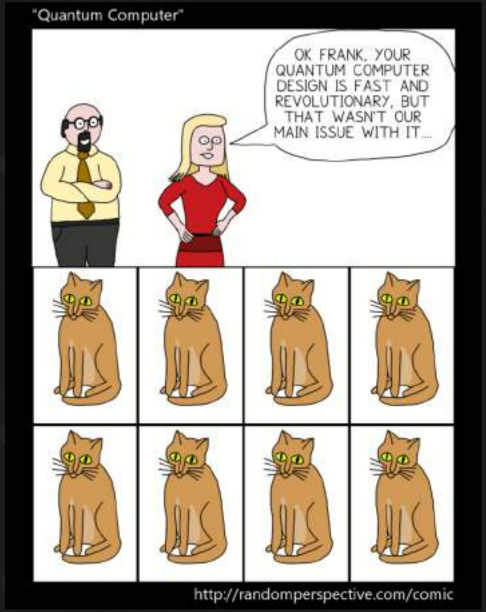
ProjectQ: Software for Quantum Computing

Damian Steiger
Work done at ETH Zurich
(now quantum researcher at Huawei)

What can we do with a Quantum Computer ?

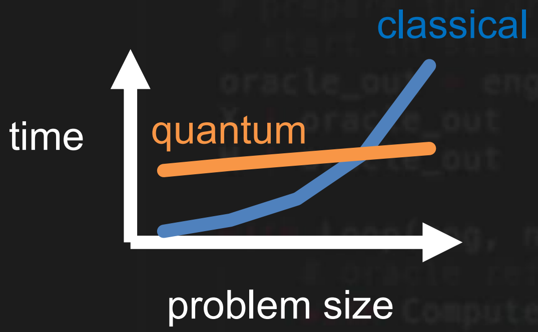


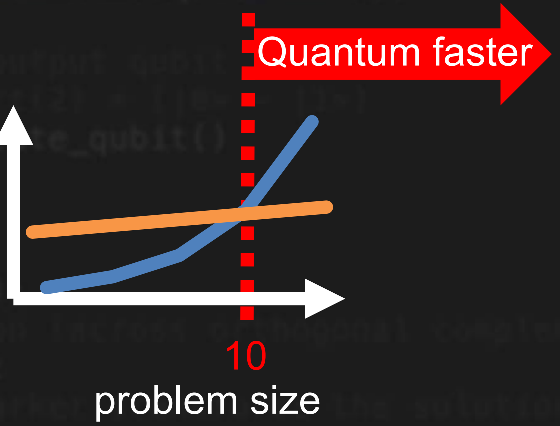
Finding a competitive application

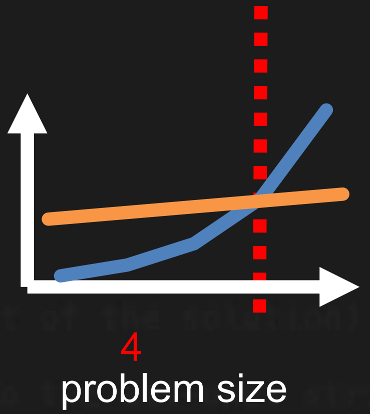
1 Find a quantum algorithm which scales better

2 Determine the exact cost

3 Improve the quantum algorithm



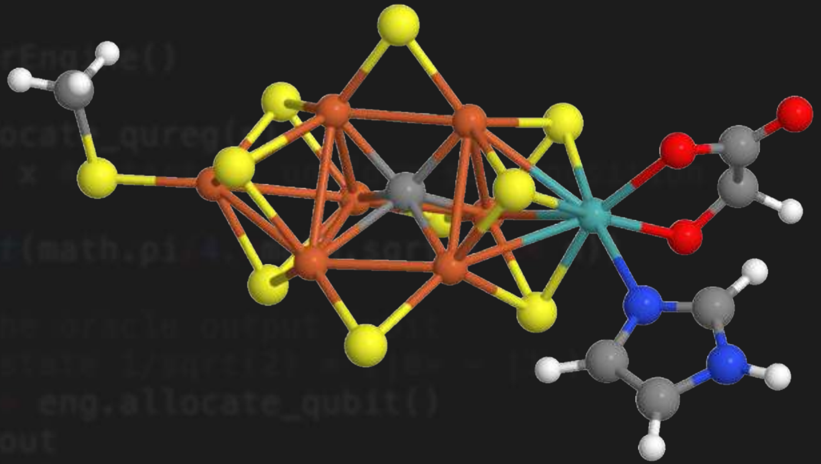




What can we do with a Quantum Computer ?

21 = 7 * 3

What else can we do with a quantum computer?



Quantum Simulation

ProjectQ (.ch)

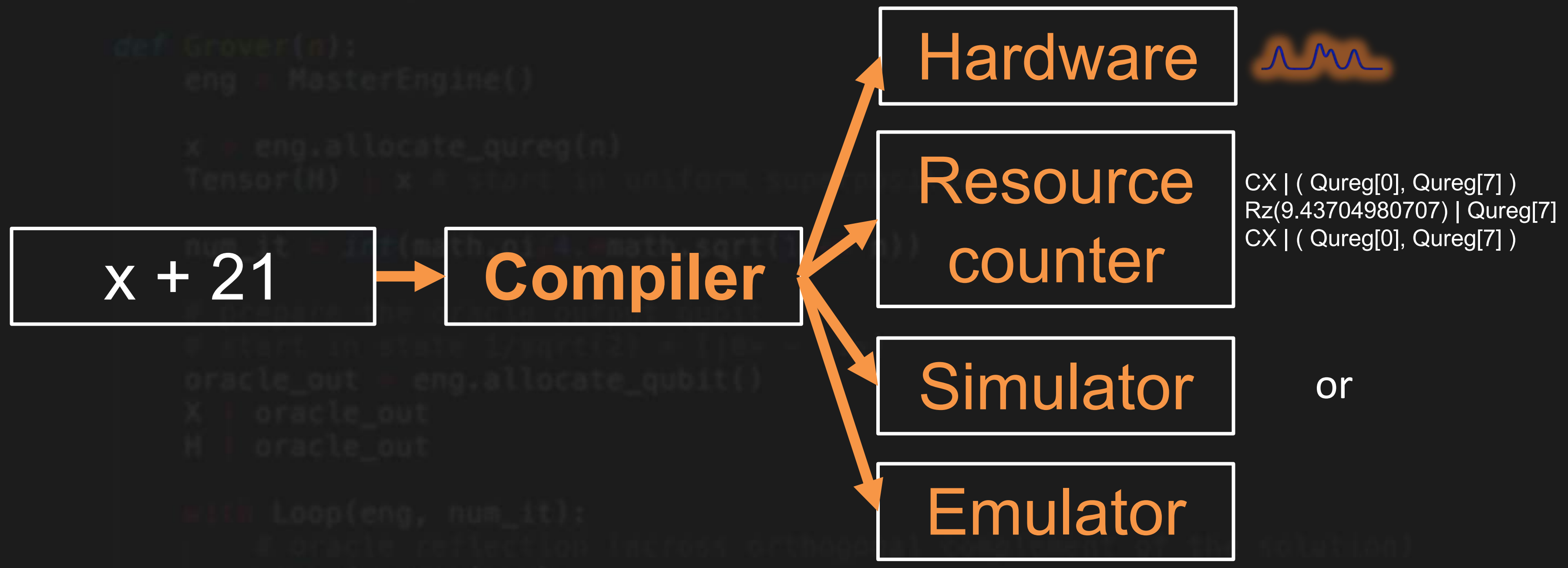
Develop standard tools for development of quantum algorithms, programming and controlling quantum computers

- **Open & Free:** *Apache 2 license*
- **Easy to Use:** *Simple learning curve by using common languages and intuitive syntax*
- **Extensible:** *Easily extensible to support new hardware or gate sets*

How to compute x+21?

```
CX | ( Qureg[4], Qureg[7] )
Rz(9.62112750162) | Qureg[7]
CX | ( Qureg[5], Qureg[6] )
CX | ( Qureg[4], Qureg[7] )
Rz(2.74889357189) | Qureg[7]
R(2.74889357189) | Qureg[5]
CX | ( Qureg[5], Qureg[7] )
Rz(9.81747704247) | Qureg[7]
H | Qureg[6]
CX | ( Qureg[5], Qureg[7] )
Rz(2.35619449019) | Qureg[7]
R(2.35619449019) | Qureg[6]
CX | ( Qureg[6], Qureg[7] )
Rz(10.2101761242) | Qureg[7]
CX | ( Qureg[6], Qureg[7] )
H | Qureg[7]
```

Unified framework



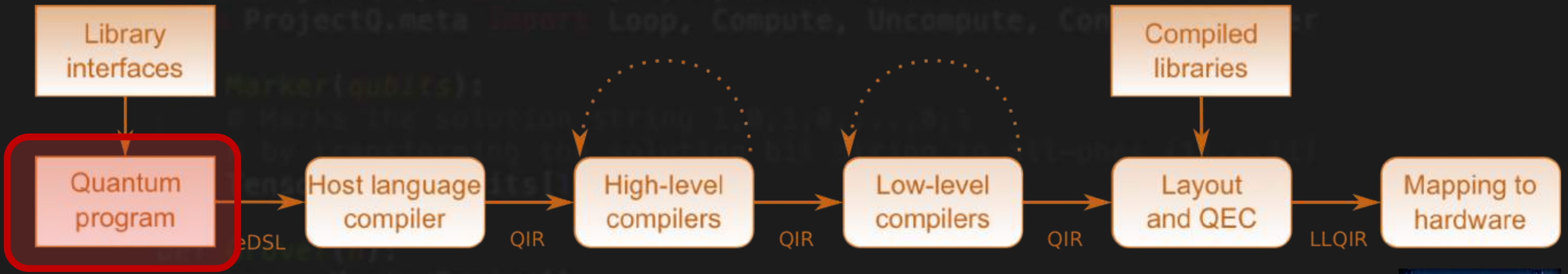
ProjectQ Syntax

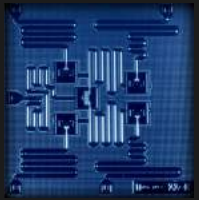
```
eng = projectq.MainEngine(backend)

qubit = eng.allocate_qubit()
qureg = eng.allocate_qureg(10)

U(classical_param) | qureg
```

$$U(theta)\,|\text{qureg}\rangle$$

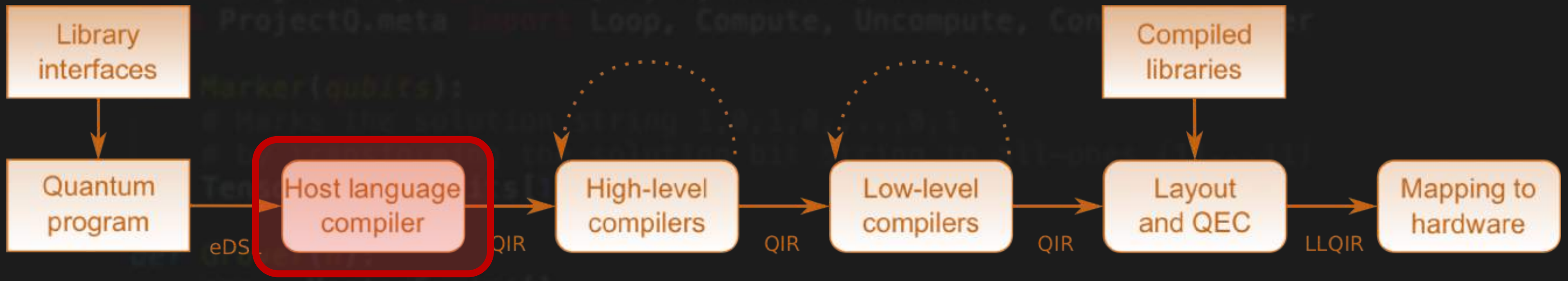
ProjectQ Example Operations

```
Rx(0.1) | qubit
H | qubit
CNOT | (qubit, qureg[0])
Measure | qubit

QFT | qureg
MultiplyByConstantModN(10, N=21) | qureg
```

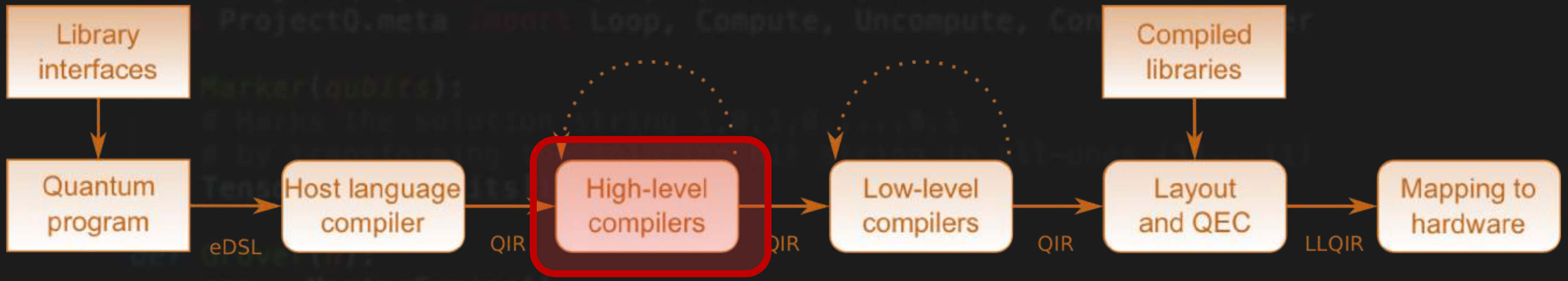


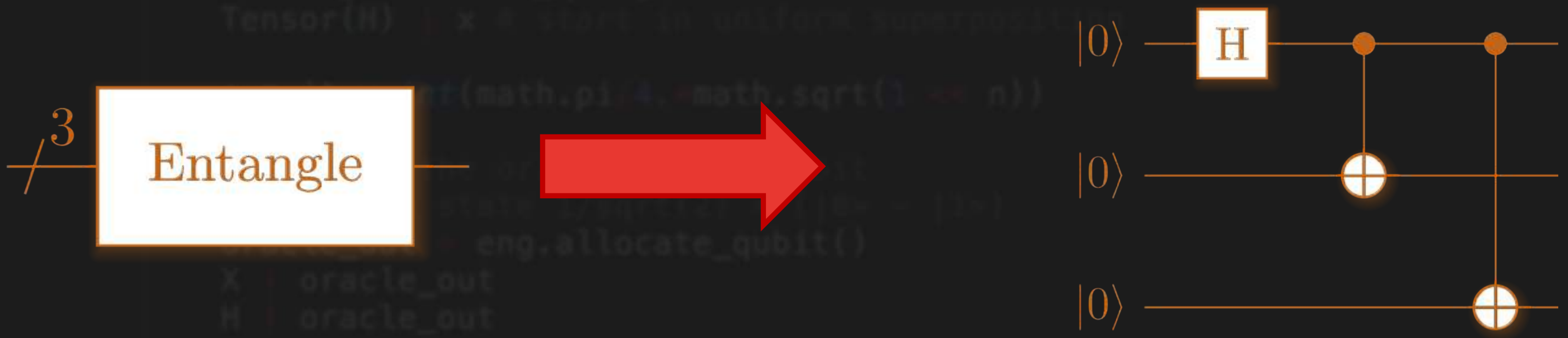


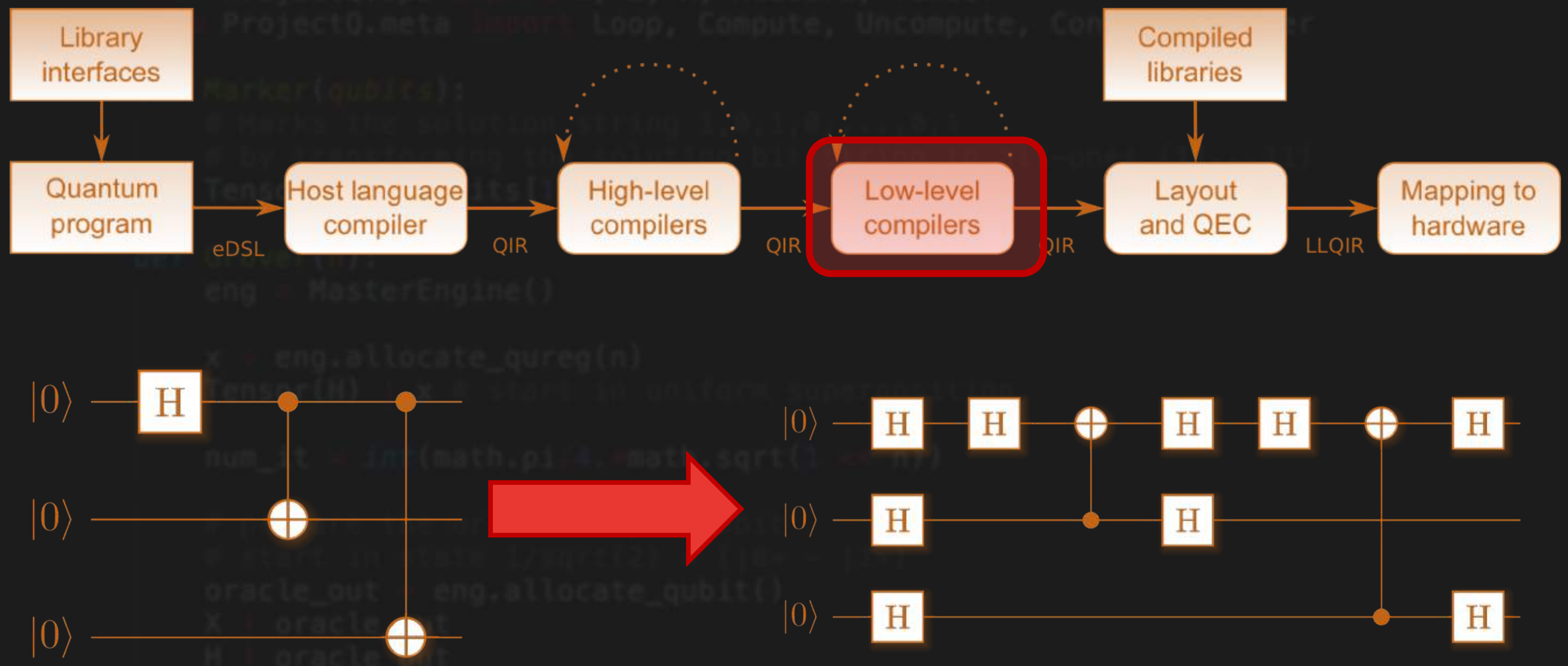
```
qureg = eng.allocate_qureg(3)
# entangle the qureg
Entangle | qureg
# measure; should be all-0 or all-1
Measure | qureg
```




```
# entangle the qureg
Entangle | qureg
```


Library interfaces
Compiled libraries
Quantum program
eDSL
Host language compiler
QIR
High-level compilers
QIR
Low-level compilers
QIR
Layout and QEC
LLQIR
Mapping to hardware


3
Entangle
|0⟩
|0⟩
|0⟩
H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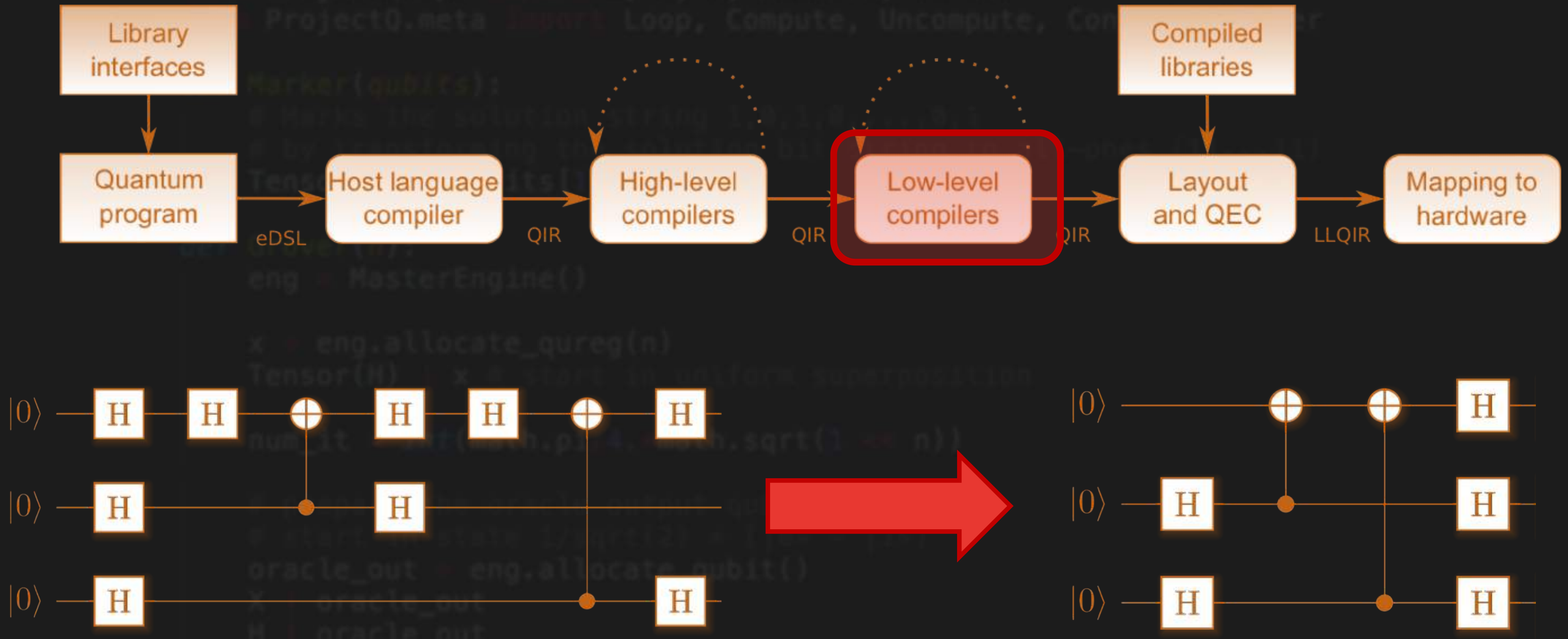
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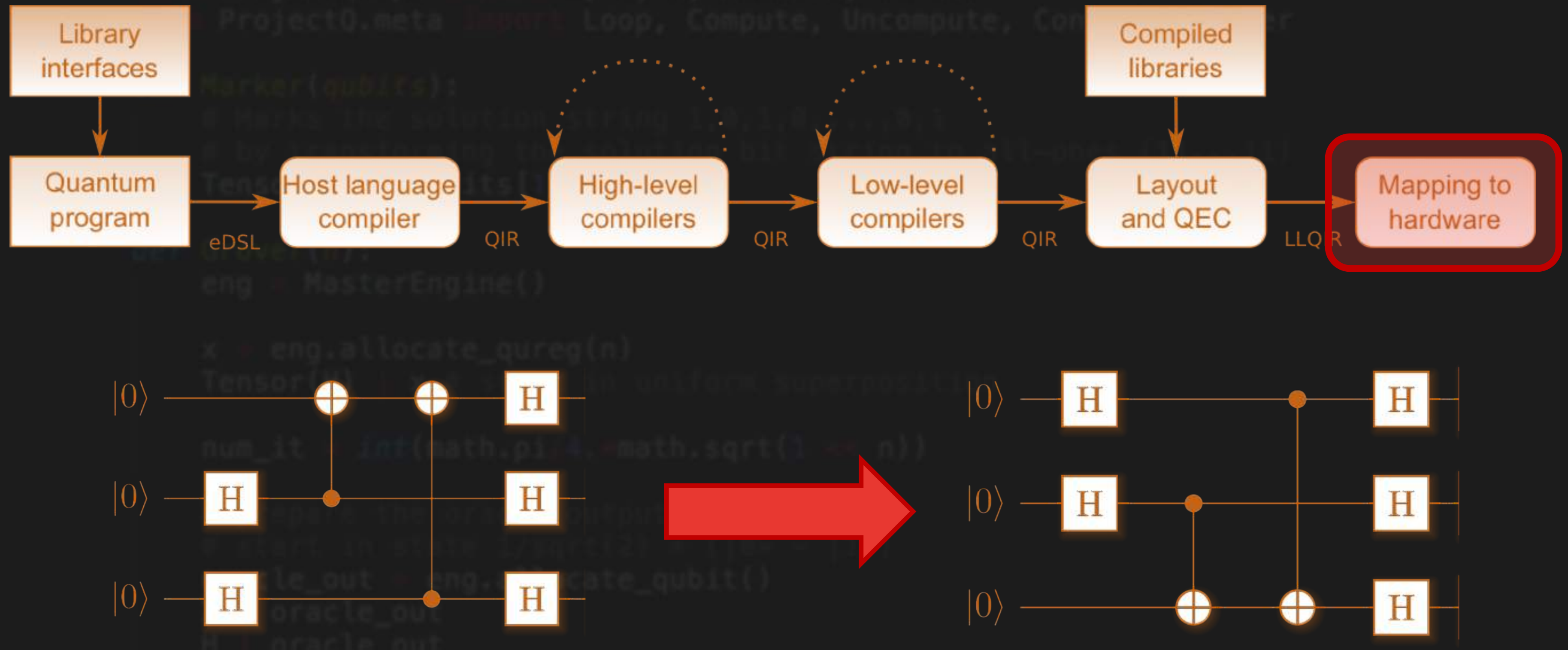
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Resource estimates

Shor's algorithm

```
x = eng.allocate_qureg(n)
X | x[0]
ctrl_qubit = eng.allocate_qubit()

for k in range(2 * n):
    current_a = pow(a, 1 << (2 * n - 1 - k), N)
    # one iteration of 1-qubit QPE
    H | ctrl_qubit
    with Control(eng, ctrl_qubit):
        MultiplyByConstantModN(current_a, N) | x

    # perform inverse QFT --> Rotations conditioned on previous outcomes
    for i in range(k):
        if measurements[i]:
            R(-math.pi/(1 << (k - i))) | ctrl_qubit
    H | ctrl_qubit

    # and measure
    Measure | ctrl_qubit
    eng.flush()
    measurements[k] = int(ctrl_qubit)
    if measurements[k]:
        X | ctrl_qubit
```

Beauregard's implementation

- Factoring a number with *n bits*
- 2n + 3 qubits
- $O(n^4)$ gates
- $O(n^3)$ circuit depth

Resource for factoring 15

- 11 qubits
- Circuit depth of 28477
- Number of gates
  - CNOT: 17832
  - Rz: 13624
  - T and inverse T: 11312
  - H: 4576
  - X: 129

Simulator backend

- Calibration and benchmarking of quantum devices
- Debugging quantum algorithms

Quantum Simulator

Qubits	Memory	Time for one gate
10	16 kByte	microseconds on a smart watch

Quantum Simulator

Qubits	Memory	Time for one gate
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20	16 MByte	milliseconds on a smartphone

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40	16 TByte	minutes on a supercomputer

Quantum Simulator

Qubits	Memory	Time for one gate
10	16 kByte	microseconds on a smart watch
20	16 MByte	milliseconds on a smartphone
30	16 GByte	seconds on a laptop
40	16 TByte	minutes on a supercomputer
260	each particle of visible universe	age of universe

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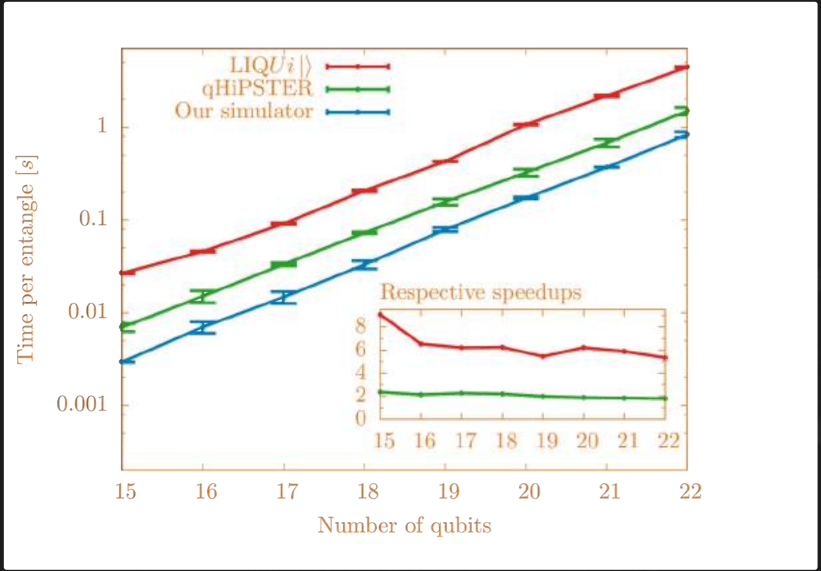
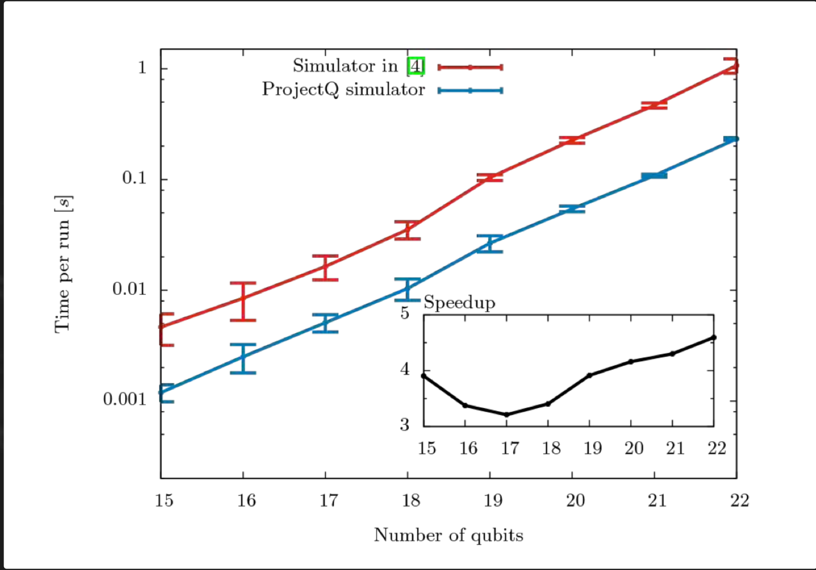
Simulator performance





Our simulator performance of spring 2016

ProjectQ simulator (winter 2016) vs our own simulator of spring 2016

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Another simulator of ours

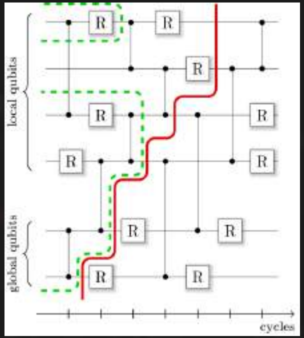
0.5 Petabyte Simulation of a 45-Qubit Quantum Circuit

Thomas Häner*, Damian S. Steiger*
**Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland*

45-Qubit Simulation

The worlds largest quantum computer simulation at that time

Cori Supercomputer
0.5 Petabyte of memory
2.2 Million logical cores



>10x speedup
45 Qubits
(previously 42)

In collaboration with
Thomas Häner

Supercomputing's monster in the closet, IEEE

ETH Zurich

T. Häner and DS, SC’17

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High Performance Emulation of Quantum Circuits

Thomas Häner*, Damian S. Steiger*, Mikhail Smelyanskiy†, and Matthias Troyer*‡§
*Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland
† Parallel Computing Lab, Intel Corporation
‡ Quantum Architectures and Computation Group, Microsoft Research, Redmond, WA (USA)
§ Corresponding Author: troyer@phys.ethz.ch

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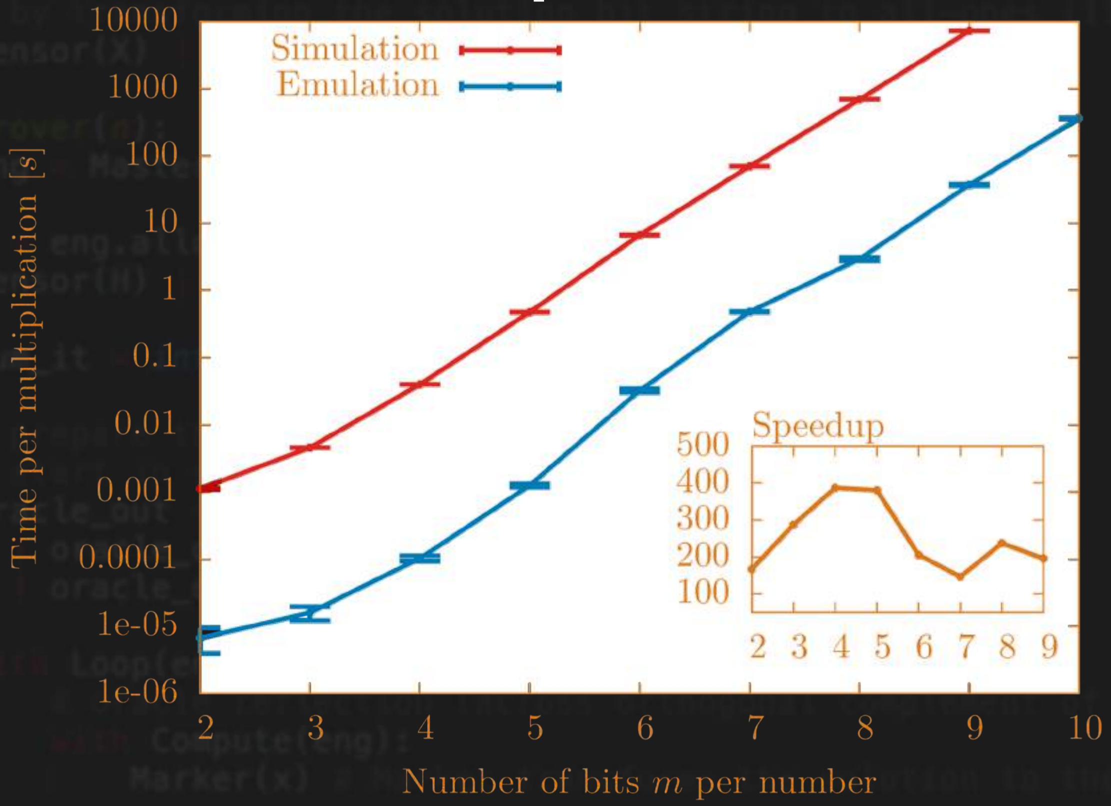
Multiplication



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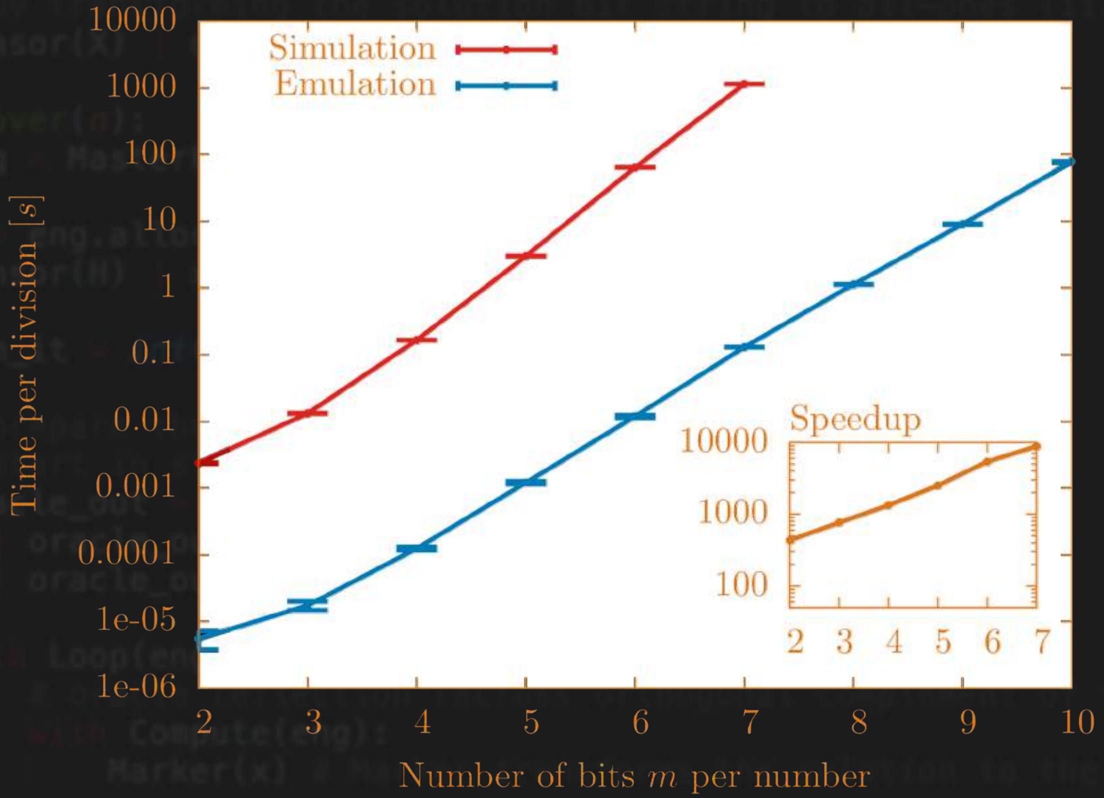
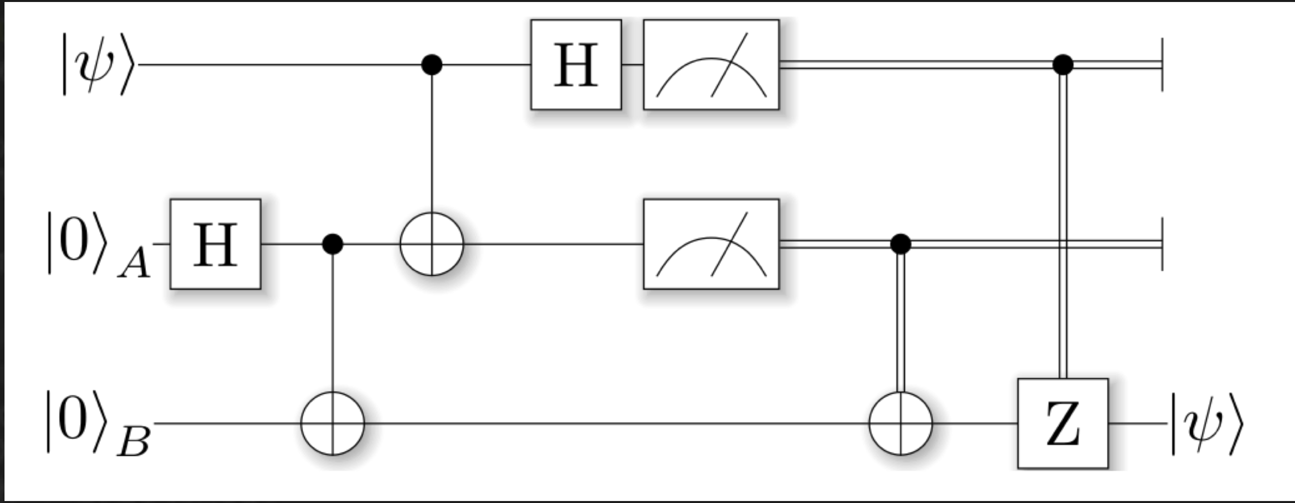
Division



Advantages of emulation

- 10x for QFT
- 400x for multiplication
- 10000x for division
- much more for more complex functions (exp, sqrt, arcsin, ...)

Latex Drawer backend



RevKit Library

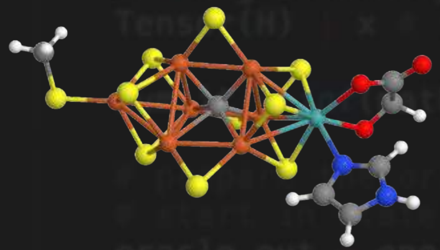
```
def f(a, b, c, d):
    return (a and b) ^ (c and d)

qubits = eng.allocate_qureg(4)
PhaseOracle(f) | qubits  # (-1)**f(qubits)
```

Programming Quantum Computers Using Design Automation ***arXiv:1803.01022***

By Mathias Soeken, Thomas Häner, Martin Roetteler

Quantum Simulation Library

- FermiLib



$$E_0\,,\ |\phi_0\rangle\ ,\ \ldots$$

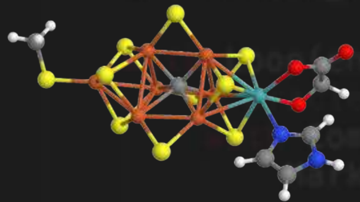
In collaboration with Ryan Babbush, Jarrod McClean, Ian Kivlichan

FermiLib

- Interface to electronic structure packages

Input:

```
geometry = [('H', (0., 0., 0.)),
            ('H', (0., 0., 0.7))]
basis = 'sto-3g'
multiplicity = 1
charge = 0
molecule = MolecularData(geometry,
                         basis,
                         multiplicity,
                         charge)
```



Output:

$$H = \sum_{pq} h_{pq} a_p^\dagger a_q + \frac{1}{2} \sum_{pqrs} h_{pqrs} a_p^\dagger a_q^\dagger a_r a_s$$

Optional classical results:

- Full CI energy
- MP2 energy
- CCSD energy
- …

FermiLib

- Transform fermionic to spin operators:

$$H = \sum_{pq} h_{pq} a_p^\dagger a_q + \frac{1}{2} \sum_{pqrs} h_{pqrs} a_p^\dagger a_q^\dagger a_r a_s \quad \Rightarrow \quad H = \sum_{j=0}^{N} \alpha_j P_j$$

Choose between:

Jordan-Wigner transform

Bravyi-Kitaev transform

...

FermiLib - ProjectQ

FermiLib provides: $$H = \sum_{j=0}^{N} \alpha_j P_j$$

Use one of the quantum algorithms in ProjectQ to find static properties using methods such as:

"Quantum Algorithm for Spectral Measurement with a Lower gate Count" *by D. Poulin, A. Kitaev, DS, M. Hastings, M. Troyer.* PRL 121, 010501 (2018)

Collaborators

Thomas Häner

Matthias Troyer

Acknowledgments

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Thanks for your attention!

www.projectq.ch