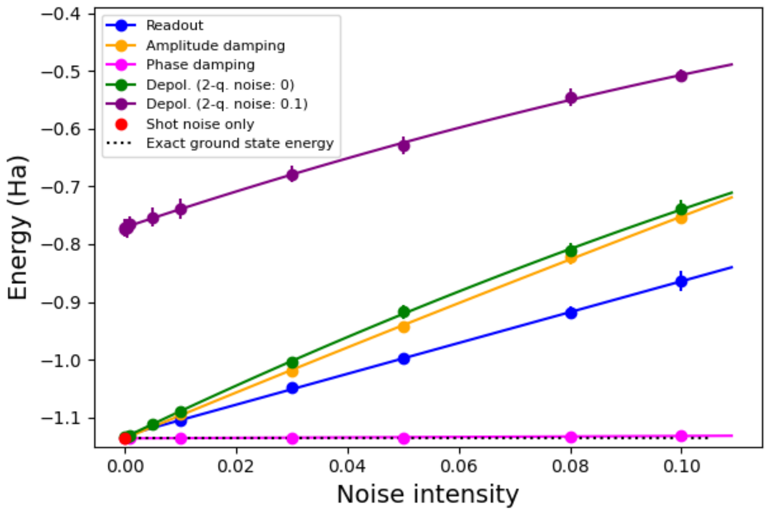
Comparison between different ansatzes

Impact of different noise sources

[M. Oliv, A. Matic, T. Messerer, J.M. Lorenz, Evaluating the impact of noise on the performance of the Variational Quantum Eigensolver, arXiv:2209.12803 [quant-ph]]

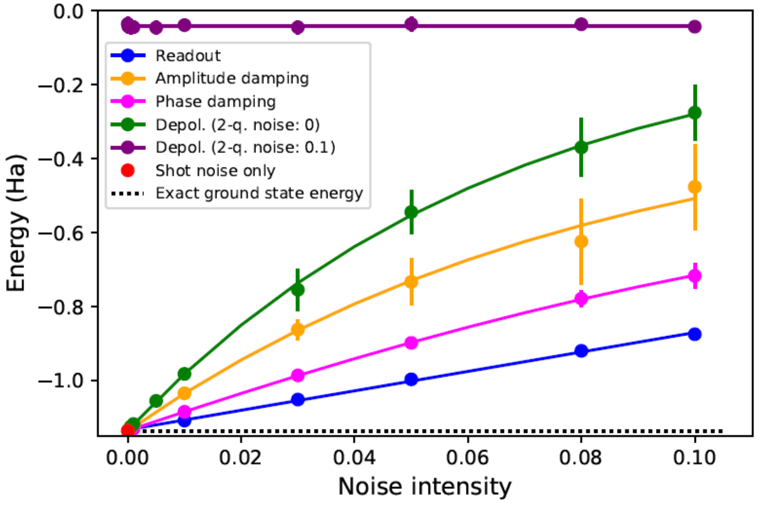
- The energy is shifted depending on the noise type, intensity and depth of ansatz.
- The type of rotation gates is not relevant.
- The readout noise just depends on the number of qubits.

5-layer R_Y ansatz



Quadratic

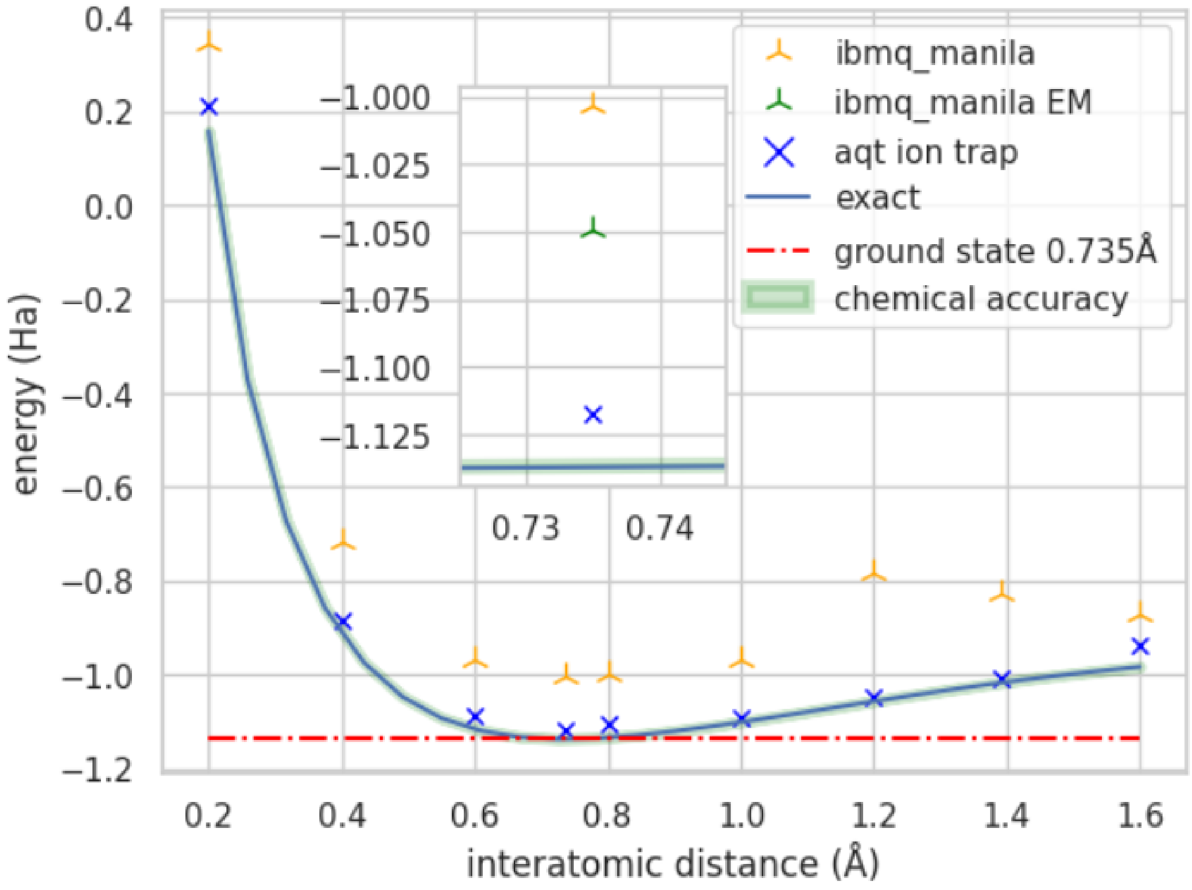
UCCSD ansatz



Dual-exponential

Is some quantum computing hardware better suited?

For this very specific problem



Joint work between Fraunhofer IKS (Munich) and Alpine Quantum Technologies (AQT, Innsbruck), group of Thomas Monz

Publication to appear soon

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Gefördert durch

Bayerisches Staatsministerium für
Wirtschaft, Landesentwicklung und Energie

Bench-QC – Application-driven benchmarking of quantum computers

Bavarian light house project

Fraunhofer IKS
Fraunhofer IIS
BMW GROUP
OptWare Optimierung unternehmen
REPLY MACHINE LEARNING
QUANTINUUM

Application-driven benchmarking of quantum computers

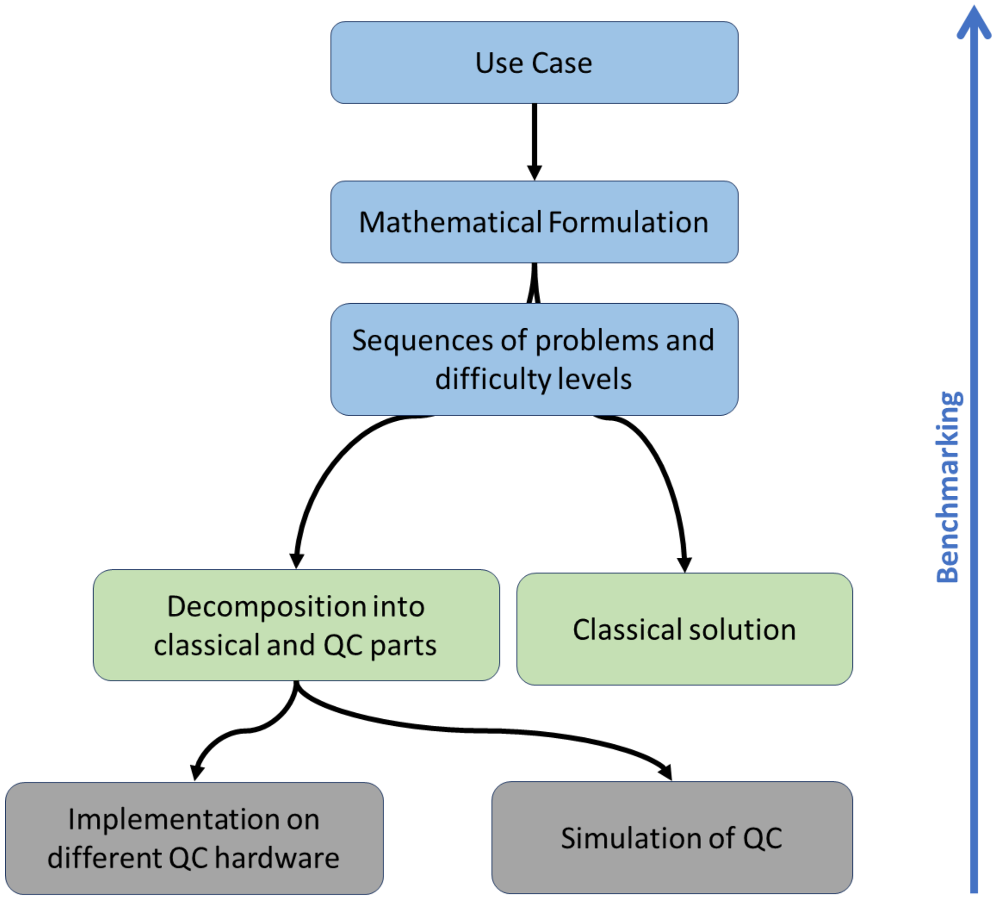
Quantum advantage currently only shown in theoretical work or in academic examples but not yet in industry use cases.

A practical quantum advantage is however expected to emerge in the next years with more powerful QC hardware getting available.

Which QC-technology will be suited for which application use case and when?
→ Potential analysis from the application perspective

Application-driven benchmarking of QC:

- Identification of use cases suited for a practical quantum advantage.
- Which QC-hardware technology (in which size, in which quality)?
- Considering the full path to the solution of a problem (e.g. including the data transfer to quantum computers, and post-procession of a quantum solution and integration into an industrial workflow)



DIN SPEC efforts

DIN SPEC: Benchmarking quantum computers with standardized KPIs

Consortium including the Quantum Business Network and the Fraunhofer FOKUS and different companies to develop benchmarks and metrics leading to benchmarks

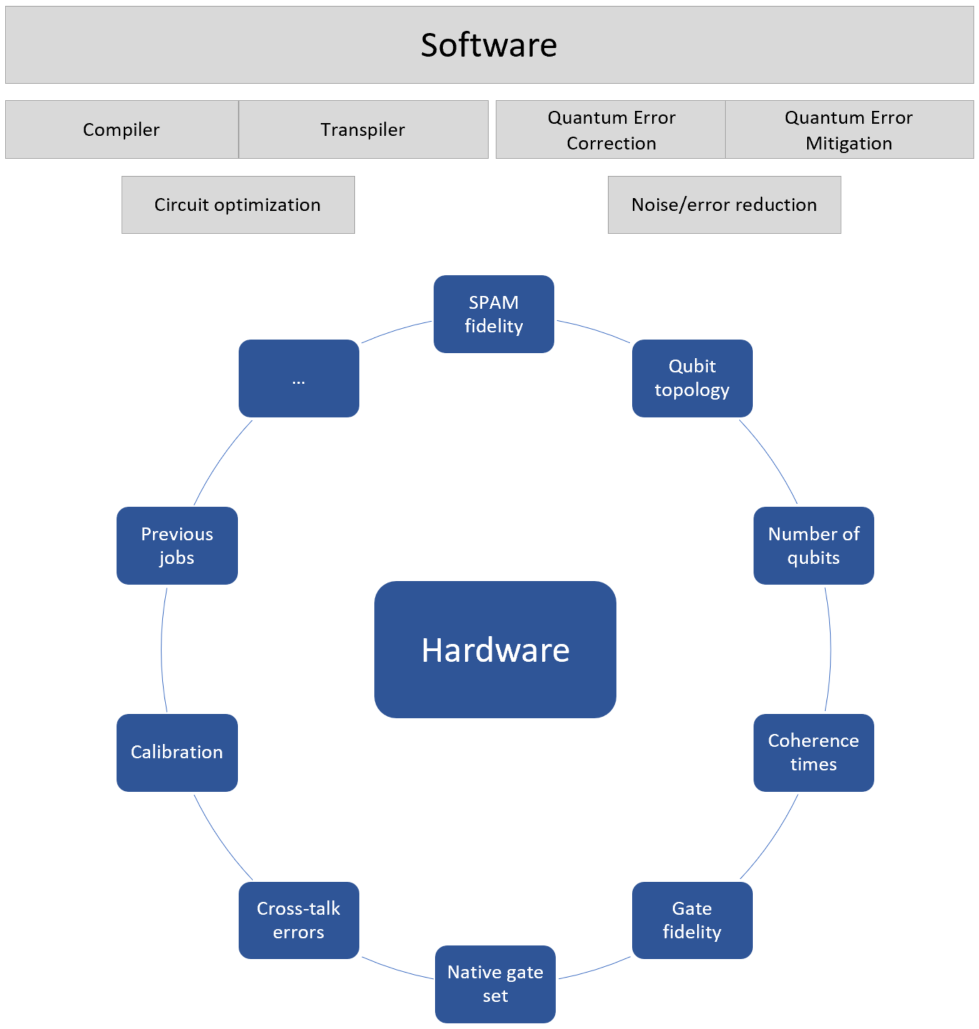
Assessing Quantum Benchmarks:

- What properties do we actually measure and how well ?
- Which parts of the whole quantum computing stack influences the benchmark?
- What does the measured properties indicate for similar or even completely different usecases?
- Relevance, Usability, Fairness, Reproducibility, Verifiability/Scalability

Benchmark results are influenced by hardware and software parameters

- Have to be really careful about distinguishing the effects of all parameters for the specification of benchmark protocols

=> Develop precise benchmarking run rules for each specification



Summary

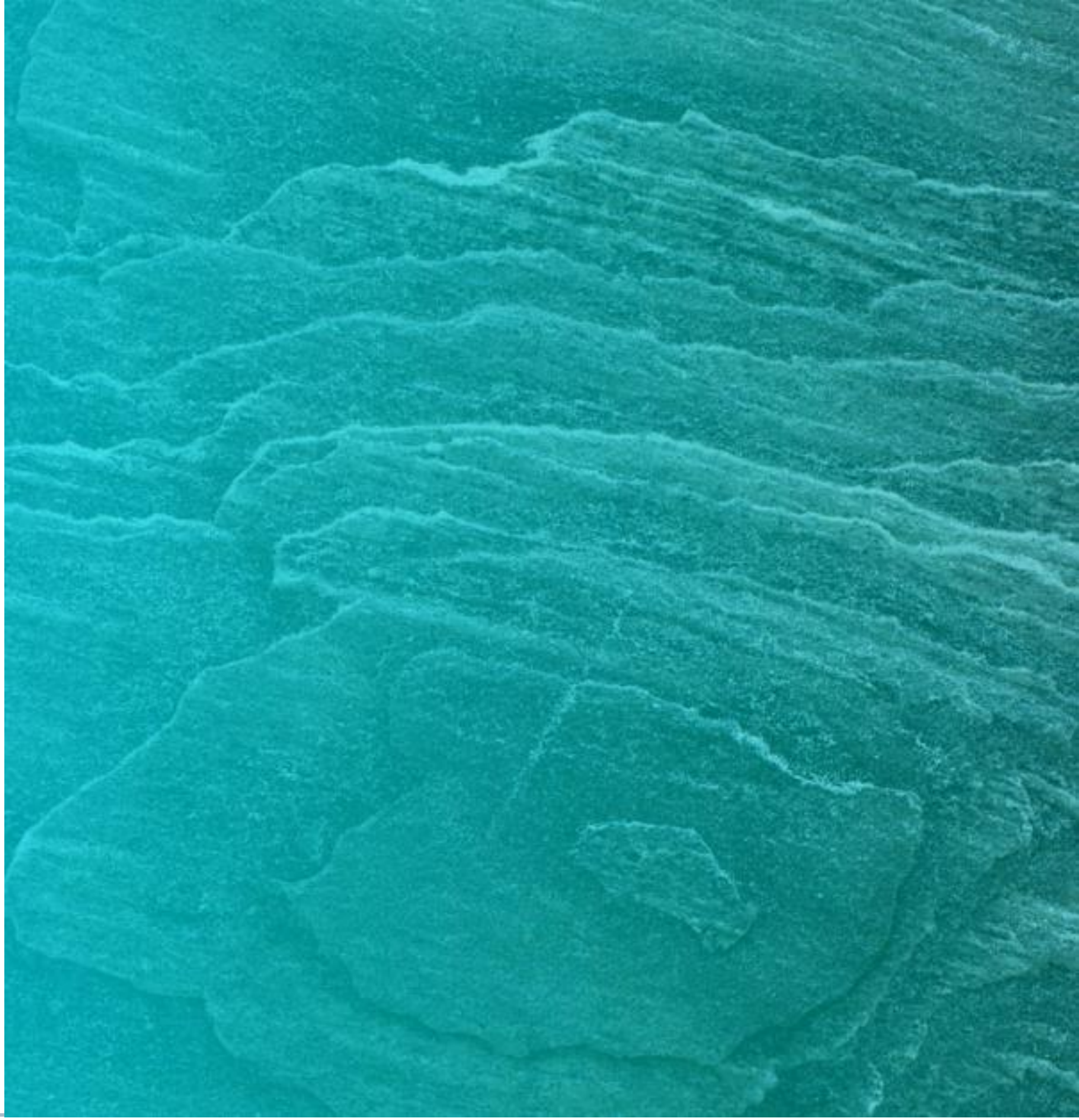
- To profit application-wise from quantum computing, a **clear practical quantum advantage** is required

- This advantage will not only depend on quantum hardware properties, but rather **need to consider the full hardware and software stack**, **coming from the application**

⇒Application-driven benchmarking required

- Different efforts now underway to realize an application-driven benchmarking in Germany, also profiting from the increasing availability of different quantum hardware systems
- **Assessing: which algorithms, when, and using which hardware**

- Establishing the route towards defining **standards**



Contact

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Fraunhofer Institute for Cognitive Systems IKS

Easy and reliable access to QC-assisted solutions of optimization problems

Project associated with the Munich Quantum Valley

Gefördert durch:

Bundesministerium für Wirtschaft und Klimaschutz

aufgrund eines Beschlusses des Deutschen Bundestages

QuaST

Fraunhofer AISEC
Fraunhofer IIS
Fraunhofer IKS
Fraunhofer IISB
DATEV
infineon
TUM
IQM
lrz
parityqc

Easy and reliable access to QC

QuaST

1 Currently the design of quantum algorithms is very uncommon for classical programmers, even if embedded in high-level languages like Python.

2 Only few high-level languages available, and not optimal in every aspect.

3 Software development needs to be quite hardware-aware:
- Which hardware (e.g. chip design) is best suited for an application?
- How to map a quantum algorithm best onto the hardware?
- How to ensure that the QC delivers robust and reliable results?

Development of an additional abstraction layer:
The end user should only need **minimal knowledge** about the QC-hardware and QC-software, but still obtain **easy** access to **reliable** QC-assisted solutions of his application problem, and by using QC-hardware as **efficiently** as possible

→ early benefit of potential quantum advantages

QuaST – Quantum-enabling Services and Tools for Industrial Applications

Unique ansatz including elements from the whole software stack:

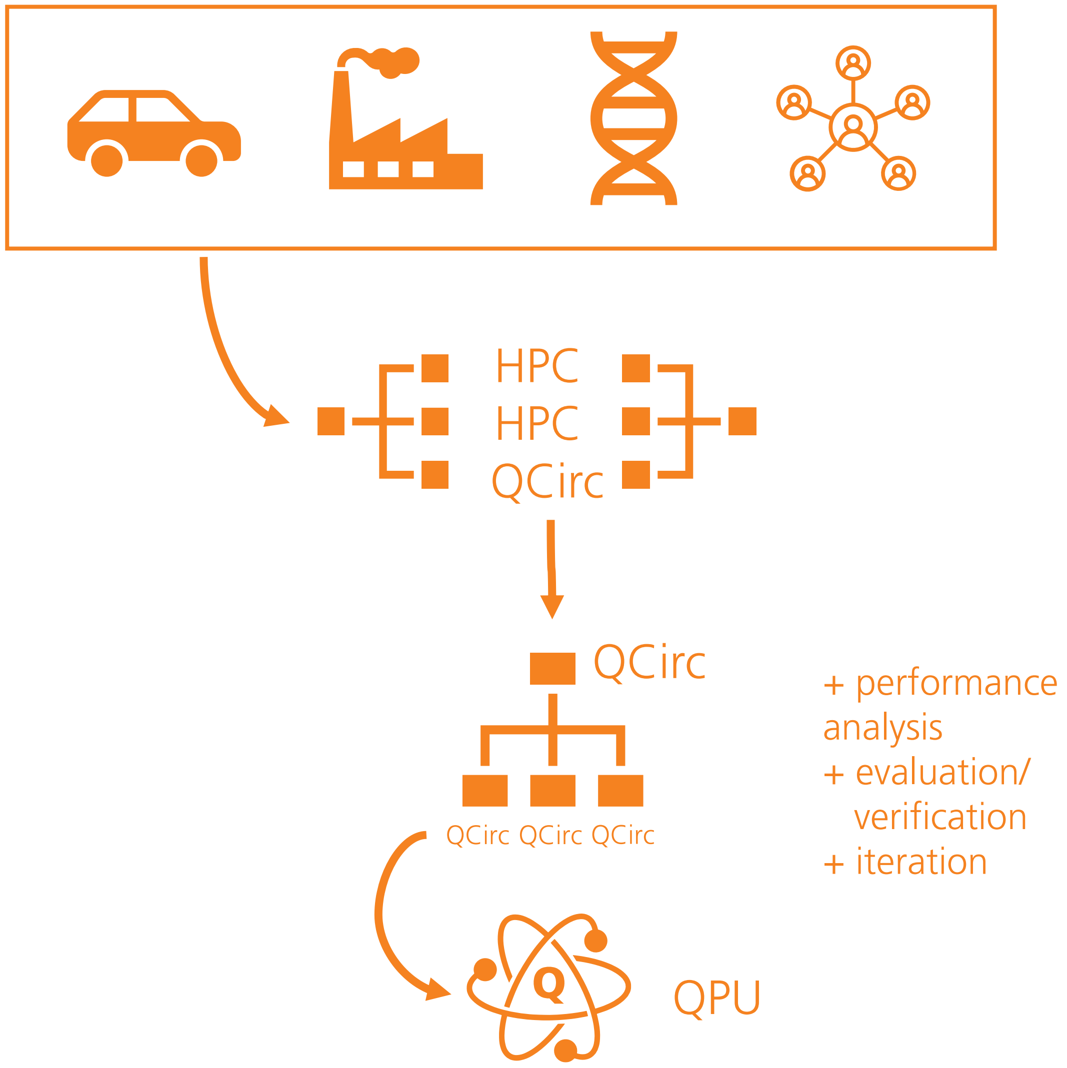
Starting from a wide set of optimization problems, **automatic decomposition** into smaller parts suited for classical or quantum computers + performance analysis.

Optimized **mapping** of the QC-parts onto the hardware via mapping libraries and **co-design** ideas.

Optimized **interaction/runtime environment** between classical and QC-systems.

Evaluation and **Verification** of the solution of the application.

Carrying out these developments targeted towards the application problems.



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Prototypical application examples

QuaST

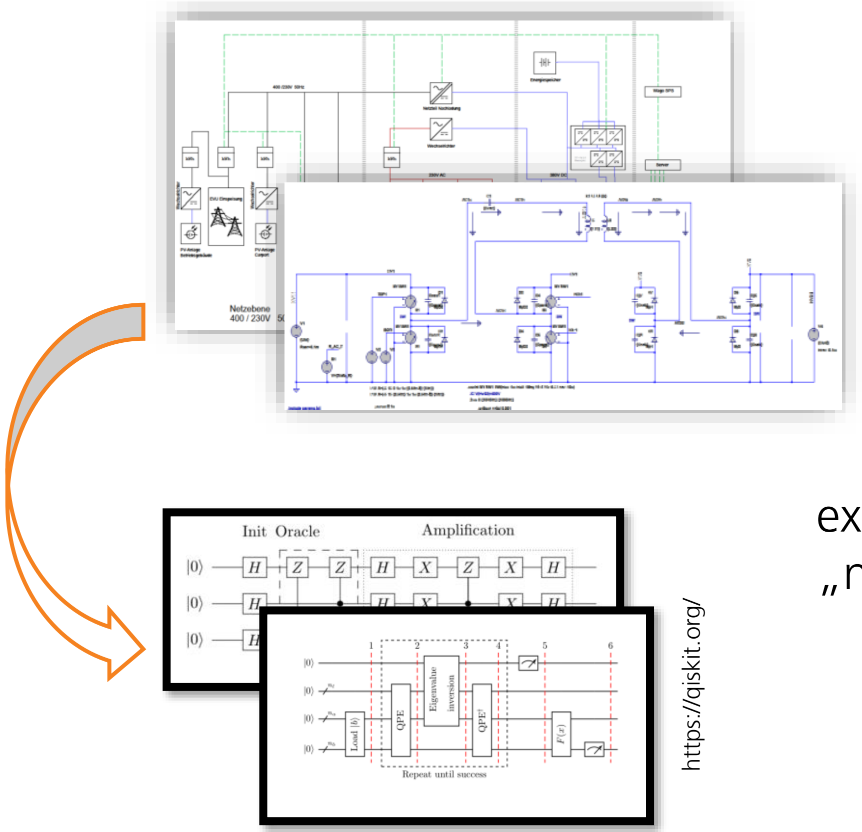
Various potential industrial use cases considered:

- Industrial networks, e.g. energy networks
- Waste management
- Scheduling tasks in the semi-conductor industry
- Economical analyses
- Classical software verification
- …

Research of applications for the use of QCs and implementation of prototypes

Software developments can be carried out targeted

Comparison to classical computers and implementations to evaluate the potential of QC for example applications



example „networks“

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An End User's Perspective

Problem:

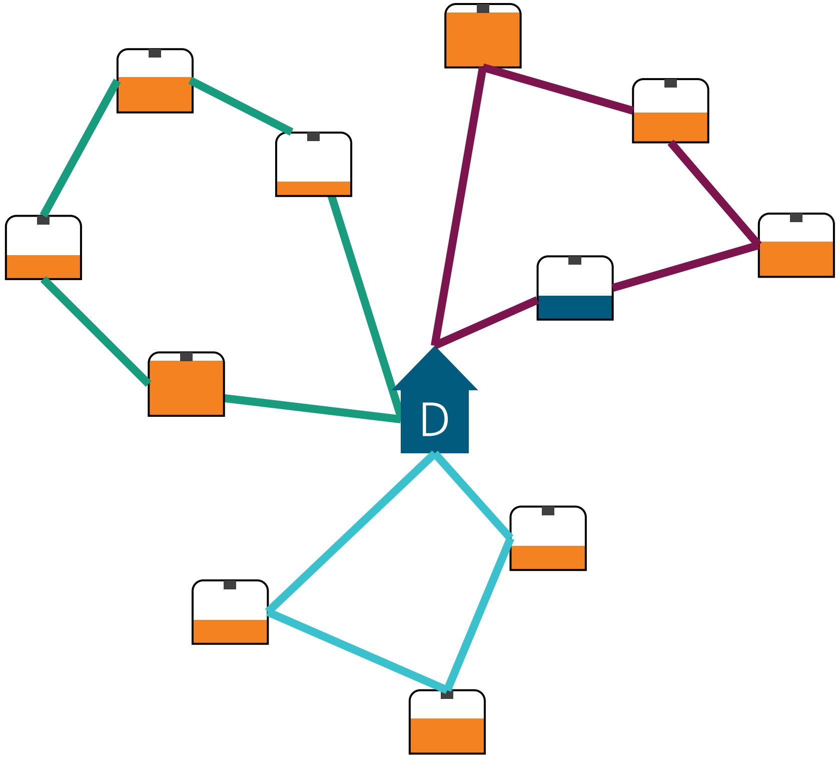
Garbage collection is inefficient: Some containers are near-empty, others at capacity or overflowing.

Solution Idea:

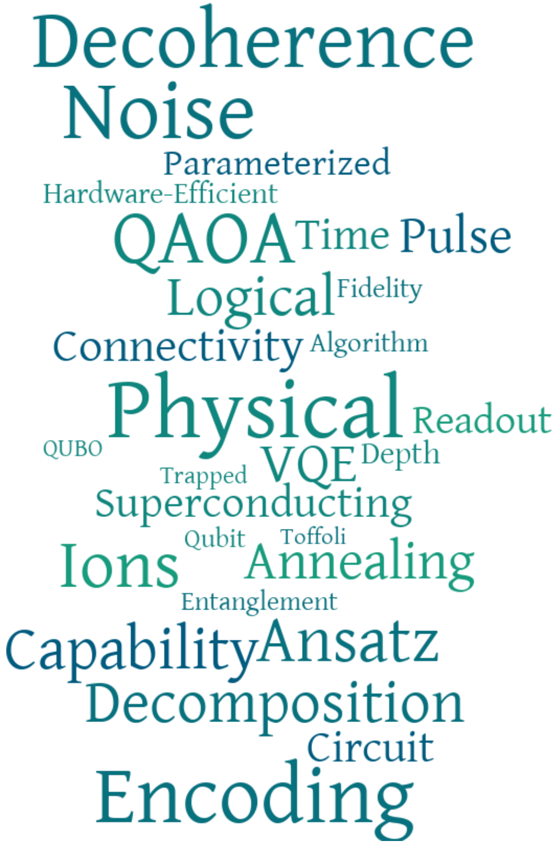
Measure their filling level and plan the collection routes dynamically.

Obstacle:

Route planning is a complex, NP-hard optimization problem that cannot be solved efficiently.



Perhaps Quantum Computing can help?



The Decision Tree

[B. Poggel, N. Quetschlich, L. Burgholzer, R. Wille, J.M. Lorenz, Recommending Solution Paths for Solving Optimization Problems with Quantum Computing, arXiv:2212.11127 [quant-ph]]

decisions depend on each other from top to bottom…

but lower-level decisions influence what's optimal on the higher levels