JOHANNES KEPLER UNIVERSITY LINZ | INSTITUTE FOR INTEGRATED CIRCUITS

Institute for Integrated Circuits

Quantum Computing

Quantum computing promises to provide a new and much more efficient way of solving hard problems such as integer factorization, database search, or simulation that is used in e.g. chemistry significantly faster (exponentially faster in many cases) than on classical machines. The key concept is the so called quantum parallelism that allows (from a simplified perspective) to evaluate functions with exponentially many input combination concurrently. While many of the quantum algorithms have already been developed in the last century, the physical realization of quantum computers are still in their infancy. However, many well-known companies like IBM, Intel, Microsoft or Google have noticed the potential of quantum computers and are currently investing into research towards physical realizations - leading to a race for building the first quantum computer that can demonstrate quantum supremacy.

Our Work

In our group, we conduct design automation for quantum computers. Since quantum computers are fundamentally different than classical ones, dedicated solutions for designing quantum circuits (i.e. programs that can be run on a quantum computer) that satisfy the physical constraints of these new machines are required. Our research is mainly focused (but not limited) to the following topics:

- **Efficient representation and core methods:** In principle, quantum states and operations are represented on a classical computer with an exponential number of complex amplitudes. We aim for a more compact representation with a dedicated type of decision diagram that exploits certain redundancies in the quantum states to gain an efficient representation to be used as basis for many design task.
- **Simulation of quantum circuits:** Efficient simulators are essential for the validation of future quantum computers. Furthermore, simulators are required for designing quantum algorithms even though real and sophisticated quantum computers are not available yet. Our advanced simulation technique is based on decision diagrams and significantly outperforms simulators of well-known companies like Microsoft or Intel by conducting simulations in minutes instead of weeks or month for many cases. For our work on this issue, we got awarded with a Google Faculty Award.
- **Noise-aware quantum circuit simulation:** Quantum circuit simulators allow simulating the execution of quantum computers on classical hardware. In doing so, they help to validate real quantum computers and support researchers in developing new quantum algorithms. Yet, real quantum computers are often affected by noise effects, which cause errors during their computation. To faithfully simulate their execution those errors have to be considered. This, however, makes a hard problem even harder. In our work, we are researching efficient approaches for simulating with consideration to errors.
- **Synthesis of quantum (and reversible) circuits:** Since quantum circuits are inherently reversible, their large Boolean components have to be modeled in reversible fashion - by reversible circuits. Since these circuits are completely different than classical circuits, dedicated design flows and methodologies are required. This includes tasks like making non-reversible functions reversible (i.e. embedding) as well as the actual synthesis. In fact, we have designed several approaches for synthesis of reversible circuits, several optimizations, and also recently developed a new design flow which combines embedding and synthesis (called one-pass design of reversible circuits).
- **Mapping of quantum circuits to real architectures:** After synthesizing a quantum circuit (i.e. a quantum algorithm), it has to be mapped to a physical quantum computer. This constitutes a non-trivial task since the real architectures require certain constraints to be satisfied. In particular, we have developed (among others) a mapping algorithm that maps quantum circuits to IBM's QX architectures that is also integrated into IBM's Python SDK Qiskit.
- **Verification of quantum circuits:** It is of utmost importance that the originally intended functionality is indeed preserved throughout all levels of abstraction when compiling a quantum circuit for execution on an actual device. This motivated methods for equivalence checking of quantum circuits. We have developed an equivalence checking methodology that is capable of efficiently verifying the results of compilation flows within seconds, whereas state-of-the-art techniques frequently time-out or require substantially more runtime.
- **The role of randomness in quantum computing:** Randomness has long been identified as a powerful resource for information processing. Randomized algorithms, for instance, often solve challenging problems substantially faster than fully deterministic ones, while randomness is also an indispensable resource in cryptography. The advent of quantum technologies further augments this already prominent role, because quantum mechanics is a probabilistic theory. This poses novel challenges, but also provides new opportunities.

To make our research more accessible, we provide the open-source JKQ quantum toolset and our installation-free web-tool JKQ DDVis that visualizes how decision diagrams can be used for design tasks such as simulation, synthesis, and verification.

Selected Papers

We developed several methods and tools which are specialized for design of quantum computation. In the following, you can find a selected set of the resulting publications. A full list of papers is available.

- L. Burgholzer, R. Raymond, and R. Wille. Verifying Results of the IBM Qiskit Quantum Circuit Compilation Flow. In IEEE International Conference on Quantum Computing (QCE), 2020. PDF (see also the implementation of the equivalence checking methodology)
- S. Hillmich, I. Markov, and R. Wille. Just Like the Real Thing: Fast Weak Simulation of Quantum Computation. In Design Automation Conference (DAC), 2020. PDF (see also the implementation of the simulator).
- A. Zulehner and R. Wille. Advanced Simulation of Quantum Computations. In IEEE Transactions on Computer Aided Design of Integrated Circuits and Systems (TCAD), 2019. PDF (see also the implementation of the simulator).
- A. Zulehner, A. Paler, and R. Wille. An Efficient Methodology for Mapping Quantum Circuits to the IBM QX Architectures. In IEEE Transactions on Computer Aided Design of Integrated Circuits and Systems (TCAD), 2018. PDF (see also the implementation of the mapping algorithm).
- A. Zulehner and R. Wille. One-pass Design of Reversible Circuits: Combining Embedding and Synthesis for Reversible Logic. IEEE Transactions on Computer Aided Design of Integrated Circuits and Systems (TCAD), 2017. PDF (see also the implementation of the one-pass synthesis).
- P. Niemann, R. Wille, and R. Drechsler. Improved Synthesis of Clifford+T Quantum Functionality. In Design, Automation and Test in Europe (DATE), 2018. PDF
- A. Zulehner and R. Wille. Exploiting Coding Techniques for Logic Synthesis of Reversible Circuits. In Asia and South Pacific Design Automation Conference (ASP-DAC), 2018. PDF
- A. Zulehner and R. Wille. Taking One-to-one Mappings for Granted: Advanced Logic Design of Encoder Circuits. In Design, Automation and Test in Europe (DATE), 818-823, 2017. PDF
- A. Zulehner and R. Wille. Make It Reversible: Efficient Embedding of Non-reversible Functions. In Design, Automation and Test in Europe (DATE), 458-463, 2017. PDF
- P. Niemann, R. Wille, D. M. Miller, M. A. Thornton, and R. Drechsler. QMDDs: Efficient Quantum Function Representation and Manipulation. IEEE Transactions on Computer Aided Design of Integrated Circuits and Systems (TCAD), 35(1):86-99, 2016. DOI
- R. Wille, A. Lye, and R. Drechsler. Exact Reordering of Circuit Lines for Nearest Neighbor Quantum Architectures. IEEE Transactions on Computer Aided Design of Integrated Circuits and Systems (TCAD), 33(12):1818-1831, 2014. DOI

Awards and Accomplishments

- ERC Consolidator Grant 2020 (for “Design Automation for Quantum Computing”)
- Third place at the IBM Quantum Challenge 2019
- Google Research Award in 2018 for our work on simulation of quantum computations
- Winner of the IBM Qiskit Developer Challenge in 2018
- Software developed by us has been integrated into tools such as IBM’s SDK Qiskit or Atos’ QLM.
- Several PhD Student Awards)

Selected Professional Services

We are also involved in organizing events to further pursue the field and to strengthen the community. Selected examples include e.g.

- Organizer of the Special Day on “Future and Emerging Technologies” with a dedicated session on quantum computation at DATE 2018
- Organizer of several tutorials e.g. on “IBM’s Qiskit Tool Chain: Working with and Developing for Real Quantum Computers” or “Computer-Aided Design for Quantum Computation” at DATE 2019, ICCAD 2018, ICCAD 2017, and more
- Organizer of several special issues on “Reversible and Quantum Computation” at ACM JETC, Springer’s LNCS, and more
- Organizer of several special sessions at DATE, ICCAD, ISCAS, ISED, and more
- Organizer of the Dagstuhl Seminar on “Design of Reversible and Quantum Circuits”

Contact

In case you have any problems with or questions feel free to contact us via iic-quantum@jku.at.

*JKU **Institute for Integrated Circuits**, Altenberger Straße 69, 4040 Linz, Austria, Tel. +43 732 2468 4730* Legal Disclosure