OTH REGENSBURG

MUNICH QUANTUM VALLEY

MQV



R&D Professorship

Quantum Algorithms and Applications

AUGUST 2023 — FEBRUARY 2026

LABORATORY FOR DIGITALISATION

PROF. DR. W. MAUERER

Opening Remarks



Prof. Dr.
Wolfgang Mauerer

The R&D Professorship ***Quantum Algorithms and Applications***, enabled by generous support from the Bavarian State Ministry of Science through the High-Tech Agenda, has allowed us to grow an exceptional team and an internationally visible programme in quantum algorithms, software and systems. It has helped secure substantial additional funding and extend a worldwide network of academic and industrial partners. This report documents what has been achieved during the first 2½ years.

Our work spans many fields and does not always adhere to traditional scientific taxonomy: Physics and the various sub-fields of computer science from software engineering to databases follow distinct academic traditions. Publishing in leading venues cannot be taken for granted; it reflects effort and dedication well beyond routine duties. I am deeply grateful to every team member for our joint achievements and internationally visible results. This gratitude also extends to all our partners, with whom it is a great pleasure to collaborate.

The balance of challenges in quantum computing has recently begun to shift. While many hardware-engineering problems remain, the physical foundations are increasingly well understood. Algorithms, applications and software have become grand challenges in their own right; many (including us) see these as a new and exciting scientific focus of quantum computing.

Nonetheless, useful quantum computing cannot arise from hardware, algorithms or applications in isolation. It requires computer science, domain knowledge and systematic engineering to advance together. Engineering is not merely implementation: abstractions, models, tool-chains and dependable systems are themselves scientific challenges. Our work spans mathematical structure, algorithm design, software architecture, and scientific and industrial applications. Close integration with industry keeps it directed towards practical needs, while progress repeatedly requires a necessary, and, for us, joyful detour through fundamental research. Understanding why approaches work and where their limits lie is essential if experiments are to mature into reliable applications.

The first 30 months in this R&D project have been intense and exciting. They have produced excellent results, strong international visibility, and firm foundations for the work ahead. Much has been achieved, but the most exciting developments may still lie before us. And we look forward to that!

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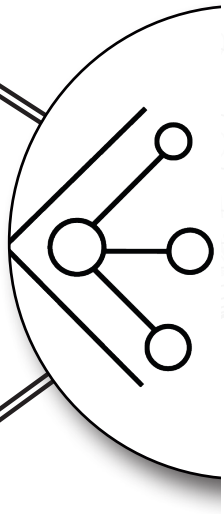
Appendix: Selected Results 65

Laboratory for Digitalisation

Software Engineering Research

We advance quantum and classical software based on quantitative insights from socio-technical data mining and analysis.



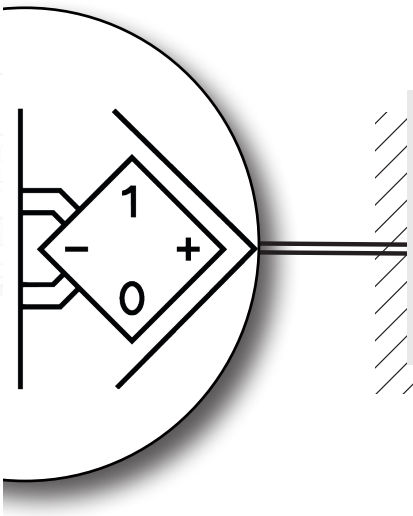


Systems Engineering Research

We architect, analyse, and model modern and open base architectures for real-time systems and quantum control.



Systems and Software Engineering Research for Quantum Computing



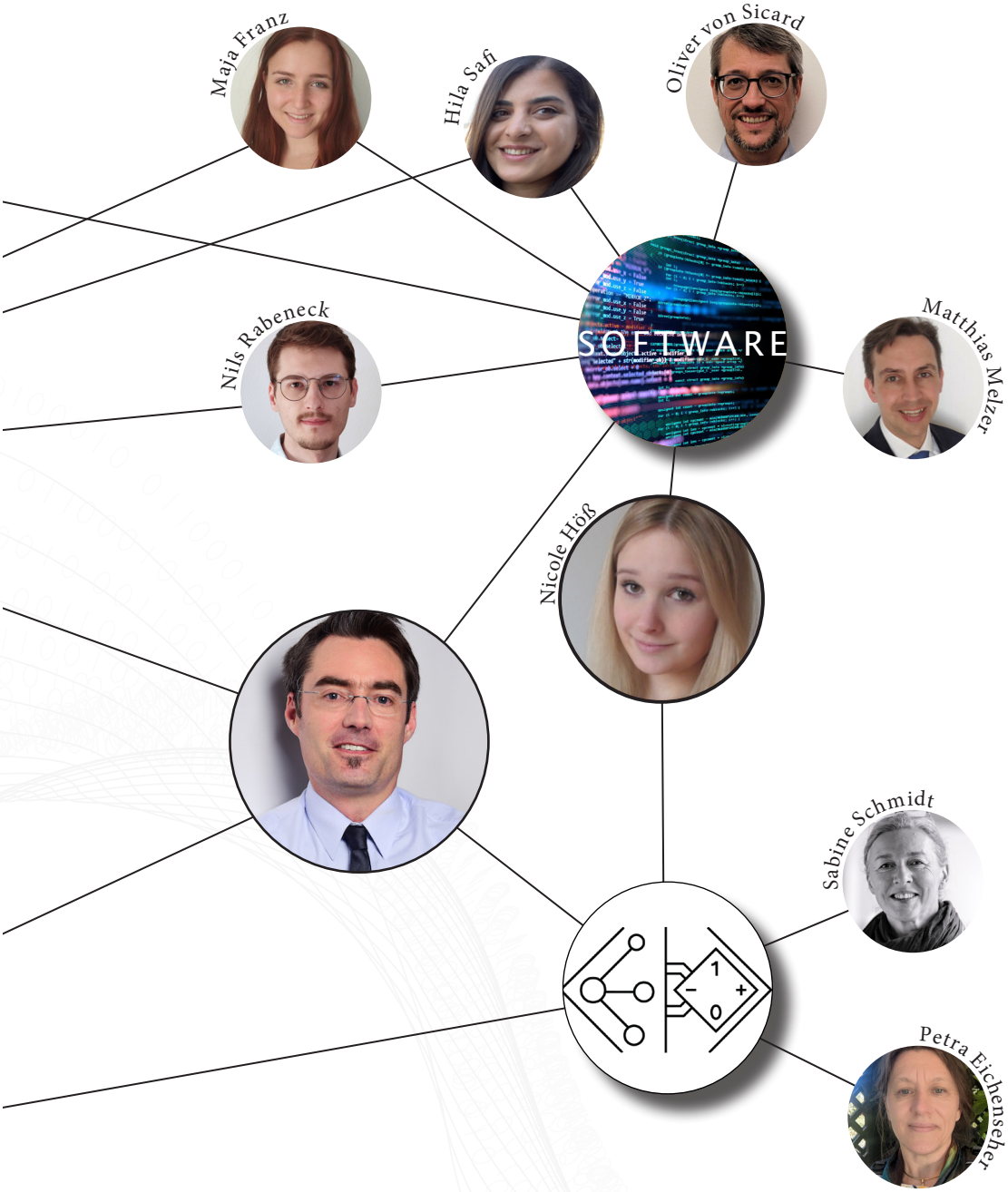
Quantum Computing

We seek quantum utility by co-designing integrated quantum algorithms, systems, and software.



The Team


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Petra Eichenseher

Facts & Figures

August 2023 — February 2026














6
Teaching Courses
3 New Curricular Offerings


35+
Programme Committees served


4
Awards
Scientific and Industrial


15+
Keynotes


20+
Reproduction Packages


8
International Workshops

1. Scientific Highlights
Aug. 2023 — Feb. 2026

Papers and Conference Contributions

Internationally recognised research, accepted by selective top-tier venues and journals, is a central objective of an R&D professorship. Building on the substantial support provided by the Bavarian High-Tech Agenda and on broad additional third-party funding, we have established a wide-ranging and genuinely interdisciplinary research programme. This work has been undertaken within the group and in collaboration with leading academic and industrial partners. Our research spans cross-cutting topics across several disciplines, including physics, theoretical and applied computer science, software engineering, and database systems.

Computer science traditionally disseminates its most significant results through highly selective conferences. Physics, by contrast, remains predominantly journal-oriented. Quantum computer science depends critically upon bridging these distinct traditions, and we pursue a balanced publication strategy. Our aim is not merely to publish within established channels of either field, but to contribute visibly across communities.

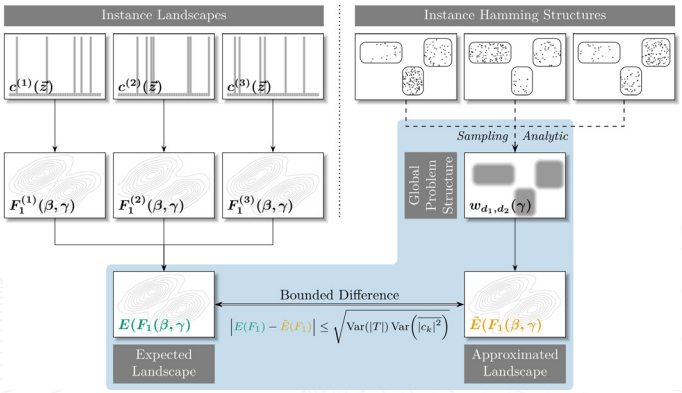
This is particularly evident in our work on systems and software engineering research for quantum computing. Our results have appeared across a diverse and interdisciplinary range of respected journals and conference proceedings: from physics-oriented publications such as Physical Review, Quantum, and the European Physical Journal; through computer-science venues including IEEE QCE, IEEE QSW, and ACM TQC; to leading specialist venues such as ACM SIGMOD and VLDB in database systems, or EMSE and IEEE SANER in software engineering. This breadth of publication reflects both the interdisciplinary character of the research and the laboratory's success in meeting the distinct scholarly standards of several established research communities.

The following pages show results that highlight how strong interdisciplinarity, a combination of breadth and depth of subject matter, international collaboration, and recognised scientific excellence define our research. Further selected work from the reporting period is summarised in the Appendix.

Out of the Loop: Structural Approximation of Optimisation Landscapes and non-Iterative Quantum Optimisation

Tom Krüger[1,2] and Wolfgang Mauerer[1,3]

[1]Technical University of Applied Sciences Regensburg, Regensburg, Germany
[2]FI CODE, Universität der Bundeswehr München, Munich, Germany
[3]Siemens AG, Technology, Munich, Germany



Our approach links structural properties of computational problems to properties of quantum optimisation algorithms.

Theorem 1. *Let $\#_d(k)$ be defined as in Lemma 2, then we can approximate the expected value of $F_1(\beta,\gamma)$ for a random instance of a problem by*

$$\tilde{E}(F_1(\beta,\gamma)) = \frac{E(|T|)}{2^n} E\left(\overline{|c_k(\beta,\gamma)|^2}\right)$$

with

$$E\left(\overline{|c_k(\beta,\gamma)|^2}\right) = \sum_{d_1,d_2=0}^{n} w_{d_1,d_2}(\gamma) f_n(\beta,d_1) f_n(\beta,d_2)^*, \tag{20}$$

where $w_{d_1,d_2}(\gamma)$ is

$$w_{d_1,d_2}(\gamma) = E\left(\overline{\#_{d_1}(k)\#_{d_2}(k)}\right)\left(e^{-i\gamma}-1\right)\left(e^{i\gamma}-1\right) + E\left(\overline{\#_{d_1}(k)}\right)\left(e^{-i\gamma}-1\right)\binom{n}{d_2} + E\left(\overline{\#_{d_2}(k)}\right)\left(e^{i\gamma}-1\right)\binom{n}{d_1} + \binom{n}{d_1}\binom{n}{d_2}.$$

We calculate mean values over all k in the instance specific target set T. The absolute approximation error is bounded by $|E(F_1(\beta,\gamma)) - \tilde{E}(F_1(\beta,\gamma))| \leq \sqrt{\mathrm{Var}(|T|)\,\mathrm{Var}\left(\overline{|c_k|^2}\right)}$.

These relationships are mathematically precise and provable. They lead to improved algorithms.

The ***Quantum Approximate Optimisation Algorithm*** (QAOA) is a widely studied quantum-classical iterative heuristic for combinatorial optimisation. Unfortunately, the classical optimisation procedure required in every iteration is as hard as the problem to be solved. Still, ***advantage over classical approaches is suspected for certain scenarios, but nature and origin of its computational power are not yet satisfactorily understood***.

By providing a sound foundation for understanding the link between structural properties of problem solutions and the quantum algorithm, we derive a ***new algorithmic variant*** of QAOA that requires running a classical optimisation procedure only for a class of problems, not every individual instance. ***It matches or outperforms unit-depth QAOA for key combinatorial problems, despite substantially reduced computational effort.*** We managed this by ***proving a long-standing conjecture*** regarding instance-independent structures in QAOA. By ensuring generality, we link existing empirical observations on QAOA parameter clustering to established approaches in theoretical computer science.

An empirical evaluation during the friendly-user phase of Q-Exa at LRZ showed:

- *Overall* ***runtime was reduced by 90%*** compared to standard QAOA, delivering a substantial speed-up.
- ***Solution quality was better*** than or comparable to standard QAOA.

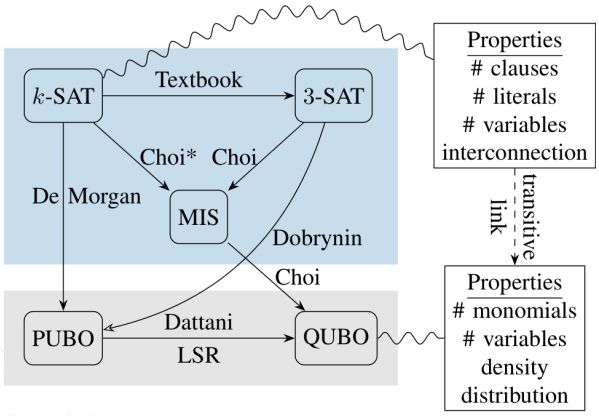


SAT Strikes Back: Parameter and Path Relations in Quantum Toolchains

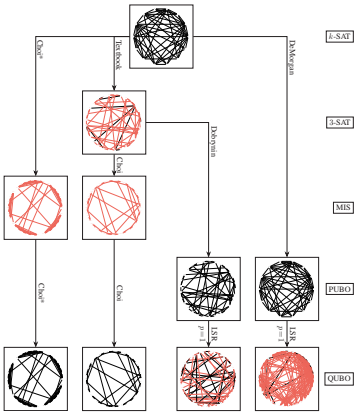
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Best Paper Award



Our approach and software tool-kit perform and analyse mathematically equivalent transformations from end-user problem descriptions into quantum-executable forms.



Different choices lead to drastically different properties of the resulting quantum formulation.

Tool-chains for quantum computing should offer automatic means of ***transforming high-level problem formulations*** provided by end-users ***down to hardware*** executable forms to allow non-quantum experts to benefit from quantum compute power. It is crucial to find optimised transformations for hardware-specific metrics, given the vastly different capabilities and properties of different quantum computers.

We analyse and characterise such transformations by focusing on k-SAT instances (a seminal computational problem of high industrial relevance) as inputs, and their transformation into mathematical forms that can be processed by quantum algorithms. We consider ***structure and characteristic metrics of input, intermediate and output representations; different mathematically identical choices lead to drastically varying efficiency on different quantum architectures***. Our results characterise transformation paths in quantum tool-chains. We lay the ground for full automation by considering stability and predictability of free parameters and transformation paths. As structural characteristics at higher-level abstraction layers benefit error-correcting codes in lower layers, our results remain applicable well beyond the era of current small-scale systems.



This work contributes towards making quantum computers useful for non-experts:

- Bridges between real-world problems and QC.
- ***Quantum resource*** requirements ***drop*** by ***up to 60%,*** which allows for fitting larger problems on constrained hardware (and improves overall utilisation).
- Up to ***85% reduction in preprocessing time***.

L. Schmidbauer and W. Mauerer: ***SAT Strikes Back: Parameter and Path Relations in Quantum Toolchains***, Proceedings of the IEEE Quantum Software Week, 2025.

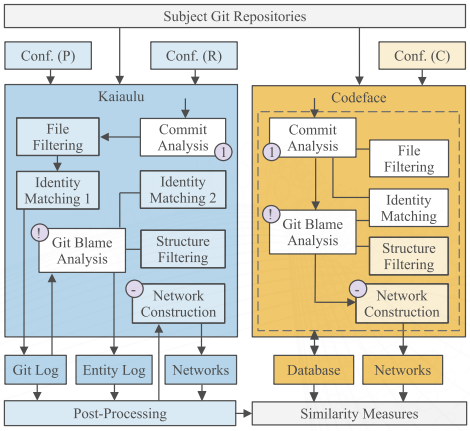
Does the Tool Matter? Exploring Some Causes of Threats to Validity in Mining Software Repositories

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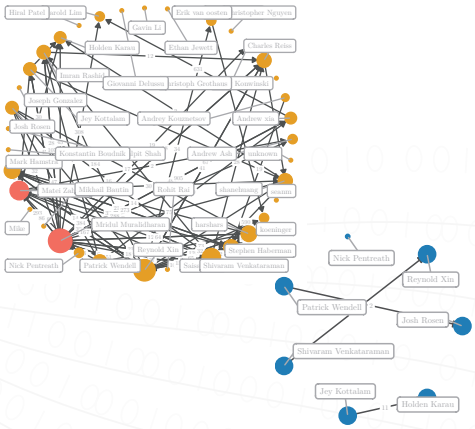
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Our meta-analysis compares conclusion stability in advanced empirical software engineering results across tools.



Tools with similar goals may deliver drastically different results caused by (seemingly minor) technical details that endanger scientific result validity.

Software repositories are an essential source of information for ***quantitative empirical software engineering research*** on topics such as project evolution and developer collaboration. Mining tools and analysis pipelines are required for many research activities. Valid results should not depend on seemingly irrelevant technical details, even if mining pipelines are complex software products.

Based on an analysis of ten large software projects over more than a decade of historical data, we find ***substantial discrepancies across tools*** that ***endanger*** the validity of ***scientific conclusions***. Our results indicate that despite similar trends, even simple metrics such as the numbers of commits and developers ***may differ by up to 500%***. These ***substantial differences*** are often caused by ***minor technical details***. Tool-level and post-processing changes can overcome these discrepancies, but may require considerable effort. We provide lessons learned to help researchers and practitioners avoid common pitfalls (that also apply to the growing quantum software analysis ecosystem), and reflect on implementation decisions and their influence in ensuring obtained data meet explicit and implicit expectations.

This work has nothing to do with quantum (for now)! Yet, it is the basis for ongoing activities:

- Quantitatively understand the ***quantum software ecosystem*** and optimise MQV contributions.
- Improve quantum software tools.
- Quantum software ***reproducibility***, community exchange and development of ***de-facto standards***.

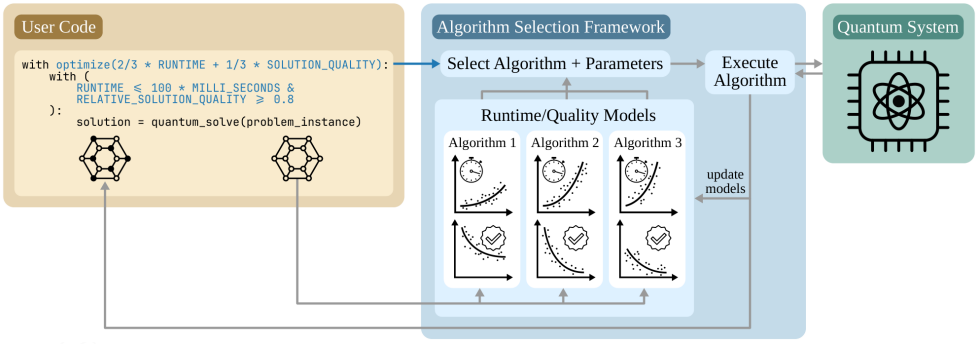


N. Höß, C. Paradis, R. Kazman, and W. Mauerer: ***Does the tool matter? Exploring Some Causes of Threats to Validity in Mining Software Repositories***, Proceedings of the IEEE International Conference on Software Analysis, Evolution and Reengineering, 2025.

Predict and Conquer: Navigating Algorithm Trade-offs with Quantum Design Automation

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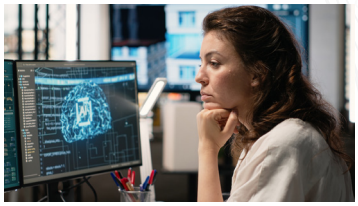
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Based on source code annotations that specify computational goals (performance, quality, etc.), our software toolkit automatically selects the most appropriate quantum approach based on a dynamically improving reference database.

While quantum advantages are expected for many algorithms, substantial theoretical and practical challenges remain: ***Speed or solution quality*** of many hybrid approaches are ***not fully understood***, and need to be ***explored empirically***. This often makes it unclear which choices are best. Accurately predicting the behaviour of quantum-classical algorithms opens possibilities for ***software abstraction layers***, which can ***automate decision-making*** for algorithm selection and parametrisation. Such techniques find frequent use in classical high-performance computing, but are mostly absent from quantum tool-chains.

Our software methodology performs ***algorithm selection based on specific requirements***, and ***simplifies decision-making for end-users***. Based on source code annotations, our framework traces key characteristics of quantum-classical algorithms, and uses this information to ***predict the most suitable approach***. Statistical models quantify the influence of various factors, and establish predictions for optimal algorithmic choices without manual effort. Our methodology generalises to problems beyond combinatorial optimisation, such as Hamiltonian simulation, and lays a foundation for integrated software layers for quantum design automation.



This work contributes towards making quantum computers more useful for non-experts:

- ***Design automation*** for quantum computing is improved at the software level.
- ***Predictable*** quantum ***performance*** before (expensive) hardware runs for up to ***75% more qubits*** than in the training data.
- A Route from specialist demonstrations to ***usable quantum applications***.

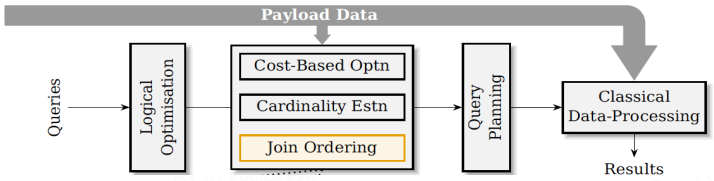
S. Thelen and W. Mauerer: Predict and Conquer: ***Navigating Algorithm Trade-Offs with Quantum Design Automation***, Proceedings of the IEEE International Conference on Quantum Computing and Engineering, 2025.

Quantum-Inspired Digital Annealing for Join Ordering

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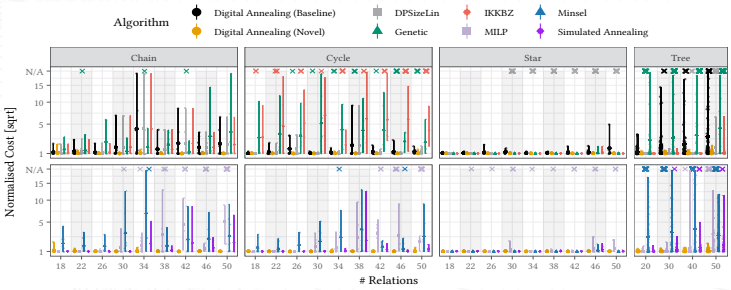
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Data management systems need to solve very hard optimisation problems on small data samples to reach optimal performance in the data-intensive stages. This provides opportunities for quantum improvements.

Our approach for join ordering, one of the hardest and longest-standing problems in database systems, improves considerably over the state of the art on quantum-inspired hardware.



Finding the ***optimal join order*** (JO) is one of the ***most important problems in database query optimisation***, and has been extensively considered in research and practice over decades in academic and industrial contexts. As it involves huge search spaces, approximation approaches and heuristics are commonly used, which explore a reduced solution space at the cost of solution quality. Even ***mature solvers cannot overcome*** the ***limitations of conventional hardware*** arising from the end of Moore's law.

Quantum-inspired digital annealing hardware can solve large instances of mathematically encoded optimisation problems today. We derive a novel, native encoding for the JO problem tailored to this class of machines that ***substantially improves over known quantum formulations***, and considerably reduces encoding size. With a ***novel post-processing method***, we boost 1%-3% correct answers of the probabilistic DA to nearly 100% validity. Our approach ***scales to practically relevant dimensions*** of around 50 relations and ***substantially improves result quality*** over conventional approaches. This underlines that ***progress in quantum applications*** is not solely a matter of building more and better qubits, but ***depends critically*** on encoding, ***architecture-aware software*** and ***intelligent*** classical ***post-processing***.



Our work demonstrated first practical advantages from quantum-inspired database acceleration:

- Entirely ***new perspective*** on a long-standing problem with decades of research tradition, ***reducing resource requirements by 60%***.
- ***Practical, real-world quality improvements*** over decades of research and engineering efforts.

M. Schönberger, I. Trummer, W. Mauerer: ***Quantum-Inspired Digital Annealing for Join Ordering***, Proceedings of the VLDB Endowment, Volume 17, Issue 3, 2023.

2. Cooperation Partners

Not restricted to reporting period




ECOPOLIS
Incubator Initiative

MOTIONDRIVE

R,KOM
Internet, TV & Telefon für Ostbayern

STEINHOFER


EFRE
BAYERN 2021-2027

ams OSRAM

AUMOVIO

AVL

B/S/H/


Jefferson Lab

VECTOR

zollner

SCHLEICHER

SIGILLUM · UNIVERSITATIS · LUBECENSIS

GEFASOFT
MACHINES

GT elektronik
Wir transformieren Leistung in Qualität!
TRANSFORMATOREN · WICKELGÜTER

HEINING BAU

img
INDUSTRIE-MECHANIK GEHÄUSEBAU

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

MTG

INIEDERMAYR

PINDL
Qualität macht Schule

Regler

STADT
REGENSBURG

scch { }
software competence
center hagenberg




OmniCert

gerresheimer

alkitronic
HOME OF TORQUE POWER

FIT

SCHAEFFLER

MR

e·on

KASSECKER

Dorfner

emz
smart solutions

MUNICH
QUANTUM
SOFTWARE COMPANY




DFG


lrz




Bundesministerium
für Digitales
und Verkehr




Leibniz
Universität
Hannover


TU/e
Technische Universiteit
Eindhoven
University of Technology
Where innovation starts




TU Delft


IQM


bayern
innovativ
Innovation leben




Bundes
Quanten
Allianz


sdp


Landkreis
Regensburg


Atos


ETH zürich


T Systems


DLR


SAP


DATEV


QANT


OODA


NEXT




ITS
GERMANY






QuTech




Argonne
NATIONAL LABORATORY




infineon


INSYS


KRONES


HORSCH


MAX BÖGL
Fortschritt baut man aus Ideen.


OptWare


KooSys




TU
WIEN


OAK
RIDGE
National Laboratory


University
of Victoria


NASA


UNIVERSIDAD DE EXTREMADURA
1973


TOKYO UNIVERSITY OF SCIENCE
since 1881



| Partners Across the Globe

New ideas emerge and established ones are tested, refined and improved through direct engagement with the leading minds in the field. We therefore place considerable emphasis on presenting our work at top-tier international conferences and on maintaining an extensive network of research partners worldwide.



| Popular Coverage

Our work is regularly covered in popular scientific media. We find this important as it justifies and explains to society the value generated from public funding. It is also a good means of attracting new talent and showing that our results matter in a broader context.



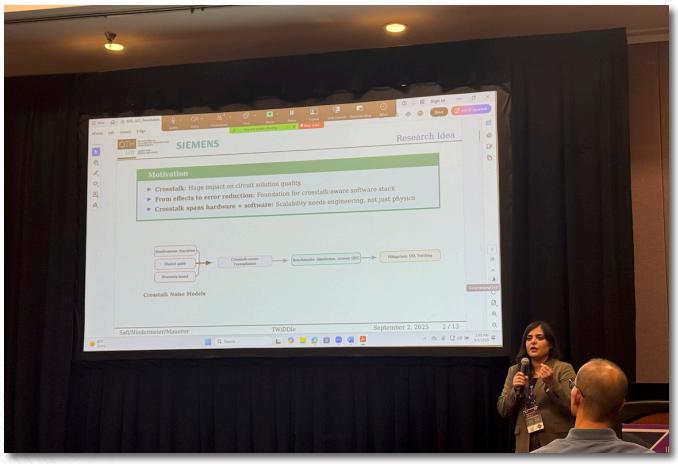
3. Community Outreach

Tutorials, Demonstrations and Talks

Our teaching and outreach activities extend well beyond the university. To provide a realistic understanding of how quantum-computing techniques may be applied across different domains (and to explain the latest advances in quantum methods), we deliver tutorials and practical demonstrations for both, specialist audiences and the wider scientific community.

Demonstrators are particularly valuable in making specific aspects of quantum computing and quantum algorithms accessible, often through engaging and deliberately playful examples. They help the general public understand both the potential societal value of our research and the reasons why sustained public investment in this area is necessary.

Hila Safi discusses quantum software at IEEE QCE'25 in Albuquerque, USA





Lukas Schmidbauer presents his research at IEEE QSW'25 in Helsinki, Finland



All-electric race track controlled by Quantum Reinforcement Learning at the celebrations marking 50 years of computer science at OTH (2025)



Vincent Gierisch joins the unveiling of the QKD Charging Station demo (joint work with UniBW Munich) at dtec.bw in Hamburg (2025)

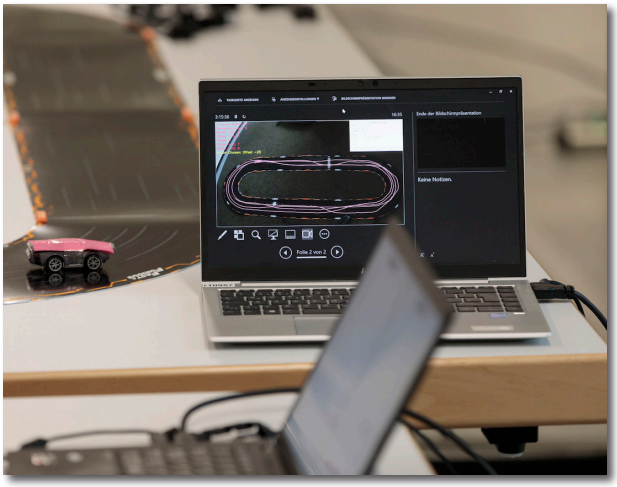


Quantum Key Distribution adversarial attack demonstration for vice minister Tobias Gotthardt, MdL (2024)



Quantum Pong Demonstrator at our World of Quantum booth (2025)





Video analysis of quantum versus classical race track performance (2023)



Quantum Database Systems Tutorial by Manuel Schönberger at IEEE QCE'24 in Montréal (Canada)



Maja Franz shows our Interactive Quantum Circuit Demonstrator (2024)

| Professional Outreach

To deepen engagement with professional peers and other interested stakeholders, particularly in industry, the group contributes actively to relevant professional associations and networks, including the German Informatics Society (Gesellschaft für Informatik, GI), Münchner Kreis, or Bitkom.



Münchner Kreis Site Visit to IBM (Munich)



Münchner Kreis Site Visit to IQM (Munich)



Münchner Kreis Site Visit to planqc (Munich)

| Community Building

We are actively engaged in developing and participating in specialist quantum-computing communities. At the same time, we place particular emphasis on identifying new application areas and domains in which quantum computing can deliver tangible scientific, economic or societal benefits.



Dagstuhl Seminar 24512 on Quantum Software Engineering (Germany)

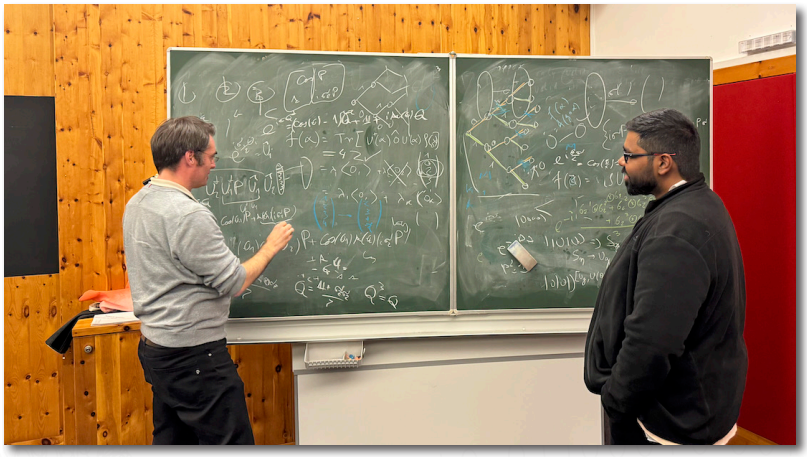


Shonan Seminar Quantum Software (Japan)



German Physical Society Seminar "Opportunities and Risks of Quantum Technologies", Bad Honnef (Germany)

Machine Learning and Quantum Physics Workshop, Obergurgl (Austria)





Visit by a delegation from Eötvös Loránd University (2025)



IEEE QCE'25 Organising Committee (performing a quantum song), Albuquerque (USA)

4. Funded Projects

Overview

Universities of Applied Sciences in Germany have traditionally placed their principal emphasis on teaching. Research has, however, become an increasingly important pillar of their mission. Recent reforms to academic governance, most notably the introduction of person-specific, merit-based rights to award doctoral degrees, have further strengthened this development. Nevertheless, institutional core funding for research remains extremely limited, and research activity therefore depends heavily on competitively secured external funding.

During the reporting period, the group attracted €4.408 million in third-party funding from highly regarded national and international sources. This substantially exceeds what would ordinarily be expected not only of a research group at a University of Applied Sciences, but also at major research universities.

This funding supports much more than research alone. A significant proportion is directed towards knowledge transfer, technology development, and application-oriented collaboration. This has enabled us to connect scientific advances in quantum computing and related areas with practical implementation and commercial exploitation.

NEW PROJECTS 08/2023—02/2026 (BEYOND MQV)

DURATION	SOURCE	TITLE	FUNDING
10/2025–09/2028	DFG	MoQel: Seamless Development of Quantum Software with Stakeholder-Specific Views	427 k€
10/2025–09/2028	BMFTR	Nachweis von Quantenvorteilen für Mobilität und Logistik (NaQuaMo)	447 k€
10/2025–09/2028	BMFTR	Quantengenerative Modelle für industrielle Simulationssysteme (Q-GeneSys)	530 k€
01/2024–12/2024	StD	KI-Transfer Plus III	373 k€
01/2026–12/2026	Industry	Q-ComSim	30 k€
10/2025–06/2026	Industry	QGate II	45 k€
10/2025–09/2028	EU	AIM-SMEs	2,100 k€
06/2025–05/2026	Subcontract	MuQuaNet	81 k€
01/2024–06/2024	Industry	EEArch	35 k€
09/2023–12/2026	EU	DinO	340 k€
TOTAL			**4,408 k€**

MoQel: Seamless Development of Quantum Software with Stakeholder-Specific Views

Oct 2025 – Sep 2028 | Volume: 284k€ + 143k€ (coordination)

Quantum computing use cases rely on different abstractions to model problems, which are then transformed into tasks for digital or analogue quantum computers. Gate-based approaches dominate current programming models, while analogue simulation is more common in physics literature. These approaches require different descriptions of input problems and computation sequences.

Different computational models – discrete and continuous in time and space – may offer distinct advantages for various tasks. For instance, quantum chromodynamics (QCD) problems, such as charge dynamics in lattice gauge theories, can be addressed with both digital and analogue quantum computers, each providing unique solutions. Recent research has explored both models for applications like simulating string-breaking dynamics in QCD and solving combinatorial optimisation problems via Ising models.

Despite significant progress in quantum hardware, quantum software still lags behind, with a lack of high-level abstractions and well-defined transformations. Existing quantum programming tools are often problem-specific, and there is a gap in developing general abstractions, model transformations, and stakeholder-specific views. This project aims to bridge that gap by developing a model-based methodology for quantum software that incorporates input from both the quantum computing and software engineering communities.

Coordination activities, which are jointly performed with the project lead KIT, particularly concern reproducibility issues in quantum computing: Given the volatility of current machines, their high susceptibility to external influences, a swiftly evolving software ecosystem, and new programming and interaction paradigms, reproducing scientific results from other groups is a formidable problem. OTH designs scientific solutions to address this challenge, and provides consulting services to all research groups participating in the priority programme.

DFG Deutsche Forschungsgemeinschaft

NaQuaMo: Demonstration of Quantum Advantages for Mobility and Logistics

Oct 2025 – Sep 2028 | Volume: 1,694k€ (LfD: 447k€)

Many proposed quantum-based methods are *heuristics* – approaches whose validity cannot be rigorously proven mathematically. Others offer only moderate advantages that are quickly negated by error correction protocols. There is therefore a substantial risk that many theoretically described quantum algorithms will not achieve any practical relevance.

NaQuaMo investigates whether real optimisation problems exist in logistics and mobility that exhibit sufficient mathematical structure to demonstrate a verifiable and substantial quantum advantage. The consortium brings together partners with expertise in theoretical and applied quantum informatics, as well as leading industrial providers in the field of supply chain management and mobility.

As arguments from theoretical computer science and empirical evidence from recent years suggest that it is not possible to achieve a demonstrable substantial quantum advantage for generic combinatorial optimisation problems, we investigate use cases that have a rich 'algebraically inspired' structure. Quantum advantages proven in other areas (e.g., cryptanalysis) are known to exist on the basis of such structures. We seek instances that are relevant to industrial applications.



Federal Ministry
of Research, Technology
and Space

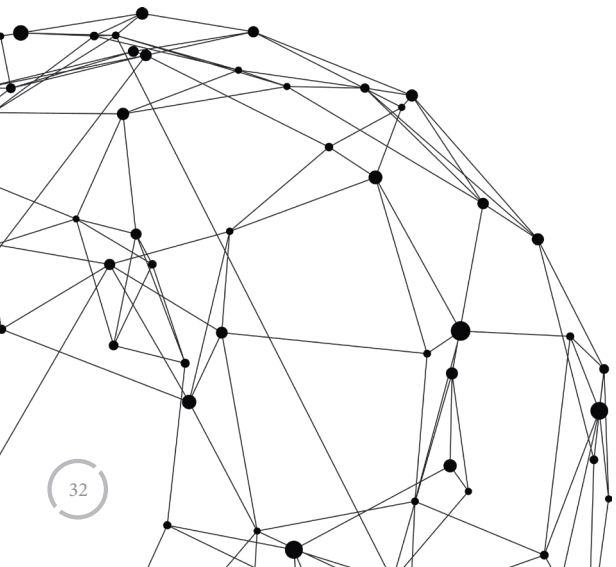
Q-GeneSys: Quantum-Generative Models for Industrial Simulation Systems

Oct 2025 – Sep 2028 | Volume: 2,672k€ (LfD: 530k€)

The findings from the quantum supremacy experiments, which demonstrate the enormous potential of quantum technology, are to be translated into practical quantum computing systems. To this end, a suitable approach for the use of quantum generative models is being developed in order to realise quantum advantages in industrial applications.

The core of the innovation lies in the targeted combination of findings from supremacy experiments in quantum computing with the field of generative learning. Instead of focusing on the development of universal quantum circuits, the approach uses specific classes of quantum circuits, such as IQP circuits, which are classically trainable but still capable of generating high-dimensional probability distributions. This reduces the requirements for quantum hardware and opens up opportunities for exceptional quantum acceleration in practical scenarios.

Federal Ministry
of Research, Technology
and Space



KI-Transfer Plus III

Jan 2024 – Dec 2024 | Volume: 373k€

This pilot programme, launched by the Bavarian State Ministry of Digital Affairs, develops best practices for the introduction of artificial intelligence and advanced compute technologies in small and medium-sized enterprises.



Bayerisches Staatsministerium
für Digitales



Q-ComSim

Jan 2026 – Dec 2026 | Volume: 30k€

This industry cooperation investigates the quantum-centric use of quantum data obtained directly from quantum sensors, and provides an initial assessment of potential utility in defence applications.

QGate II

Oct 2025 – Jun 2026 | Volume: 45k€

This industry cooperation tracks, in a second iteration, progress and latest development in gate-based quantum algorithms, and provides an assessment of potential industrial applications, as well as limitations and practical obstacles.

EEArch

Jan 2024 – Jun 2024 | Volume: 35k€

This industry cooperation establishes the foundations of a safety-critical, hard real-time, highly adaptable and ultra-low footprint hypervisor that serves as a basis for ongoing work on low-level quantum control.

MuQuaNet

Jun 2025 – May 2026 | Volume: 81k€

We contribute our expertise in building quantum demonstrators around our quantum key distribution appliance to the MuQuaNet consortium, as a subcontractor of the University of the Bundeswehr Munich.

AIM-SMEs: Accelerating AI-Based Innovations in SMEs

Oct 2025 – Sep 2028 | Volume: 2,100 k€

AIM-SMEs promotes the sustainable creation of innovation based on artificial intelligence (AI) and other future compute technologies like photonics and quantum computing in small and medium-sized enterprises (SMEs) through tailor-made technology transfer. Within three years, a total of 18 regional SMEs will receive intensive support from the laboratory in all phases of AI projects.

The focus is on individual processes and products that are revolutionised in terms of efficiency, quality, productivity and sustainability through the use of machine learning to achieve added value for the company, the region and Europe. Methods and technologies are specifically tailored to the needs of the companies in line with the latest scientific and technical developments. The resulting innovations serve as guidelines for subsequent innovations within the company and act as supra-regional, inspiring lighthouse projects.

Bayerisches Staatsministerium für Wissenschaft und Kunst

DInO: Digital Innovation Ostbayern

Sep 2023 – Dec 2026 | Volume: 5,010k€ (LfD: 340k€)

The DInO initiative (Digital Innovation in Eastern Bavaria) fuses academic expertise and applied innovation, creating technological opportunities that address challenges faced by rural communities in the digital era. DInO is part of the European Digital Innovation Hubs Network. Our joint contributions include cutting-edge research emphasising AI and data technologies. These insights are translated into open innovation and test laboratories, aligning with the *Test before Invest* principle for innovation viability.

Beyond research, DInO emphasises knowledge dissemination and skills development, empowering the local workforce through targeted training and bridging the gap between theoretical understanding and practical implementation. This fosters continuous learning and cultivates digital adaptability.

Digital Innovation Ostbayern

Bayerisches Staatsministerium für Wirtschaft, Landesentwicklung und Energie

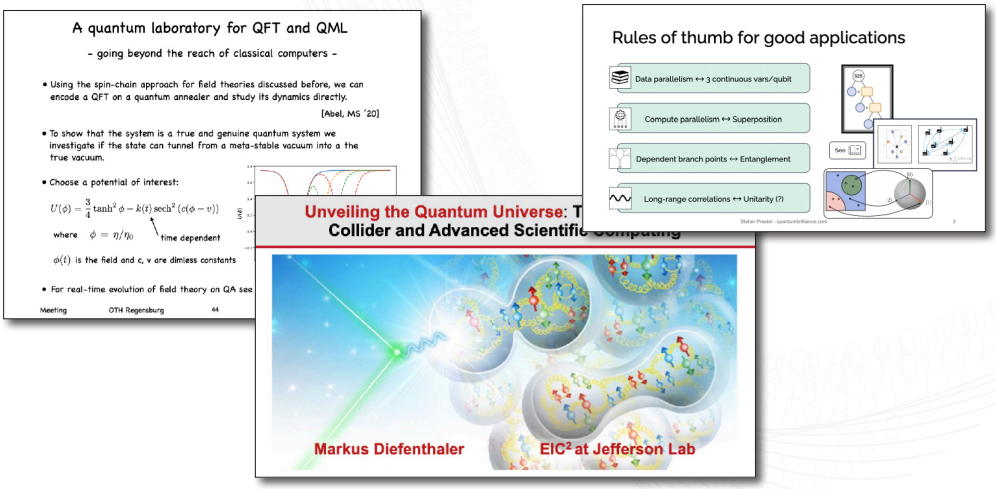
5. Workshops

In computer science, novel, high-risk and exploratory research ideas that are not yet sufficiently mature for full publication are traditionally discussed in specialist workshop settings. Such workshops are commonly organised as satellite events alongside major conferences, while retaining rigorous peer-review procedures and publishing accepted contributions as part of the host conference proceedings.

For an emerging discipline such as quantum computer science, these forums are particularly important. They provide an opportunity to establish realistic expectations regarding both the capabilities and the limitations of quantum methods when applied in other domains. They also enable early-career researchers to obtain constructive feedback, develop their work and become integrated into the wider research community. The laboratory has established and coordinated a number of workshops at leading international venues.

Workshop on Quantum Computing for Nuclear and High Energy Physics

Given that a quantum computer has negligible cost compared to a particle accelerator, making such large-scale research endeavours the potentially first users of the technology, the laboratory invited leading researchers from Jefferson Lab, KIT, Durham University, Complutense University of Madrid and Quantum Brilliance to an in-house workshop aimed at understanding potential uses of QC in nuclear and high energy physics. The goal is to establish dedicated research in this direction.



International Workshop on Quantum Machine Learning: First (2023), Second (2024) and Third (2025) Edition@IEEE QCE

Based on discussions in the BMBF-funded QLindA consortium, the International Workshop on Quantum Machine Learning (QML) as part of the IEEE Conference on Quantum Computing and Engineering was established to discuss potential applications of quantum machine learning, but also to obtain a balanced and realistic picture of limitations from technical and fundamental challenges.

After the first (Bellevue, Washington), second (Montréal, Québec) and third (Albuquerque, New Mexico) edition, the event had become the largest of the about 40 workshops at IEEE QCE. It attracts enthusiastic participation from researchers from all over the world with around 100 attendees. An acceptance rate of roughly 40% balances academic selectivity with community inclusiveness.







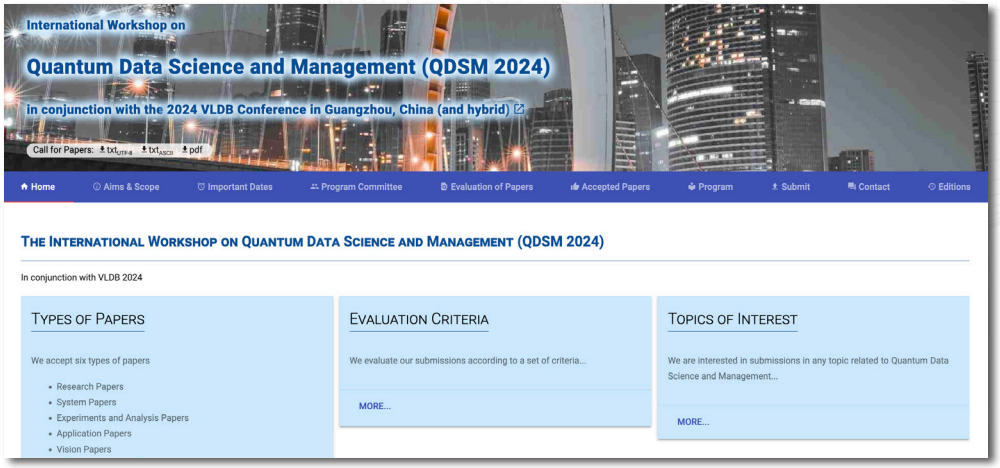


Impressions from the workshop over the years

International Workshop on Quantum Data Science and Management (QDSM): First (2023) and Second (2024) Edition @ VLDB

The workshop series at VLDB, one of the leading CORE A* conferences in the database management systems community, was established by Wolfgang Mauerer jointly with Sven Groppe (University of Lübeck), Jiaheng Lu (University of Helsinki), and Le Gruenwald (University of Oklahoma).

For most database researchers, quantum computing and quantum machine learning are still new research fields. The workshop bring together academic researchers and industry practitioners from multiple disciplines (e.g., database, AI, software, physics) to discuss the challenges, solutions, and applications of quantum computing and quantum machine learning that have the potential to advance the state of the art of data science and data management technologies. Our purpose is to foster interaction between database researchers and more traditional quantum disciplines, as well as industrial users. The workshop serves as a forum for the growing quantum computing community to connect with database researchers to discuss the broader questions and applications of how quantum resources can benefit data science and data management tasks, and how quantum software can support this endeavour.



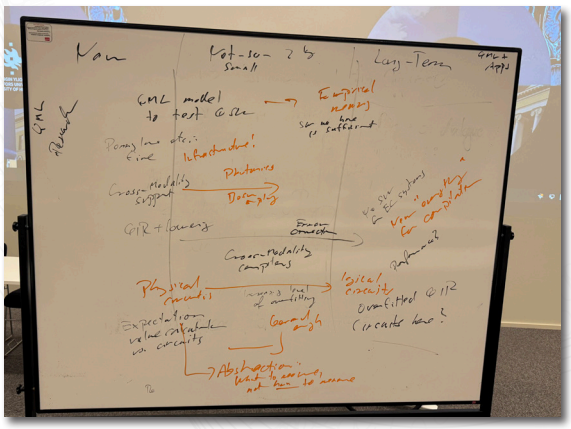
International Workshop on Interfaces and Abstractions: First (Jul 2025, IEEE QSW) and Second (Sep 2025, IEEE QCE) Edition

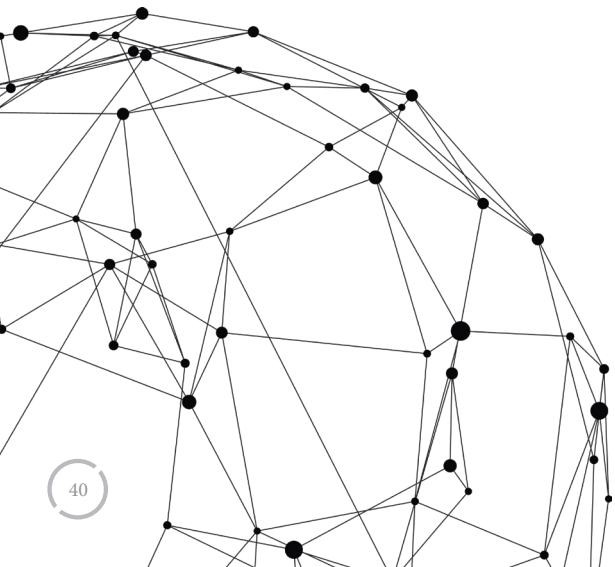
Together with colleagues from KIT, we host a series of workshops on interfaces and abstractions in quantum software, whose systematic construction is one of the major open issues of contemporary quantum software.

Based on ideas from discussions in a 2024 Dagstuhl seminar on quantum software engineering, the workshops systematically elicited knowledge from a wide array of relevant stakeholders and international quantum experts to establishing shared terminology and understanding of all aspects related to this challenge. Quantum software layers were, building on the principles of model-driven architecture, structured into distinct layers that align high-level requirements with hardware-specific constraints. This serves to manage complexity and to support a gradual evolution of quantum systems in line with hardware advances. A computation-independent model captures essential requirements and business objectives; this is then refined into a platform-independent model that defines core functionalities. A platform-specific model adapts these functionalities to the particular characteristics and limitations of individual quantum hardware. The results of the workshops served as a basis for continued research in an international consortium.



Dagstuhl discussion session between leading quantum software scientists that gave rise to the workshop series





6. Teaching

| Supplementary Study Programme "Quantum Technologies"

A supplementary study programme in ***Quantum Technologies*** was established starting winter semester 2023/24: "Quantum technologies hold immense potential for solving the most complex problems that have so far pushed classical computers to their limits. The supplementary course offers students a gentle introduction to this complex topic – from basics of fascinating phenomena of quantum mechanics, their exploitation in cryptography to the simulation of quantum circuits and quantum problem formulations." The study programme prepares students in the best possible way for the technology of the future. The programme is part of the Regensburg School for Digital Sciences (RSDS).

The additional study programme is an interdisciplinary initiative of Professors I. Serban (Applied Natural and Cultural Sciences), J. Mottok (Electrical and Information Technologies) and W. Mauerer (Computer Science).





| Curricular Lectures

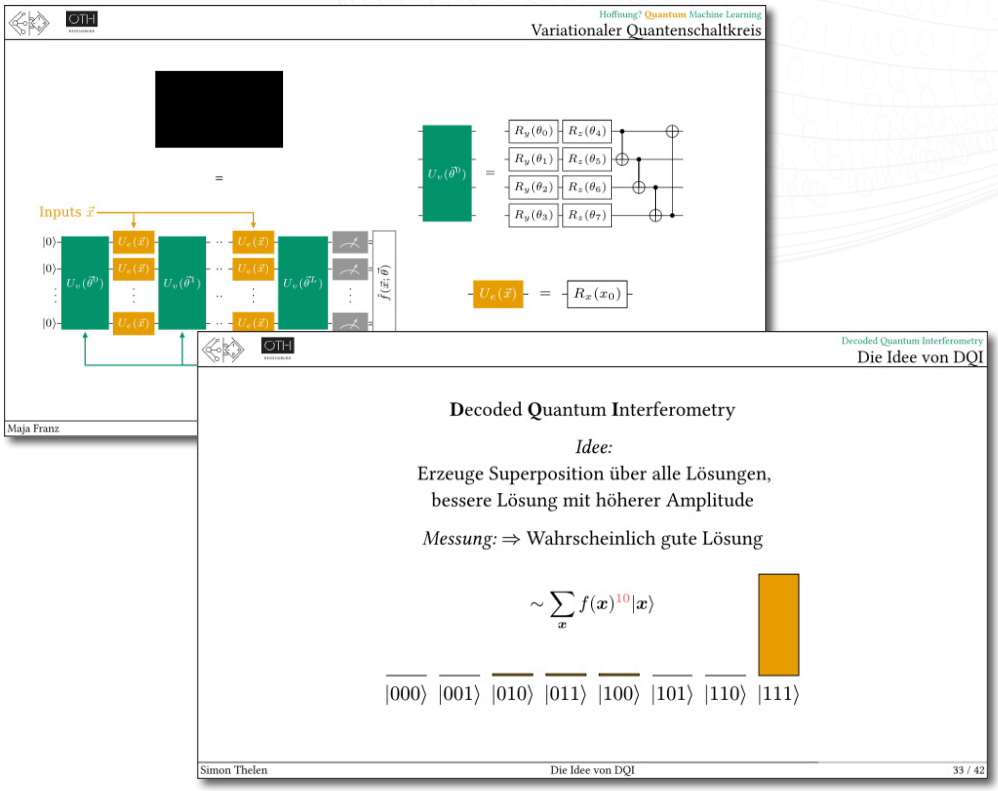
Within the standard curriculum, the laboratory offers the following courses:

- **Quantencomputing** (Quantum Computing), de/en: 4 SWS
  Bachelor, 7th semester
- **Quantum Computer Science** (Quanteninformatik), en/de: 4 SWS
  Master, 2nd semester
- **Seminar Quantum Computing**, en: 4 SWS
  Master, 1st/3rd semester
- **Research Master** with focus on quantum computing
- **Hauptstudiumsprojekt** (student research projects, Master)
- **Theoretische Informatik** (Theoretical Computer Science), de: 4 SWS
  Bachelor, 1st semester

| LfD Lecture Series

Doctoral researchers, postdocs and engineers offer an extracurricular lecture series for advanced Bachelor's and early-stage Master's students, providing an accessible introduction to the group's current research. In addition to communicating recent scientific and technological developments, the series opens an important pathway for engaging talented students and encouraging them to undertake their Bachelor's or Master's theses within the laboratory. The series will be continued and expanded in the future.

LECTURERS	TOPIC
Lukas Schmidbauer Simon Thelen Maja Franz	Das Quantentutorial: Vom Optimierungsproblem zum Schaltkreis
Dr.-Ing. Ralf Ramsauer	Vom Prompt zum Treiber: Interaktive Linux Kernelentwicklung mit KI
Oliver von Sicard	Preise und Pixel: KI erkennt Prospekt-Pannen mit YOLO, LLM und OpenCV – meistens
Maja Franz	Hype oder Hoffnung? Quantencomputing in maschinellem Lernen
Simon Thelen	Zwischen Qubits und QR-Codes: Googles neuer Quantenalgorithmus



7. Community Service

Scientific Peer Review

- Physical Review A
- Physical Review Letters
- Optics Express
- Carl Hanser
- O'Reilly
- Journal of Systems and Software
- International Journal of Theoretical Physics
- Computer Science Review
- Journal of Software: Evolution and Process
- IEEE Transactions on Software Engineering
- IEEE CogMI
- IEEE Resilience Week
- SIGMOD Demo
- IEEE ICDE
- EDBT/ICDT
- Empirical Software Engineering Journal
- ACM Transactions on Database Systems
- IEEE ICWS
- Information Systems
- Physica A
- LITES
- npj Quantum Information
- Enrico Fermi Fellowships
- IEEE Software
- ASCR (DOE): Accelerated Research in Quantum Computing
- European Physical Journal
- EU HORIZON EIC
- EU EISMEA
- EU HORIZON Digital Emerging
- German Federal Ministry of Research, Technology and Space
- IEEE Design & Test
- DFG (German Research Council)

Programme Committees

Programme Committees are a crucial component of every scientific conference and serve a role similar to that of peer review for journals – except that in addition to strict standards for evaluating the merits and drawbacks of research contributions, timely reliable contributions are required. Members of the lab served on about 35 programme committees in the reporting period.

Q-SE@ICSE	2023, 2024, 2025
IEEE QSW	2022, 2023, 2024, 2025
QP@Programming	2023, 2024, 2025
Q-SANER@SANER	2023, 2024, 2025
SQS@ICSOC	2023, 2024, 2025
IEEE QCE (QML main track; QML & QSYS main tracks, Posters)	2024, 2025, 2026
WIHPQC@QCE	2025
Q-SET@QCCE	2024, 2025
QAIO@ICART	2025
ACM SIGSAC	2024
IEEE CCGRID	2025, 2026
IEEE QDML@ICDE	2025, 2026

| Awards

We are proud to celebrate the achievements of our students, whose dedication and talent have been recognised through a range of awards and honours. The photographs on this page highlight these accomplishments and the individuals.









8. Theses

Student Theses

We supervise Bachelor's and Master's theses on a wide variety of topics matching our interests in quantum computing, system architecture research and software engineering research. We co-supervise theses in collaboration with other faculties (EE, ANK), and work intensively with regional and international partners.

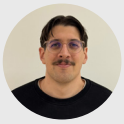
Investigation of the Performance of Different QAOA Variants Under the Influence of Realistic Noise

Simon Thelen
Master, October 2023



Analysis and Evaluation of Quantum Compilers

Vincent Gierisch
Master, May 2024



Order Reduction Analysis of Higher Order Terms in a Quantum-Computing Context

Lukas Schmidbauer
Bachelor, November 2023



Improving the QUantum Computing Application benchmaRK (QUARK) Framework

Martin Meilinger
Bachelor, September 2023



Formal Verification of Real-Time Systems Using Model-Based Quantification

Benno Bielmeier
Master, February 2025



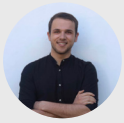
Porting Simulated Quantum Algorithms to the Q-Exa20: Challenges and Results

Laura Madajczyk
Bachelor, April 2025



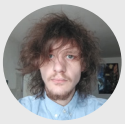
Comparative Analysis of Tracing Mechanisms in Linux for Real-Time Systems

Alexander Letaief
Bachelor, February 2025



Comparative Analysis of Parameter Selection Heuristics for the QAOA Algorithm

Vincent Eichenseher
Bachelor, March 2024



Optimisation of Quantum Gates via ZX-calculus

Jonathan Reyersbach
Master, May 2025



Vergleich von Variationalen Quantenschaltkreis-Strukturen für Reinforcement Learning

Andreas Fellner
Bachelor, February 2024



Offline Runtime Verification of Automotive ECUs via Hardware Trace

Ernyou Lim
Bachelor, April 2026



Conception and Integration of Accessible Hardware Demonstrators for Quantum Computing

Benjamin Zec
Bachelor, January 2026



Performance Characterisation of Quantum Circuit Simulators

Philipp Holz
Bachelor, May 2026



Quantum Random Number Generator as a Service

Simon Rothe
Bachelor, October 2023



Integration of Optical Computation in Processor Architectures for Automotive Use Cases



Florian Schulenberg
Bachelor, March 2024

Reduction of Virtual Memory Management Overhead



Lukas Landgraf
Bachelor, February 2025

Tailoring CPUs: Custom modifications of the Rocket-Chip Core in Chisel



Felix Wagner
Bachelor, February 2025

Entwicklung eines Linux-Kernel-Moduls zum transparenten Tunneln von CAN über IP



Matthias Unterrainer
Bachelor, October 2023

Automatisierte Übungs-erfassung und Wieder-holungserkennung mithilfe einer Smartwatch



Markus Schottenhammer
Bachelor, March 2024

Human Gait through Reinforcement Learning in Simulated Agents



Jonas Schmidt
Bachelor, July 2024

Dissertations

ONGOING DISSERTATION PROJECTS

NAME	WORKING TITLE	START
Nils Rabeneck	Analogue Quantum Simulation	2025
Dominik Köster	Quantum Error Mitigation and Correction	2025
Nicole Höß	Socio-Technical Software Engineering	2025
Vincent Gierisch	Reproducible Quantum Systems Design	2025
Maja Franz	Quantum Machine Learning	2024
Simon Thelen	FTQC-Centric Quantum Optimisation	2024
Lukas Schmidbauer	Quantum Programming Abstractions	2024
Tom Krüger	Foundations of Quantum Algorithms	2022

PHD THESES AWAITING DEFENCE

NAME	TITLE	START
Maniraman Periyasamy	Scalable Quantum Machine Learning in the NISQ Era	2023
Hila Safi	Hardware-Software Co-Design for Quantum Computing: Full-Stack Optimisation and Industrial Application to NP-Complete Problems	2023

External Reviewer/Committee

NAME	UNIVERSITY	SUPERVISORS
Emmanuelle Dri	Politecnico di Torino	Prof. Dr. Bartolomeo Montrucchio
Ilmo Salmenperä	University of Helsinki	Prof. Dr. Jukka K. Nurminen
Giuseppe Bisicchia	University of Pisa	Prof. Dr. Antonio Brogi Prof. Dr. Jose García-Alonso

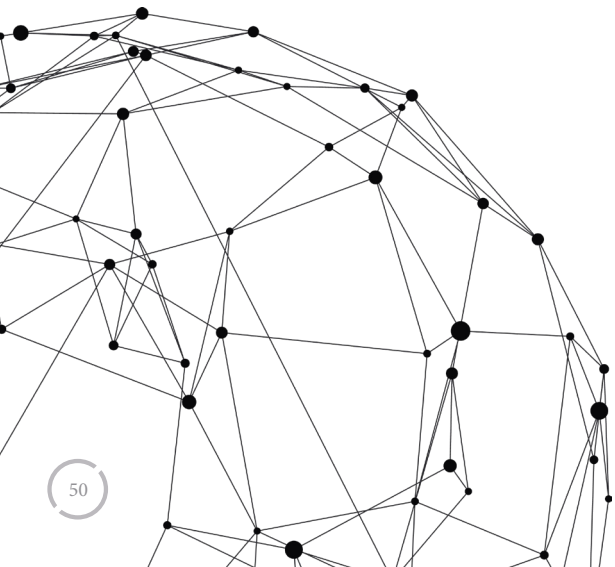
| Finished PhD Theses

04/21 – 06/25: Manuel Schönberger

Manuel Schönberger successfully defended his PhD thesis before an internationally acclaimed committee comprising Prof. Dr. Immanuel Trummer from Cornell University, Prof. Dr. Kurt Stockinger from University of Zürich and Zürcher Hochschule, Prof. Dr. Jürgen Frikel from OTH as head of the committee, and Wolfgang Mauerer as his supervisor and first examiner. Schönberger's excellent dissertation that produced (among others) three CORE A* papers, which is only matched by very few such endeavours, led to the first native PhD that was ever awarded at OTH Regensburg. It has not only broken new ground, but set high standards for any upcoming efforts.







9. Scientific Leadership

2017–present
Scientific Director
Bavarian Science Forum (BayWISS) for Digitalisation
23 participating universities

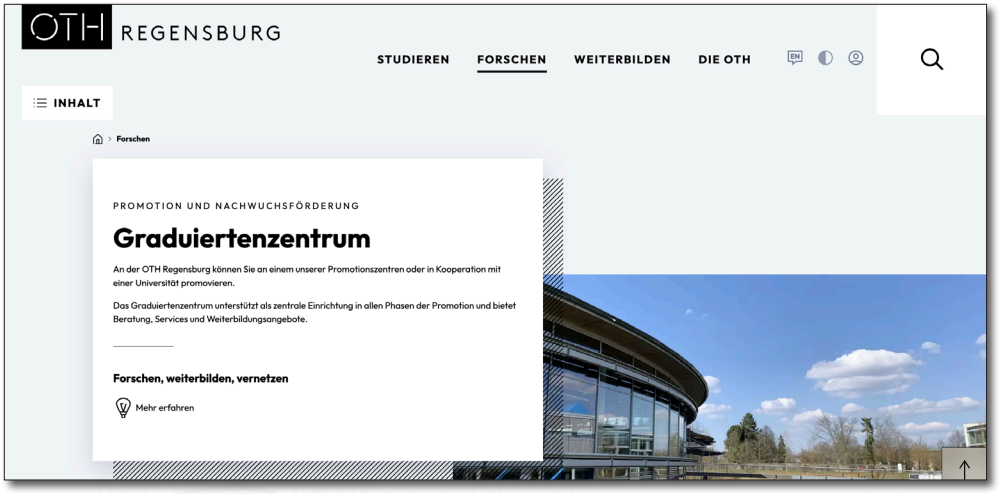
2020–present
Scientific Director
Regensburg Centre for Artificial Intelligence (RCAI)
39 professors across 5 faculties

2022–present
Co-Spokesperson
Jointly with Prof. Wille (TUM) and Prof. Lässig (HSZG)
Working Group Quantum Computing
German Computer Science Society (Gesellschaft für Informatik, GI)

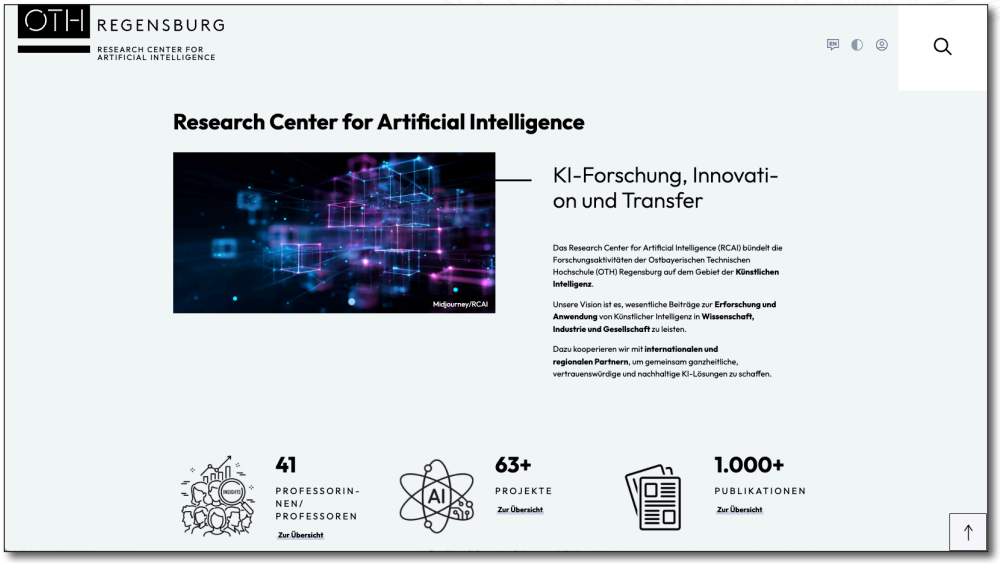
2024–present
Scientific Director
Promotionszentrum Angewandte Informatik und Mathematik (PZAI)
Graduate School for Applied Computer Science and Mathematics
Members: Technical University of Applied Sciences Regensburg
University of Applied Sciences Munich
Technical University of Applied Sciences Nuremberg

2024–present
Co-Initiator and Programme Board Member
Jointly with Prof. Schäfer (KIT), Prof. Eisert (FUB),
Prof. Wille (TUM) and Prof. Fauseweh (U Dortmund)
Priority Programme 2514: Quantum Software, Algorithms and Systems
German Research Council (Deutsche Forschungsgemeinschaft, DFG)

2023–present
Münchner Kreis
Member of the Research Council
Head of Working Group "Quantum Computing"


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STUDIEREN
FORSCHEN
WEITERBILDEN
DIE OTH
INHALT
Forschen
PROMOTION UND NACHWUCHSFÖRDERUNG
Graduiertenzentrum
An der OTH Regensburg können Sie an einem unserer Promotionszentren oder in Kooperation mit einer Universität promovieren.
Das Graduiertenzentrum unterstützt als zentrale Einrichtung in allen Phasen der Promotion und bietet Beratung, Services und Weiterbildungsangebote.
Forschen, weiterbilden, vernetzen
Mehr erfahren


OTH REGENSBURG
STUDIEREN
FORSCHEN
WEITERBILDEN
DIE OTH
Studieren
Studiengangübersicht
ZERTIFIKAT
Zusatzstudium Quantentechnologie
Das modular aufgebaute Zusatzstudium dient dem Erwerb von Kompetenzen theoretischer und praktischer Art in der Quantentechnologie. Insbesondere wird den Studierenden ein tiefgehendes Verständnis in den Bereichen Quantencomputing, Quantenkommunikation und Quantensensorik vermittelt. Das Zusatzstudium ist für Masterstudierende, umfasst eine Regelstudienzeit von drei Semestern und erfolgt studienbegleitend außerhalb bestehender Studiengänge. Das Zusatzstudium kann im Sommer- und im Wintersemester begonnen werden.
AUF EINEN BLICK
Abschluss
Zertifikat
Angebotstyp
Zusatzstudium
ECTS-Punkte
15


OTH REGENSBURG
RESEARCH CENTER FOR ARTIFICIAL INTELLIGENCE
Research Center for Artificial Intelligence
Midjourney/RCAI
KI-Forschung, Innovation und Transfer
Das Research Center for Artificial Intelligence (RCAI) bündelt die Forschungsaktivitäten der Ostbayerischen Technischen Hochschule (OTH) Regensburg auf dem Gebiet der Künstlichen Intelligenz.
Unsere Vision ist es, wesentliche Beiträge zur Erforschung und Anwendung von Künstlicher Intelligenz in Wissenschaft, Industrie und Gesellschaft zu leisten.
Dazu kooperieren wir mit internationalen und regionalen Partnern, um gemeinsam ganzheitliche, vertrauenswürdige und nachhaltige KI-Lösungen zu schaffen.
41
PROFESSORINNEN/ PROFESSOREN
Zur Übersicht
63+
PROJEKTE
Zur Übersicht
1.000+
PUBLIKATIONEN
Zur Übersicht

10. Software

Open Source Tools and Components

Mauerer and his laboratory have published all their scientific results as Open Source-Software since 2005, considerably pre-dating recent trends towards scientific openness. The group has produced more than 5,000 commits in internal and external repositories, from small tools to the Linux kernel. We are actively engaged in the quantum ecosystem, and also target it for scientific studies on quantitative software engineering of their own. Software packages are actively maintained by the group: We continuously extend their functionality, fix bugs, and bring them up to date with the latest developments in any underlying libraries.

QML Essentials



Tool-kit for commonly used quantum machine learning ansätze and utility functions for working with QML and data re-uploading models for current and error-corrected machines.

Mind the QApp



Visualisation and teaching tool for training scenarios to study effects and problems in Quantum Machine Learning.

Grinch



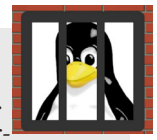
Minimalist operating system as well as a hypervisor for RISC-V chips. It is a basis for real-time quantum control, and also used for education.

PaStA



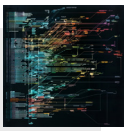
Tool for tracking maintenance and process quality of OSS projects used in safety-critical, certification-relevant or high-reliability scenarios.

Jailhouse



Lightweight, real-time, static partitioning hypervisor. We contribute ARM and RISC-V architectures (superseded by Grinch).

Codeface



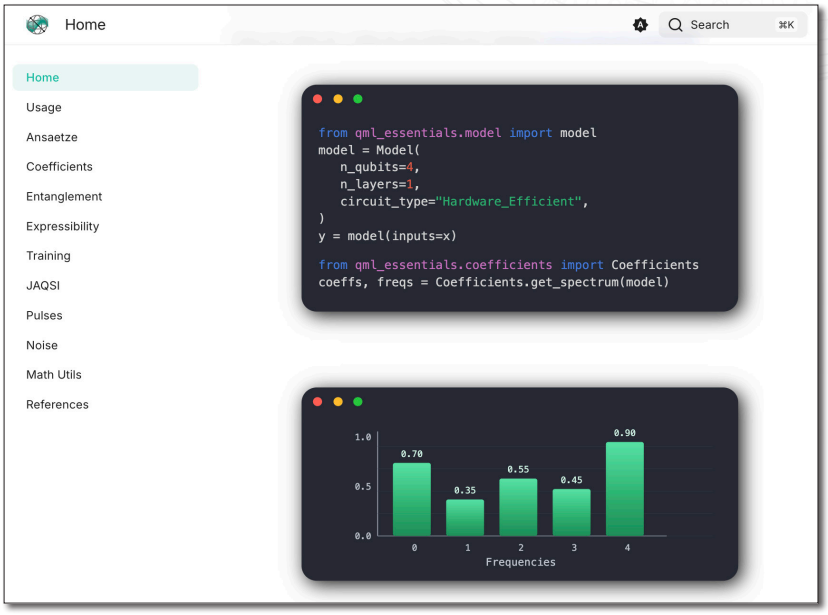
Framework for analysing the technical and social evolution of software projects, including the quantum computing ecosystem.

Accessing the "Digital Twin" of a quantum processing unit through our Linux kernel interface

```
root@qal:~# uname -a
Linux buildroot 6.16.0-rc4 #1 SMP PREEMPT_RT riscv64 GNU/Linux

root@qal:~# dmesg | grep qal
qal_qpx_mmio 200000.qpx: Found QPX version 0.1
qal_qpx_mmio 200000.qpx: Maximum number of qubits: 100
qal_qpx_mmio 200000.qpx: Maximum shots per job: 100000
qal_qpx_mmio 200000.qpx: Registered /dev/qal0
qal_qpx_pci 0000:00:0e.0: enabling device (0000 -> 0002)
qal_qpx_pci 0000:00:0e.0: Using MSI(-X) Interrupt 20
qal_qpx_pci 0000:00:0e.0: Using MSI(-X) Interrupt 21
qal_qpx_pci 0000:00:0e.0: Found QPX version 0.1
qal_qpx_pci 0000:00:0e.0: Maximum number of qubits: 100
qal_qpx_pci 0000:00:0e.0: Maximum shots per job: 100000
qal_qpx_pci 0000:00:0e.0: Registered /dev/qal1

root@qal:~# qal_execute /dev/qal0 /share/circuits/Hadamard.qal 10000
/dev/qal0: Job 0 finished: The operation was successful
Dumping Job 0 (10000 shots)
Histogram:
  0x0000001f 4964
  0x00000000 5036
Closing /dev/qal0
```



QML Essentials documentation in a web browser

| Reproduction Packages

Reproduction packages make results transparent, verifiable, and reusable by other research groups. The packages contain all materials needed to inspect and reproduce experiments and analyses. In contrast to software packages, we do not continuously maintain reproduction packages, but make sure they can be re-used indefinitely and without external dependencies that might get lost over time.

Hybrid Mixed-Integer Linear Programming for Large-Scale Join Order Optimisation



Manuel Schönberger, Immanuel Trummer, and Wolfgang Mauerer

From Hope to Heuristic: Realistic Runtime Estimates for Quantum Optimisation in NHEP



Maja Franz, Manuel Schönberger, Melvin Strobl, Eileen Kühn, Achim Streit, Pía Zurita, Markus Diefenthaler, and Wolfgang Mauerer

Structural Approximation of Optimisation Landscapes and non-Iterative Quantum Optimisation



Tom Krüger and Wolfgang Mauerer

Large-Scale Multiple Query Optimisation with Incremental Quantum(-Inspired) Annealing



Manuel Schönberger, Immanuel Trummer, and Wolfgang Mauerer

Predict and Conquer: Navigating Algorithm Trade-Offs with Quantum Design Automation



Simon Thelen and Wolfgang Mauerer

From Tracepoints to Timeliness: A Semi-Markov Framework for Predictive Runtime Analysis



Benno Bielmeier, Ralf Ramsauer, Takahiro Yoshida, and Wolfgang Mauerer

Out of Tune: Demystifying Noise-Effects on Quantum Fourier Models



Maja Franz, Melvin Strobl, Leonid Chaichenets, Eileen Kühn, Achim Streit, and Wolfgang Mauerer

QML-Essentials: A Framework for Working with Quantum Fourier Models

Melvin Strobl, Maja Franz, Eileen Kühn, Wolfgang Mauerer, and Achim Streit



SAT Strikes Back: Parameter and Path Relations in Quantum Toolchains

Lukas Schmidbauer and Wolfgang Mauerer



Stacking the Odds: Full-Stack Quantum System Design Space Exploration

Hila Safi, Medina Bandic, Christoph Niedermeier, Carmen G. Almudever, Sebastian Feld, and Wolfgang Mauerer



Path Matters: Industrial Data Meet Quantum Optimisation

Lukas Schmidbauer, Carlos A. Riofrío, Florian Heinrich, Vanessa Junk, Ulrich Schwenk, Thomas Husslein, and Wolfgang Mauerer



Does the Tool Matter? Exploring Some Causes of Threats to Validity in Mining Software Repositories

Nicole Höß, Carlos Paradis, Rick Kazman, and Wolfgang Mauerer



Approximating under the Influence of Quantum Noise and Compute Power

Simon Thelen, Hila Safi, and Wolfgang Mauerer



Quantum Data Encoding Patterns and their Consequences

Martin Gogeißl, Hila Safi, and Wolfgang Mauerer



Co-Design of Quantum Hardware and Algorithms in Nuclear and High Energy Physics

Maja Franz, Pía Zurita, Markus Diefenthaler, and Wolfgang Mauerer



Quantum-Inspired Digital Annealing for Join Ordering

Manuel Schönberger, Immanuel Trummer, and Wolfgang Mauerer



Ready to Leap (by Co-Design)? Join Order Optimisation on Quantum Hardware

Manuel Schönberger, Stefanie Scherzinger, and Wolfgang Mauerer



Polynomial Reduction Methods and their Impact on QAOA Circuits

Lukas Schmidbauer, Karen Wintersperger, Elisabeth Lobe, and Wolfgang Mauerer

Hype or Heuristic? Quantum Reinforcement Learning for Join Order Optimisation

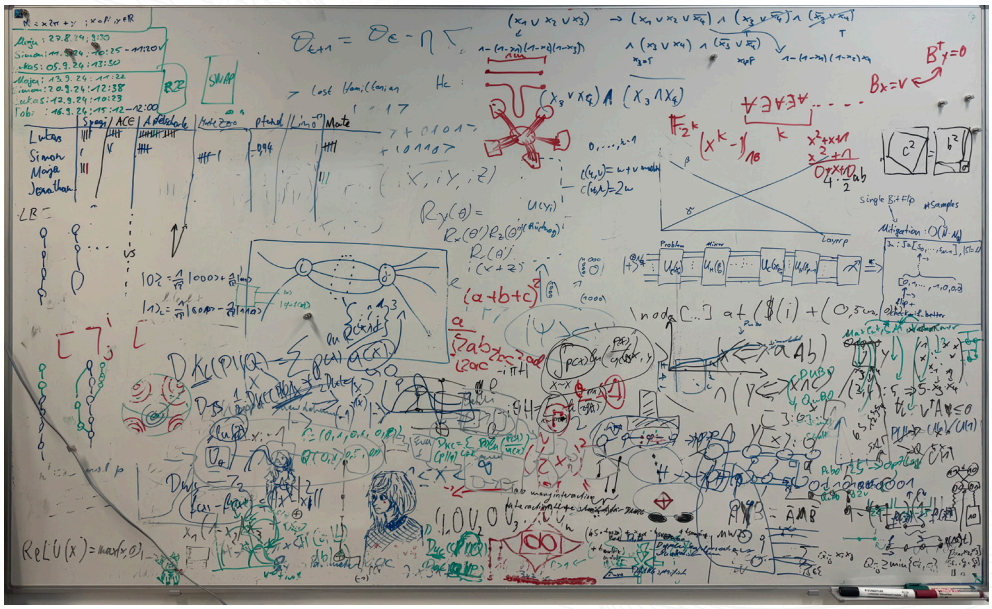
Maja Franz, Tobias Winker, Sven Groppe, and Wolfgang Mauerer

Effects of Imperfections on Quantum Algorithms: A Software Engineering Perspective

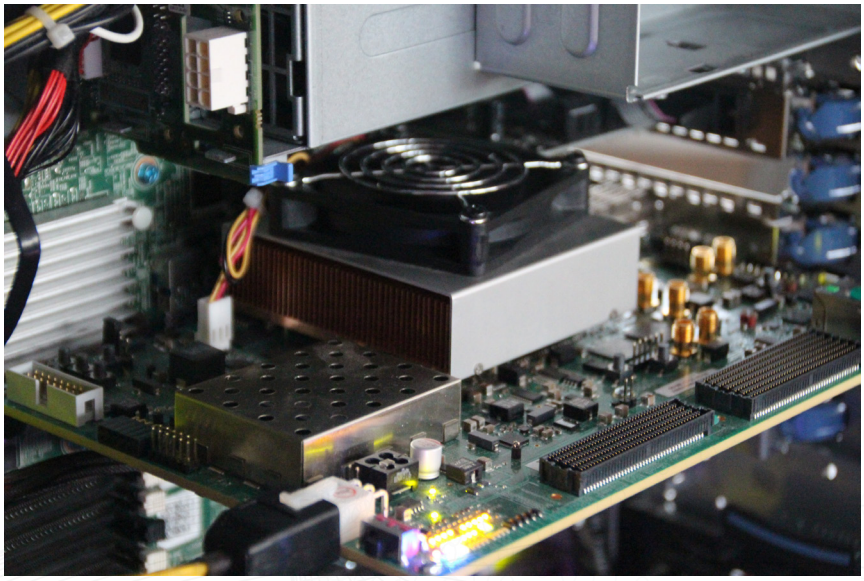
Felix Greiwe, Tom Krüger, and Wolfgang Mauerer

Make Some Noise! Measuring Noise Model Quality in Real-World Quantum Software

Stefan Raimund Maschek, Jürgen Schwitalla, Maja Franz, and Wolfgang Mauerer



The actual research, long before any reproduction package exists



A Field-Programmable Gate Array acts as Digital Twin for a Quantum Processing Unit, and interacts with a controller on a classical host system. This allows for pre-hardware interface design and testing.

```
from quantum_framework import *
import networkx as nx

# load benchmark instances, train model
framework = AlgorithmSelectionFramework()
framework.add_results(load_results())
instance = MaxCut(nx.erdos_renyi_graph(n = 30, p = 0.5))

# find sufficiently large cuts quickly
with minimize(RUNTIME):
    with RELATIVE_SOLUTION_QUALITY ≥ 0.75:
        result = framework.quantum_solve(instance)
    with SOLUTION_QUALITY ≥ 200:
        result = framework.quantum_solve(instance)

# favor quality over runtime (ratio 2:1)
with maximize(2/3 * SOLUTION_QUALITY - 1/3 * RUNTIME):
    result = framework.quantum_solve(instance)

# find best solution in 10s, given there is a 10%
# improvement per second
with maximize(SOLUTION_QUALITY), (
    (RUNTIME ≤ 10 * SECONDS) &
    (RELATIVE_SOLUTION_QUALITY_PER_RUNTIME ≥ 0.1)
):
    result = framework.quantum_solve(instance)
```

Code example using our algorithm selection framework to solve an optimisation problem while taking desired target qualities into account.

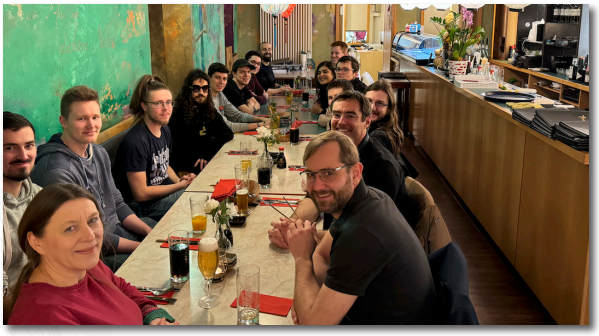
11. Team at Work
... and Beyond



Simon Thelen discusses his research at IEEE QCE'25 in Albuquerque (USA)



Vincent Gierisch shows his work at IEEE ICSOC'25 in Shenzhen (China)



Christmas Gathering 2023



QLindA Consortium Meeting (BMBF) at OTH Regensburg

Tom Krüger in front of his poster at IEEE QCE'25 in Albuquerque (USA)



Simon Thelen, Lukas Schmidbauer, Mani Periyasamy, Hila Safi and Wolfgang Mauerer with other MQV conference attendees at IEEE QCE'25 in Albuquerque (USA)





Welcoming new team members in 2025



Team retreat at the end of 2024

12. Engagement with Policymakers

We continuously interact with political stakeholders at regional and national levels, provide guidance and advice on quantum technologies, contribute to roadmapping processes, and use our comprehensive connections with industry and knowledge of their needs to connect policymakers, technology providers and users.



AI.BAY booth with minister Judith Gerlach, MdL



Policy Discussions with Dr. Caroline Wagner, MdB



Minister Dr. Fabian Mehring, MdL, with fellow IBM quantum hackathon jurors Prof. Mauerer and Prof. Wille (TUM)

Minister Dr. Markus Blume activates our quantum key distribution system





Round table on quantum software with vice minister Tobias Gotthardt, MdL



Minister Hubert Aiwanger, MdL, learns about quantum AI



Peter Aumer, MdB, launches our Quantum Random Number generation service



Round table on Quantum-HPC integration at the Federal Ministry of Digitalisation

Lab visit by Johannes Becher, MdL and Jürgen Mistol, MdL





Vice Minister Tobias Gotthardt, MdL, visits our laboratory

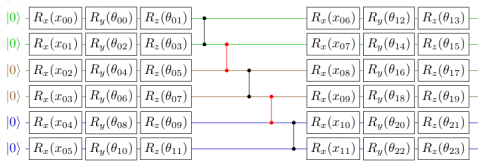
Appendix
Selected Results

CutReg: A loss regularizer for enhancing the scalability of QML via adaptive circuit cutting

Maniraman Periyasamy*†, Christian Ufrecht* Daniel D. Scherer*, Wolfgang Mauerer†‡
*Fraunhofer IIS, Fraunhofer Institute for Integrated Circuits IIS, Nürnberg, Germany
†Technical University of Applied Sciences Regensburg, Regensburg, Germany
‡Siemens AG, Corporate Research, Munich, Germany

Summary—Whether QML can offer a transformative advantage remains an open question. The severe constraints of NISQ hardware, particularly in circuit depth and connectivity, hinder both the validation of quantum advantage and the empirical investigation of major obstacles like barren plateaus. Circuit cutting techniques have emerged as a strategy to execute larger quantum circuits on smaller, less connected hardware by dividing them into sub-circuits. However, this partitioning increases the number of samples needed to estimate the expectation value accurately through classical post-processing compared to estimating it directly from the full circuit.

We introduce a novel regularisation term into the QML optimisation process, directly penalising the overhead associated with sampling. We demonstrate that this approach enables the optimiser to balance the advantages of gate cutting against the optimisation of the typical ML cost function. Specifically, it navigates the trade-off between minimising the cutting overhead and maintaining the overall accuracy of the QML model, paving the way to study larger complex problems in pursuit of quantum advantage.



QML-Essentials—A Framework for working with Quantum Fourier Models

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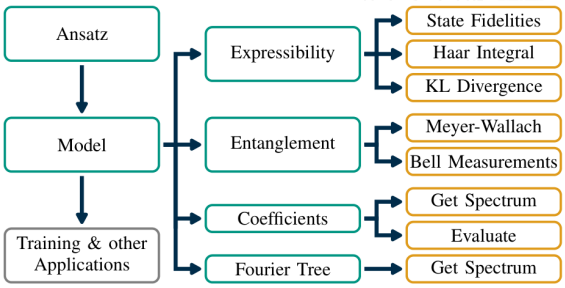
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Summary—We propose a framework designed for the analysis of Quantum Machine Learning models. It is based on the PennyLane simulator and facilitates the evaluation and training of Variational Quantum Circuits. It provides additional functionality including the ability to add different types of noise to the classical simulation, to different parameter initialisation strategies, to the calculation of expressibility and entanglement for a given model. As an intrinsic property of Quantum Fourier Models, it provides two methods for calculating the corresponding Fourier spectrum: one via the Fast Fourier Transform and another analytical method based on the expansion of the expectation value using trigonometric polynomials. It also provides a set of approaches that allow a fast and straightforward implementation of Quantum Machine Learning models. We extend the PennyLane simulator with tools that allow researchers a more convenient start with Quantum Fourier Models and aim to unify the analysis of Variational Quantum Circuits.



From Tracepoints to Timeliness: A Semi-Markov Framework for Predictive Runtime Analysis

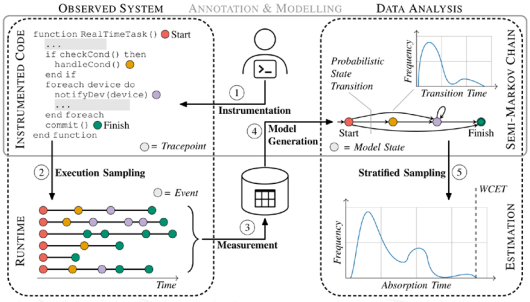
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***Summary*—Detecting and resolving violations of temporal constraints in real-time systems is both, time-consuming and resource-intensive, particularly in complex software environments. Measurement-based approaches are widely used during development, but often are unable to deliver reliable predictions with limited data. This paper presents a hybrid method for worst-case execution time estimation, combining lightweight runtime tracing with probabilistic modelling. Timestamped system events are used to construct a semi-Markov chain, where transitions represent empirically observed timing between events. Execution duration is interpreted as time-to-absorption in the semi-Markov chain, enabling worst-case execution time estimation with fewer assumptions and reduced overhead. Empirical results from real-time Linux systems indicate that the method captures both regular and extreme timing behaviours accurately, even from short observation periods. The model supports holistic, low-intrusion analysis across system layers and remains interpretable and adaptable for practical use.**



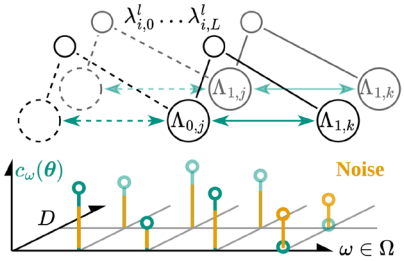
Out of Tune: Demystifying Noise-Effects on Quantum Fourier Models

Maja Franz[1†], Melvin Strobl[2†], Leonid Chaichenets[2], Eileen Kuehn[2], Achim Streit[2], Wolfgang Mauerer[1, 3]

[1]Technical University of Applied Sciences Regensburg, Germany.
[2]Karlsruhe Institute of Technology, Germany.
[3]Siemens AG, Technology, Munich, Germany.

***Summary*—Variational quantum algorithms have received substantial theoretical and empirical attention. As the underlying variational quantum circuit (VQC) can be represented by Fourier series that contain an exponentially large spectrum in the number of input features, hope for quantum advantage remains. Nevertheless, it remains an open problem if and how quantum Fourier models (QFMs) can concretely outperform classical alternatives, as the eventual sources of non-classical computational power are far from being fully understood. Likewise, hardware noise continues to pose a challenge that will persist also along the path towards fault tolerant quantum computers.**

We study VQCs with Fourier lenses, which provides possibilities to improve their understanding, while also illuminating and quantifying constraints and challenges. We seek to elucidate critical characteristics of QFMs under the influence of noise. Specifically, we undertake a systematic investigation into the impact of noise on the Fourier spectrum, expressibility, and entangling capability of QFMs through extensive numerical simulations and link these properties to training performance. The insights may inform more efficient utilisation of quantum hardware and support the design of tailored error mitigation and correction strategies. Decoherence imparts an expected and broad detrimental influence across all ansätze. Nonetheless, we observe that the severity of these deleterious effects varies among different model architectures, suggesting that certain configurations may exhibit enhanced robustness to noise and show computational utility.

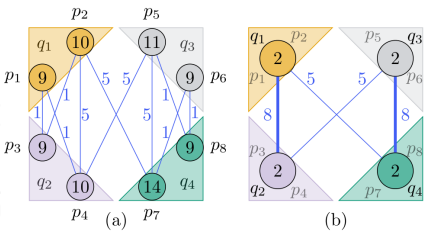


Large-Scale Multiple Query Optimisation with Incremental Quantum(-Inspired) Annealing

MANUEL SCHÖNBERGER, Technical University of Applied Sciences Regensburg, Germany
IMMANUEL TRUMMER, Cornell University, USA
WOLFGANG MAUERER, Technical University of Applied Sciences Regensburg, Germany and Siemens AG, Technology, Germany

Summary—Multiple-query optimisation (MQO) seeks to reduce redundant work across query batches. While MQO offers opportunities for dramatic performance improvements, the problem is NP-hard, limiting the sizes of problems that can be solved on generic hardware. We propose to leverage specialised hardware solvers for optimisation, such as Fujitsu's Digital Annealer (DA), to scale up MQO to problem sizes formerly out of reach.

We present a novel incremental processing approach that combines classical computation with DA acceleration. By efficiently partitioning MQO problems into sets of partial problems, and by applying a dynamic search steering strategy that reapplies initially discarded information to incrementally process individual problems, our method overcomes capacity limitations, and scales to extremely large MQO instances (up to 1000 queries). A thorough and comprehensive empirical evaluation finds our method substantially outperforms existing approaches. Our generalisable framework lays the ground for other database use-cases on quantum-inspired hardware, and bridges towards future quantum accelerators.

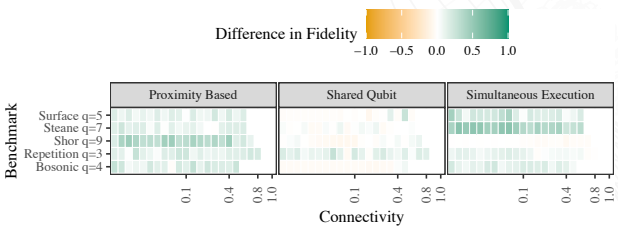


Stacking the odds: full-stack quantum system design space exploration

Hila Safi[1,4*†], Medina Bandic[2,3*†], Christoph Niedermeier[4], Carmen G. Almudever[5], Sebastian Feld[2,3] and Wolfgang Mauerer[1,4]

Summary—Design space exploration (DSE) plays an important role in optimising quantum circuit execution by systematically evaluating different configurations of compilation strategies and hardware settings. In this work, we study the impact of layout methods, qubit routing techniques, compiler optimisation levels, and hardware-specific properties, including noise characteristics, topological structures, connectivity densities, and device sizes. By traversing these dimensions, we aim to understand how compilation choices interact with hardware features. A central question in our study is whether carefully selected device parameters and mapping strategies, including initial layouts and routing heuristics, can mitigate hardware-induced errors beyond standard error mitigation methods.

We show that choosing the right software strategies (e.g., layout and routing) and tailoring hardware properties (e.g., reducing noise or leveraging connectivity) significantly enhances the fidelity of quantum circuit executions. We provide performance estimates using metrics such as circuit depth, gate count, and expected fidelity. These findings highlight the value of hardware-software co-design, especially as quantum systems scale and move toward error-corrected computing. Our noisy simulations include quantum error correction (QEC) scenarios, revealing similar sensitivities to layout and connectivity. Co-design principles will be vital for integrating QEC in future devices, and we offer practical guidance for co-optimizing mapping, routing, and hardware configuration in real-world quantum computing.



Hybrid Mixed Integer Linear Programming for Large-Scale Join Order Optimisation

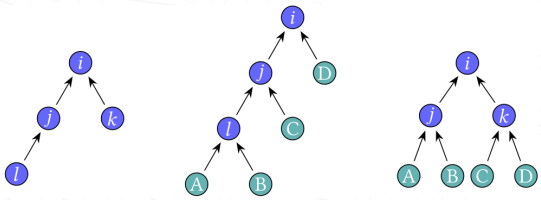
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***Summary*—Finding optimal join orders is among the most crucial steps to be performed by query optimisers. Though extensively studied in data management research, the problem remains far from solved: While query optimisers rely on exhaustive search methods to determine ideal solutions for small problems, such methods reach their limits once queries grow in size. Yet, large queries become increasingly common in real-world scenarios, and require suitable methods to generate efficient execution plans. A variety of proposed heuristics for large-scale query optimisation suffer from declining solution quality as queries grow in size, or feature highly sub-optimal worst-case behaviour.**

We propose a novel method based on the paradigm of mixed-integer linear programming (MILP): By deriving a novel MILP model capable of optimising arbitrary bushy tree structures, we address the limitations of existing MILP methods for join ordering, and can rely on highly optimised MILP solvers to derive efficient tree structures that elude competing methods. To ensure optimisation efficiency, we embed our MILP method into a hybrid framework, which applies MILP solvers precisely where they provide the greatest advantage over competitors, while relying on more efficient methods for less complex optimisation steps. Our approach gracefully scales to extremely large query sizes joining up to 100 relations, and consistently achieves the most robust plan quality among a large variety of competing join ordering methods.



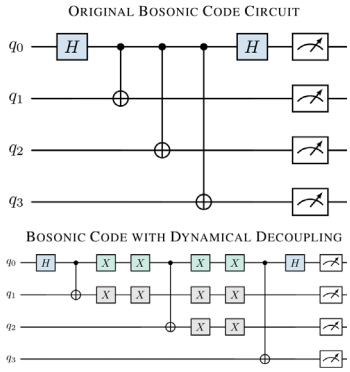
TWiDDle: Twirling and Dynamical Decoupling, and Crosstalk Noise Modeling

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***Summary*—Crosstalk remains a major source of correlated error in quantum systems, yet lacks a precise, community-wide definition – hindering systematic analysis and mitigation. We introduce a model-driven approach to crosstalk characterisation through three architecture-inspired noise models: (1) simultaneous two-qubit gate execution, (2) shared qubit interference, and (3) proximity-induced noise from shared control or readout hardware. These models act as both, diagnostic tools and building blocks for crosstalk-aware quantum programming. We assess their impact across a broad benchmark suite – quantum simulation, Grover's algorithm, and fault-tolerant primitives like surface, Shor, and Steane codes – and evaluate two mitigation techniques: dynamical decoupling and Pauli twirling. While both are discussed in the literature, only dynamical decoupling consistently enhances fidelity across noise types. Our work links low-level noise effects to high-level software engineering, underscoring the role of hardware-software co-design in scalable quantum computing. Model-based, hardware-aware design flows and composable noise abstractions improve error mitigation and program portability. Integrating such strategies into the tool-chain is essential for building resilient quantum programs under realistic noise conditions.**



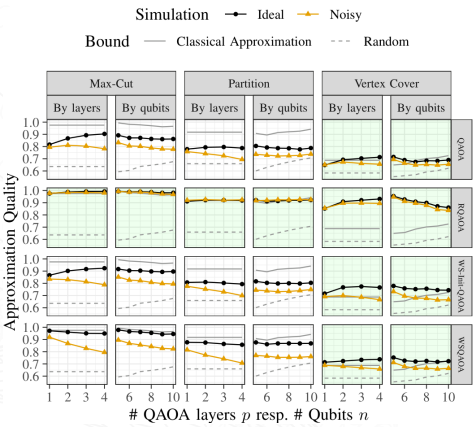
Approximating under the Influence of Quantum Noise and Compute Power

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***Summary*—The quantum approximate optimisation algorithm (QAOA) is at the core of many scenarios that aim to combine the power of quantum computers and classical high-performance computing appliances for combinatorial optimisation. Several obstacles challenge concrete benefits now and in the foreseeable future: Imperfections quickly degrade algorithmic performance below practical utility; overheads arising from alternating between classical and quantum primitives can counter any advantage; and the choice of parameters or algorithmic variant can substantially influence runtime and result quality. Selecting the optimal combination is a non-trivial issue, as it not only depends on user requirements, but also on details of the hardware and software stack. Appropriate automation can lift the burden of choosing optimal combinations for end-users: They should not be required to understand technicalities, but should receive best possible fulfilment of their non-functional requirements.**

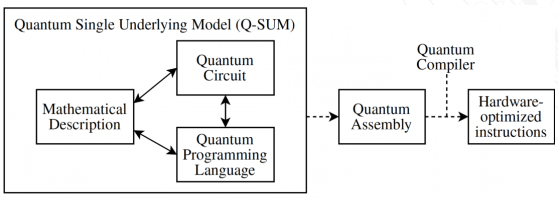


We determine factors that affect solution quality and temporal behaviour of four QAOA variants using comprehensive density-matrix-based simulations targeting three widely studied optimisation problems. Our simulations consider ideal quantum computation, and a continuum of scenarios troubled by realistic imperfections. Our results show strong differences between QAOA variants that can be pinpointed to narrow and specific effects. We identify influential co-variables and relevant non-functional quality goals that mark the relevant ingredients for designing abstraction mechanisms and automated tool-chains for devising quantum solutions from high-level problem specifications.

Towards View-based Development of Quantum Software

Joshua Ammermann [1], Wolfgang Mauerer [2], and Ina Schaefer [1]

***Summary*—Quantum computing is an interdisciplinary field that relies on the expertise of many different stakeholders. The views of various stakeholders on the subject of quantum computing may differ, thereby complicating communication. To address this, we propose a view-based quantum development approach based on a Single Underlying Model (SUM) and a supporting quantum Integrated Development Environment (IDE). We highlight emerging challenges for future research. Notably, this paper introduced the idea behind our DFG-funded fundamental research project within the priority programme 2514.**



Polynomial Reduction Methods and their Impact on QAOA Circuits

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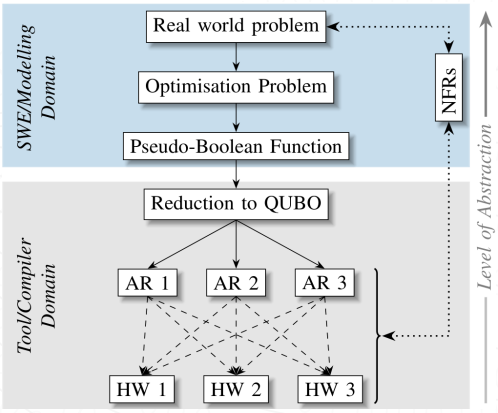
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***Summary*—Abstraction layers are of paramount importance in software architecture, as they shield the higher-level formulation of payload computations from lower-level details. Since quantum computing (QC) introduces many such details that are often unfamiliar to computer scientists, an obvious desideratum is to devise appropriate abstraction layers for QC. For discrete optimisation, one such abstraction is to cast problems in quadratic unconstrained binary optimisation (QUBO) form, which is amenable to a variety of quantum approaches. However, different mathematically equivalent forms can lead to different behaviour on quantum hardware, ranging from ease of mapping onto qubits to performance scalability.**

We show how using higher-order problem formulations (that provide better expressivity than plain QUBO formulations) and their automatic transformation into QUBO form can be used to leverage such differences to prioritise among different desired non-functional properties for quantum optimisation. Our quantitative study shows that the approach allows us to satisfy different trade-offs, and suggests various possibilities for the future construction of general-purpose abstractions and automatic generation of useful quantum circuits from high-level descriptions.

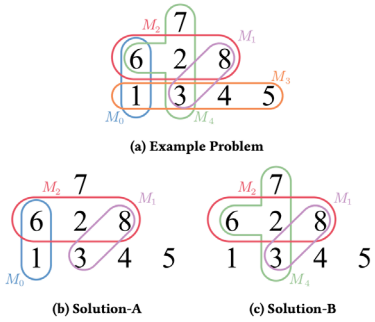


QCEDA: Using Quantum Computers for EDA

Matthias Jung[1,3(✉)], Sven O. Krumke[2], Christof Schroth[1], Elisabeth Lobe[4], and Wolfgang Mauerer[5]

***Summary*—The field of Electronic Design Automation (EDA) is crucial for microelectronics, but the increasing complexity of Integrated Circuits (ICs) poses challenges for conventional EDA: Corresponding problems are often NP-hard and are therefore in general solved by heuristics, not guaranteeing optimal solutions. Quantum computers may offer better solutions due to their potential for optimisation through entanglement, superposition, and interference. Most of the work in the area of EDA and quantum computers focus on how to use EDA for building quantum circuits; almost no research focuses on exploiting quantum computers to solve EDA problems.**

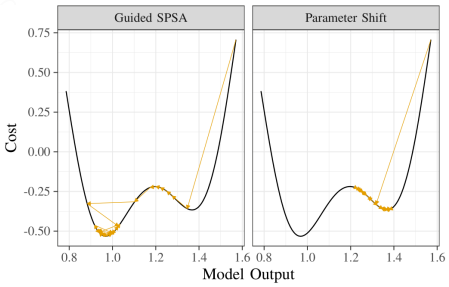
We investigate the feasibility and potential of quantum computing for a typical EDA optimisation problem reduced to the Min-k-Union problem. The problem is mathematically transformed into a Quadratic Unconstrained Binary Optimisation (QUBO) problem, which was successfully solved on an IBM quantum computer and a D-Wave quantum annealer.



Guided-SPSA: Simultaneous Perturbation Stochastic Approximation assisted by the Parameter Shift Rule

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***Summary*—The study of variational quantum circuits (VQCs) has received significant attention from the quantum computing community in recent years. These hybrid algorithms, utilising both classical and quantum components, are well-suited for noisy intermediate-scale quantum devices. Although estimating exact gradients using the parameter-shift rule to optimise the VQCs is realisable in NISQ devices, this approach does not scale well for larger problem sizes. The computational complexity, in terms of the number of circuit evaluations required for gradient estimation by the parameter-shift rule, scales linearly with the number of parameters in VQCs. On the other hand, techniques that approximate the gradients of the VQCs, such as the simultaneous perturbation stochastic approximation (SPSA), do not scale with the number of parameters but struggle with instability and often attain sub-optimal solutions. We introduce a novel gradient estimation approach called Guided-SPSA, which meaningfully combines the parameter-shift rule and SPSA-based gradient approximation. The Guided-SPSA results in a 15% to 25% reduction in the number of circuit evaluations required during training for a similar or better optimality of the solution found compared to the parameter-shift rule. The Guided-SPSA outperforms standard SPSA in all scenarios and outperforms the parameter-shift rule in scenarios such as sub-optimal initialisation of the parameters. We demonstrate numerically the performance of Guided-SPSA on different paradigms of quantum machine learning, such as regression, classification, and reinforcement learning.**

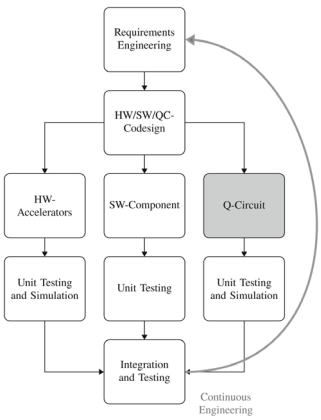


Challenges for Quantum Software Engineering: An Industrial Application Scenario Perspective

Cecilia Carbonelli, Michael Felderer, Matthias Jung, Elisabeth Lobe, Malte Lochau, Sebastian Luber, Wolfgang Mauerer, Rudolf Ramler, Ina Schaefer, and Christoph Schroth

***Summary*—Quantum software is becoming a key enabler for applying quantum computing to industrial use cases. This poses challenges to quantum software engineering in providing efficient and effective means to develop such software. Eventually, this must be reliably achieved using sound and well-principled engineering approaches. Given that quantum computers are based on fundamentally different principles from classical machines, this raises the question if, how, and to what extent established techniques for systematically engineering software need to be adapted.**

We analyse three paradigmatic application scenarios for quantum software engineering from an industrial perspective. The respective use cases centre around (1) optimisation and quantum cloud services, (2) quantum simulation, and (3) embedded quantum computing. Our aim is to provide a concise overview of the current and future applications of quantum computing in diverse industrial settings. We derive presumed challenges and provide research directions for this emerging field.

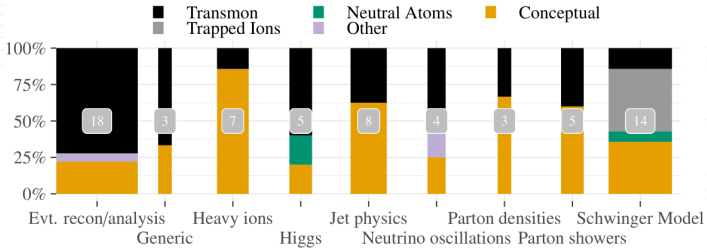


Co-Design of Quantum Hardware and Algorithms in Nuclear and High Energy Physics

Maja Franz[1,*], *Pía* Zurita[2,**], *Markus* Diefenthaler[3,***], and *Wolfgang* Mauerer[1,4,****]

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Summary—Quantum computing (QC) has emerged as a promising technology, and is believed to have the potential to advance nuclear and high energy physics (NHEP) by harnessing quantum mechanical phenomena to accelerate computations. In this paper, we give a brief overview of the current state of quantum computing by highlighting challenges it poses and opportunities it offers to the NHEP community. Noisy intermediate-scale quantum (NISQ) computers, while limited by imperfections and small scale, may hold promise for near-term quantum advantages when coupled with co-designed quantum algorithms and special-purpose quantum processing units (QPUs). We explore various applications in NHEP, including quantum simulation, event classification, and real-time experiment control, emphasising the potential of variational quantum circuits and related techniques. To identify current interests of the community, we perform an analysis of recent literature in NHEP related to QC.



Quantum Optimisation of General Join Trees

Manuel Schönberger[1,*], Immanuel Trummer[2] and Wolfgang Mauerer[1,3]

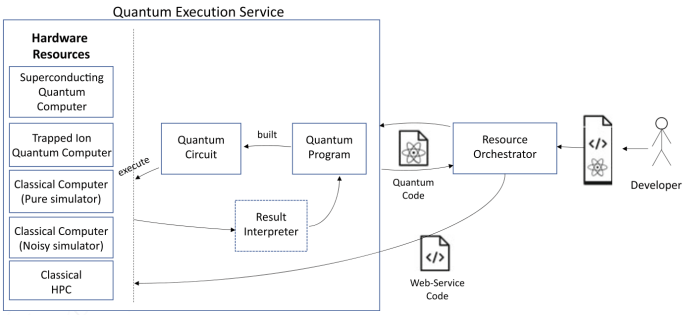
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Summary—Recent advances in the manufacture of quantum computers have attracted considerable attention across a wide range of fields, as early-stage quantum processing units (QPU) have become accessible. While contemporary quantum machines are very limited in size and capabilities, mature QPUs are speculated to eventually excel at optimisation problems. This makes them an attractive technology for database problems, many of which are based on complex optimisation problems with large solution spaces. Yet, the use of quantum approaches on database problems remains largely unexplored.
We address the long-standing join ordering problem, one of the most extensively researched database problems. Rather than running arbitrary code, QPUs require specific mathematical problem encodings. An encoding for the join ordering problem was recently proposed, allowing first small-scale queries to be optimised on quantum hardware. However, it is based on a faithful transformation of a mixed-integer linear programming (MILP) formulation for JO, and inherits all limitations of the MILP method. Most strikingly, the existing encoding only considers a solution space with left-deep join trees, which tend to yield larger costs than general, bushy join trees. We propose a novel QUBO encoding for the join ordering problem. Rather than transforming existing formulations, we construct a native encoding tailored to quantum systems, which allows us to process general bushy join trees. This makes the full potential of QPUs available for solving join order optimisation problems.

Challenges and Opportunities in Quantum Software Architecture

Tao Yue, Wolfgang Mauerer, Shaukat Ali, and Davide Taibi

Summary—Quantum computing is a relatively new paradigm that has raised considerable interest in physics and computer science in general but has so far received little attention in software engineering and architecture. Hybrid applications that consist of both quantum and classical components require the development of appropriate quantum software architectures. However, given that quantum software engineering (QSE) in general is a new research area, quantum software architecture – a sub-research area in QSE – is also understudied. We provide a list of research challenges and opportunities for such architectures. In addition, to make the content understandable to a broader computer science audience, we provide a brief overview of quantum computing and explain the essential technical foundations.



Effects of Imperfections on Quantum Algorithms: A Software Engineering Perspective

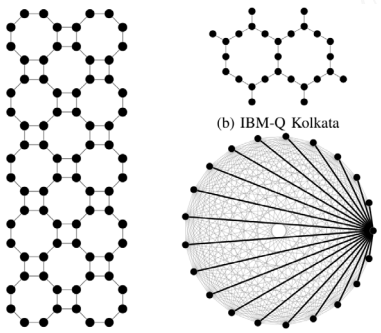
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Summary—Quantum computers promise speed-ups over classical approaches. Since any currently available implementations suffer from noise and imperfections, achieving concrete speed-ups for meaningful problem sizes remains a major challenge. Yet, imperfections and noise may remain present in quantum computing for a long while. Such limitations play no role in classical software computing, and software engineers are typically not well accustomed to considering such imperfections, although they substantially influence core properties of software and systems.

We show how to model imperfections with an approach tailored to (quantum) software engineers. We intuitively illustrate, using numerical simulations, how imperfections influence core properties of quantum algorithms on NISQ systems, and show possible options for tailoring future machines in a co-design approach. Our results are obtained from a software framework that we provide in form of an easy-to-use reproduction package. It does not require computer scientists to acquire deep physical knowledge on noise, yet provides tangible and intuitively accessible means of interpreting the influence of noise on common software quality and performance indicators.



Quantum Machine Learning: Foundation, New Techniques, and Opportunities for Database Research

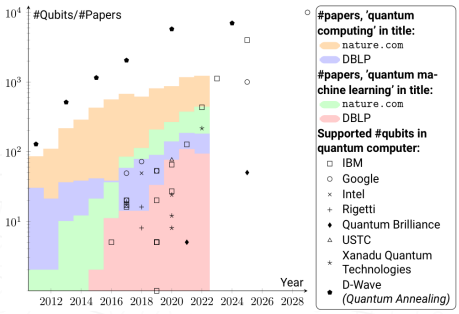
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Summary—In the last few years, the field of quantum computing has experienced remarkable progress. The prototypes of quantum computers already exist and have been made available to users through cloud services. While fault-tolerant and large-scale quantum computers are not available yet, the potential of this new technology is undeniable. Quantum algorithms have the proven ability to either outperform classical approaches for several tasks, or are impossible to be efficiently simulated by classical means under reasonable complexity-theoretic assumptions. Even current-day technology is speculated to exhibit computational advantages. Recent work uses quantum computers to solve machine learning tasks. As the database community has also successfully applied various machine learning algorithms on data management tasks, combining the fields seems to be a promising endeavour. Yet, quantum machine learning is a new research field for most database researchers.

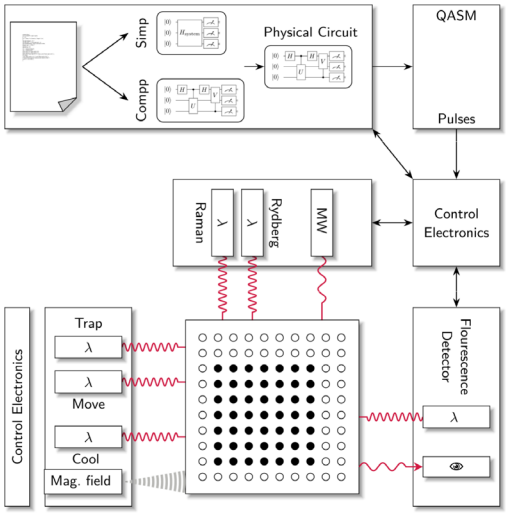
We provide a fundamental introduction to quantum computing and quantum machine learning and show the potential benefits and applications for database research. In addition, we demonstrate how to apply quantum machine learning to the join order optimisation problem in databases.



Neutral atom quantum computing hardware: performance and end-user perspective

Karen Wintersperger[1*], Florian Dommert[2], Thomas Ehmer[3], Andrey Hoursanov[4], Johannes Klepsch[5], Wolfgang Mauerer[1], Georg Reuber[6], Thomas Strohm[7], Ming Yin[8] and Sebastian Luber[9]

Summary—We present an industrial end-user perspective on the current state of quantum computing hardware for one specific technological approach, the neutral atom platform. Our aim is to assist developers in understanding the impact of the specific properties of these devices on the effectiveness of algorithm execution. Based on discussions with different vendors and recent literature, we discuss the performance data of the neutral atom platform. Specifically, we focus on the physical qubit architecture, which affects state preparation, qubit-to-qubit connectivity, gate fidelities, native gate instruction set, and individual qubit stability. These factors determine both the quantum-part execution time and the end-to-end wall clock time relevant for end-users, but also the ability to perform fault-tolerant quantum computation in the future. We end with an overview of which applications have been shown to be well suited for the peculiar properties of neutral atom-based quantum computers.



Make Some Noise! Measuring Noise Model Quality in Real-World Quantum Software

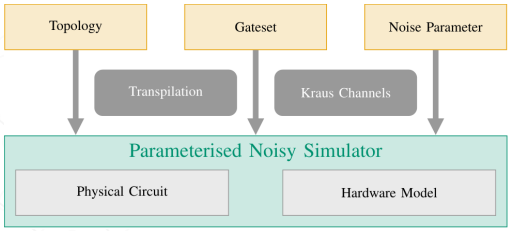
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***Summary*—Noise and imperfections are prevalent challenges in current systems. They will remain important in the post-NISQ era, as logical, error-corrected qubits will be based on software mechanisms. Noise models for classical simulation – that can exceed dimensions of actual systems – play a critical role in obtaining insights into properties of mechanisms for error correction and mitigation.**

We present, implement and validate a tunable noise model building on the Kraus channel formalism on a large-scale quantum simulator system (Qaptiva). We use empirical noise measurements from IBM quantum (IBMQ) systems to calibrate the model and create a realistic simulation environment. Experimental evaluation of our approach with Greenberger-Horne-Zeilinger (GHZ) state preparation and QAOA applied to an industrial use-case validates our approach, and demonstrates accurate simulation of hardware behaviour at reasonable computational cost.



We devise a method that allows for determining the quality of noise models for larger problem instances than is possible with existing metrics. To identify potentials of future quantum software and algorithms, we extrapolate the model to partially fault-tolerant systems, and give insights into the interplay between noise modelling and hardware-aware algorithm development.

Path Matters: Industrial Data Meet Quantum Optimization

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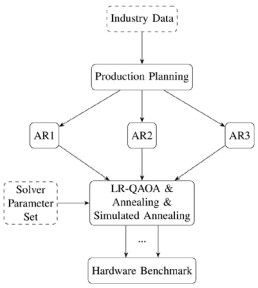
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***Summary*—Real-world optimisation problems must undergo a series of transformations before becoming solvable on current quantum hardware. Even for a fixed problem, the number of possible transformation paths – from industry-relevant formulations through binary constrained linear programs (BILPs), to quadratic unconstrained binary optimisation (QUBO), and finally to a hardware-executable representation – is remarkably large. Each step introduces free parameters, such as Lagrange multipliers, encoding strategies, or slack variables, making brute-force exploration of all paths intractable.**

We benchmark a representative subset of transformation paths using a real-world industrial production planning problem: The optimisation of work allocation in a press shop producing vehicle parts. We focus on QUBO reformulations and algorithmic parameters for quantum annealing (QA) and the Linear Ramp Quantum Approximate Optimisation Algorithm (LR-QAOA). Our goal is to identify effective configurations applicable to similar settings. Our results show QA consistently produces near-optimal solutions, whereas LR-QAOA struggles to reach comparable performance. Hence, the choice of hardware and solver strategy significantly impacts performance. The problem formulation and especially the penalisation strategy determine the solution quality. Most importantly, mathematically defined penalisation strategies are equally successful as hand-picked penalty factors, paving the way for automated QUBO formulation. Moreover, we observe a strong correlation between simulated and quantum annealing performance metrics, offering a scalable proxy for predicting QA behaviour on larger problem instances.



Influence of HW-SW-Co-Design on Quantum Computing Scalability

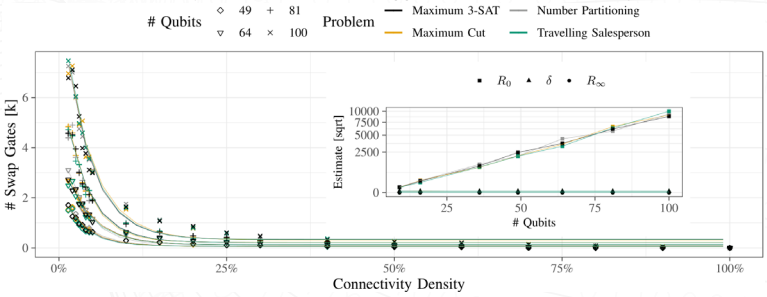
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Summary—Quantum processing units (QPUs) promise speed-ups for computational problems. Yet, current devices are limited by the number of qubits and suffer from significant imperfections, which prevents them from achieving quantum advantage. To progress towards practical utility, one approach is to apply hardware-software co-design methods. This can involve tailoring problem formulations tp QPU properties, but also adapting QPU properties to applications. We follow the latter path.

We study how key metrics for four cornerstone NP-complete problems vary with tailored hardware properties. Achieving near-optimal performance does not necessarily require optimal quantum hardware, but can be realised with simpler structures that can be realised for many hardware approaches. We identify an underlying general model that applies to all subject problems; this suggests that our results may be applicable to other algorithms and problem domains, and tailored QPUs can find utility outside initially envisaged domains. The substantial potential improvements highlight the importance of QPU tailoring.



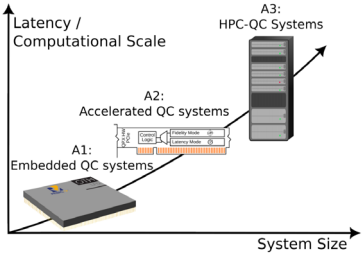
Towards System-Level Quantum-Accelerator Integration

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Summary—Quantum computers are often treated as experimental add-ons that are loosely coupled to classical infrastructure through high-level interpreted languages and cloud-like orchestration. However, future deployments in both, high-performance computing (HPC) and embedded environments, will demand tighter integration for lower latencies, stronger determinism, and architectural consistency, as well as to implement error correction and other tasks that require tight quantum-classical interaction as generically as possible.

We propose a vertically integrated architecture that treats quantum accelerators as peripheral system components. A central element is the Quantum Abstraction Layer (QAL) at operating system kernel level. It aims at real-time, low-latency, and high-throughput interaction between quantum and classical resources, as well as robust low-level quantum operations scheduling and generic resource management. It can serve as blueprint for orchestration of low-level computational components "around" a QPU (and inside a quantum computer), and across different modalities. We present results towards an integrated architecture, including a virtual QPU model based on QEMU. The architecture is validated through functional emulation on three base architectures (x86-64, ARM64, and RISC-V), and timing-accurate FPGA-based simulations. This allows for a realistic evaluation of hybrid system performance. Our work lays the ground for a system-level co-design methodology tailored for the next generation of quantum-classical computing.



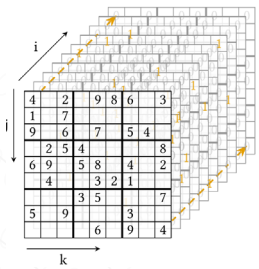
Quantum Data Encoding Patterns and their Consequences

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Summary—The use of quantum processing units (QPUs) promises speed-ups for computational problems, in particular discrete optimisation. While a few ground-breaking algorithmic approaches are known that provably outperform classical computers, we observe a scarcity of programming abstractions for constructing quantum algorithms. A good fraction of the literature that addresses concrete problems related to database management concentrates on casting them as quadratic unconstrained binary optimisation problems (QUBOs). These can be processed on gate-based machines or on quantum annealers. A critical aspect that affects efficiency and scalability is how classical data are loaded into qubits, and how problems are encoded into QUBO representation. The effectiveness of encodings is known to be of crucial importance for quantum computers, especially since the number of available qubits is strongly limited in the era of noisy, intermediate-size quantum computers.



We present three encoding patterns, discuss their impact on scalability, and their ease of use. We consider the computationally challenging Sudoku problem and its reduction to graph colouring as an illustrative example to discuss their individual benefits and disadvantages. Our aim is to enable database researchers to choose an appropriate encoding scheme without having to acquire in-depth knowledge on quantum peculiarities, thus easing the path towards applying quantum acceleration on data management systems.

Hype or Heuristic? Quantum Reinforcement Learning for Join Order Optimisation

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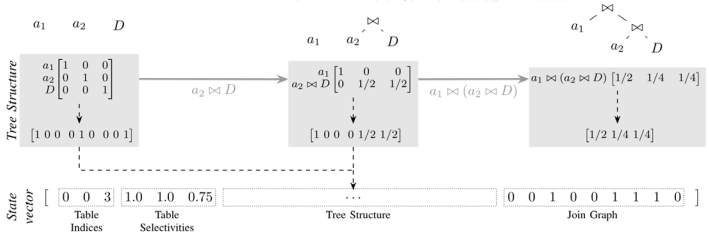
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Summary—Identifying optimal join orders (JOs) is a key challenge in database research. Classical methods rely on approximations and heuristics. Recent efforts explore reinforcement learning (RL) for JO. Quantum versions of RL exist, yet it is unclear if they can achieve practical advantage.

Our novel approach uses quantum reinforcement learning (QRL) for JO. It handles general bushy join trees instead simpler left-deep variants as many quantum(-inspired) optimisation approaches, yet requires orders of magnitude fewer qubits, which is a scarce resource even for post-NISQ systems. Despite moderate circuit depth, the ansatz exceeds current NISQ capabilities, which requires evaluation through numerical simulation. While QRL may not significantly outperform classical approaches in solving the JO problem with respect to result quality (albeit we see parity), we find a drastic reduction in required trainable parameters. This benefits practically relevant aspects ranging from shorter training times compared to classical RL, less computationally intensive classical optimisation passes, or better use of available training data, and fits data-stream and low-latency processing scenarios. Our evaluation delivers a balanced perspective on possible practical advantage, provides insights for future approaches, and allows for quantitatively assessing trade-offs of quantum approaches for one of the most crucial problems of database management systems.







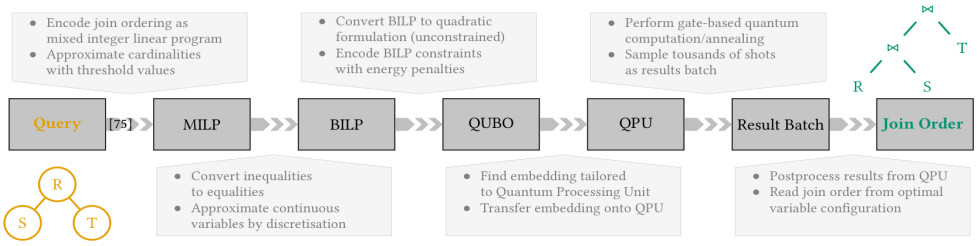
Ready to Leap (by Co-Design)? Join Order Optimisation on Quantum Hardware

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Summary—The prospect of achieving computational speed-ups by exploiting quantum phenomena makes the use of quantum processing units (QPUs) attractive for many algorithmic database problems. Query optimisation, which concerns problems that typically need to explore large search spaces, seems like an ideal match for quantum algorithms.

We present the first quantum implementation of join ordering, one of the most investigated and fundamental query optimisation problems, based on a reformulation to quadratic unconstrained binary optimisation problems. We empirically characterise our method on two state-of-the-art approaches (gate-based quantum computing and quantum annealing), and identify speed-ups compared to the best-known classical join ordering approaches for input sizes that fit on current quantum annealers. Yet, we also confirm that limitations of early-stage technology are quickly reached. Current QPUs are classified as noisy, intermediate scale quantum computers (NISQ), and are restricted by a variety of limitations that reduce their capabilities as compared with ideal future QPUs, which prevent us from scaling up problem dimensions and reaching practical utility. To overcome these challenges, our formulation accounts for specific QPU properties and limitations, and allows us to trade off between achievable solution quality and problem size.

In contrast to all prior work on quantum computing for query optimisation and database-related challenges, we go beyond currently available QPUs, and explicitly target the scalability limitations: Using insights gained from numerical simulations and our experimental analysis, we identify key criteria for co-designing QPUs to improve their usefulness for join ordering, and show how even relatively minor physical architectural improvements can result in substantial enhancements. Finally, we outline a path towards practical utility of custom-designed QPUs.





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