Quantum Computing Hardware Interfacing

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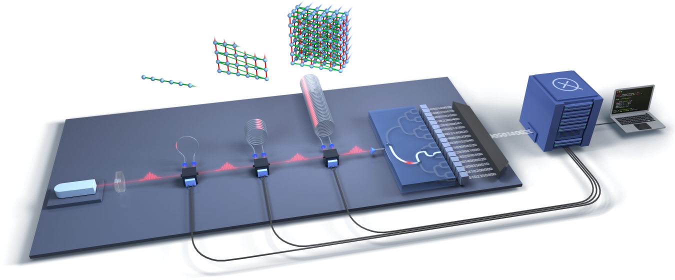
Dutch developmentts

- Supercomputing SURF: Virtual tour Snellius
- Quantum Delta
- TNO: technology development, Quantum sensing testbed

Xanadu technology



Photonics, Xanadu X-series

Quantum Computing Hardware Interfacing

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- Update on hardware
- Transpiling
- Simplifying circuits
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- Background theory
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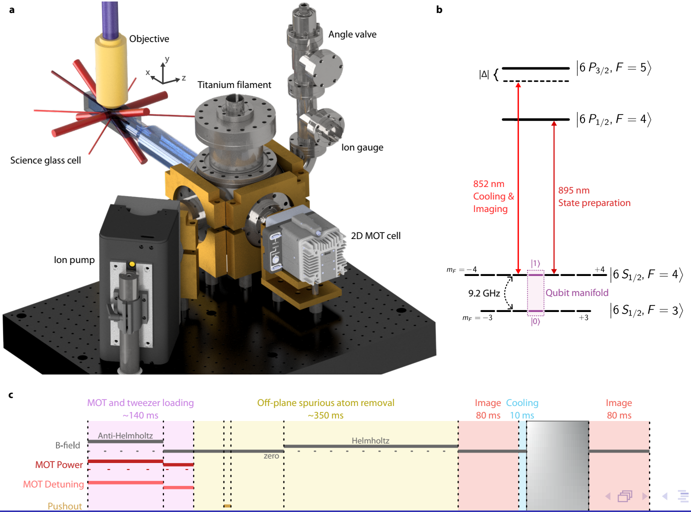
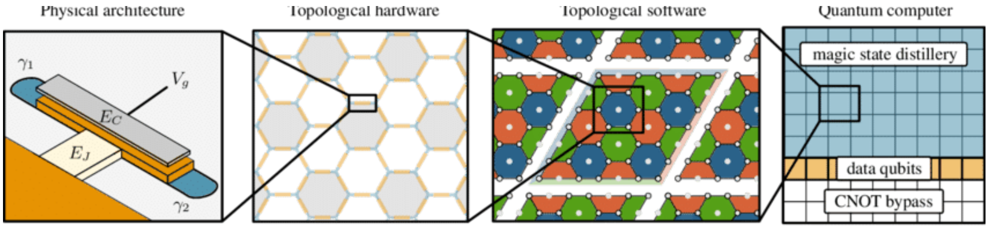
Tweezer array

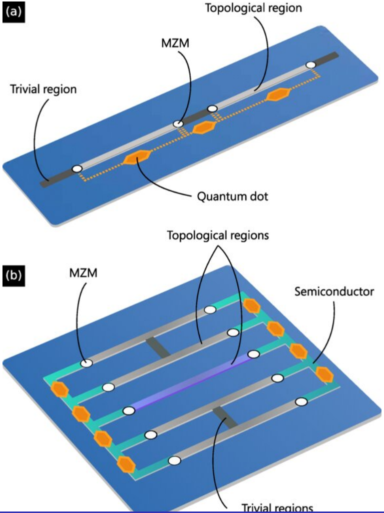


quantum computing Microsoft

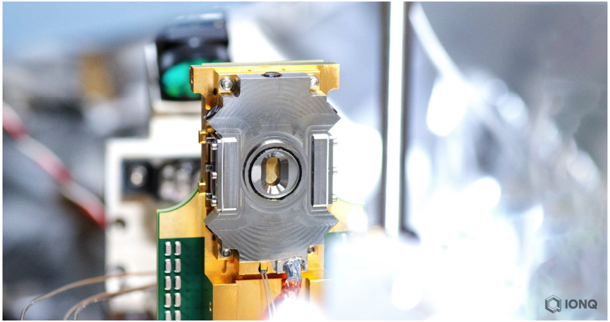


a) Majorana Cooper pair box *b*) Physical qubits: hexagonal cells *c*) Logical qubits: diamond color code *d*) Qubit arrangement

Toplogical approach Microsoft



Trappend ions IONQ, Technology Trapped Ions

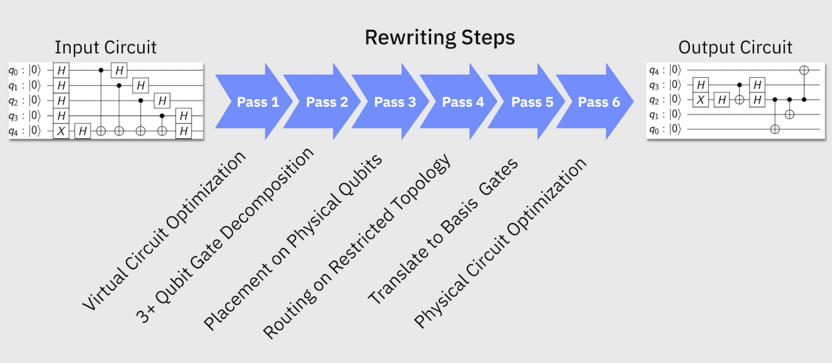


Simplyfing circuits

- Use of Transpiler
- Manual simplification
- Use of dedicated libraries
- Classical for Boolean algebra, e.g. Karnaugh Maps, simplification rules

Transpiling

Transforming quantum computer programs to executable code

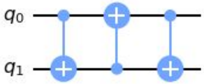


Transpiling SWAP-gate

See: Transpiler in Qiskit

. A SWAP gate is not a native gate on the IBM Q devices, and must be decomposed into three CNOT gates:

```
swap_circ = QuantumCircuit(2)
swap_circ.swap(0, 1)
swap_circ.decompose().draw(output='mpl')
```

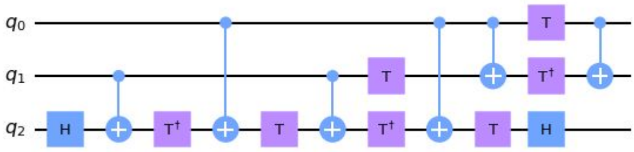


Transpiling Toffoli-gate

See: Transpiler in Qiskit

A Toffoli, or controlled-controlled-not gate (*ccx*), is a three-qubit gate. Given that our basis gate set includes only single- and two-qubit gates, it is obvious that this gate must be decomposed. This decomposition is quite costly:

```
ccx_circ = QuantumCircuit(3)
ccx_circ.ccx(0, 1, 2)
ccx_circ.decompose().draw(output='mpl')
```

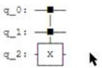


Examples

Figure: Transpiling

```
In [8]: #Basic Toffoli gate,
        qc = QuantumCircuit(3)
        qc.ccx(0,1,2)
        qc.draw()
```

Out[8]:




```
In [9]: qc_decomposed = qc.decompose()
        qc_decomposed.draw()
```

Out[9]:

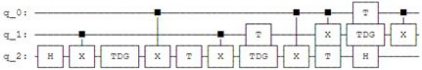
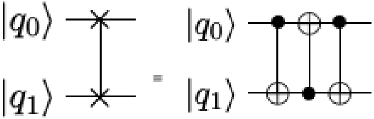
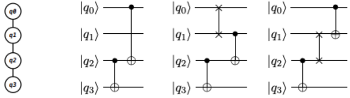


Figure: Swap and CNOT



(a) A SWAP gate (b) Three CNOT gates

Figure: Routing



(a) 4-qubit topology (b) Circuit (c) Routed circuit c_1 (d) Routed circuit c_2

Analysis gates placing and routing

Subgoals: Modelling of circuit synthesis

Challenges:

1.) Preprocessing algorithms, e.g. reducing number of gates, gate type
2.) Transpiling and performance estimates
3.) Analysing target language (QASM)
4.) Analysing constraints and criteria
5.) Machine Learning options (reinforcement learning) [3]
6.) References: [4], [5]

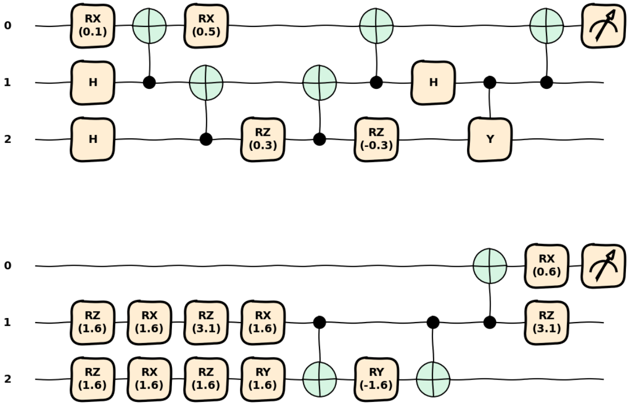
Controlling transpiler output

- Transpiler API
- Qiskit tutorial transpiling and passmanager
- Option discussed in SURFproject: Test Crosstalk adaptive scheduler

Transpiling approaches

- Pennylane
- Qiskit transpiling
- Qiskit API

Compilation of quantum circuits



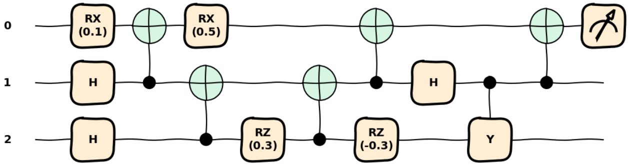
Example Qiskit transpiler notebooks

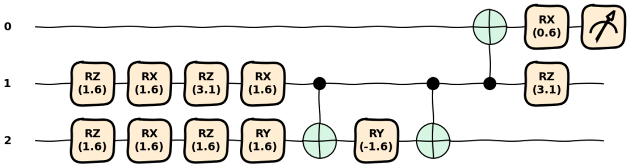
Submit transpiled circuits

- common-parameters.ipynb
- defaults-and-configuration-options.ipynb
- dynamical-decoupling-pass-manager.ipynb
- representing_quantum_computers.ipynb
- set-optimization.ipynb
- transpile-with-pass-managers.ipynb
- create-a-transpiler-plugin.ipynb
- custom-backend.ipynb
- custom-transpiler-pass.ipynb

Example Qiskit transpiling

Compilation of quantum circuits





Example PyZX library

PyZX (pronounce as Pisics) is a Python tool implementing the theory of ZX-calculus for the creation, visualisation, and automated rewriting of large-scale quantum circuits (Github library, [6])

- `Circuit` - The name of the circuit
- `qubits` - Amount of qubits in the circuit
- `G-count` - Gate count of original circuit
- `2-count` - Amount of 2-qubit gates in original circuit
- `G/2-NRSCM` - Total amount and 2-qubit gate amount from optimized circuit of [1]
- `G/2-Tpar` - Total amount and 2-qubit gate amount from optimized circuit of [2]
- `G/2-PyZX` - Total amount and 2-qubit gate amount from optimized circuit made by PyZX
- `Time-Simp` - The time taken for running the simplification routine on the circuit
- `Time-Extract` - The time taken for extracting the circuit after the simplification

Examples PyZX library

In [4]:
```
print("Circuit".ljust(20), "qubits", "G-count", "2-count", "G-NRSCM", "2-NRSCM", " G-Tpar", "2-Tpar", '
for c in fast_circuits:
    print(c.get_output())
```

```
Circuit              qubits G-count 2-count G-NRSCM 2-NRSCM  G-Tpar 2-Tpar G-PyZX 2-PyZX Time-Simp Ti
me-Opt
Adder8                   23 |    637    243 |    190      94 |      -      - |    362    199      1.06
0.13
adder_8                  24 |    900    409 |    606     291 |   1280    885 |    677    337      2.03
0.21
barenco_tof_10           19 |    450    192 |    264     130 |    517    328 |    365    176      0.62
```

```
hwb8.qc                  12 | 14856   7129 |      -       - |      -      - |  12491   6234    174.24
13.42
mod_adder_1024           28 |  4285   1720 |   2736    1278 |   5183   3540 |   3136   1430     12.82
1.80
nth_prime8.tfc           12 | 16968   8235 |      -       - |      -      - |  14511   7229    136.90
18.58
QFT32                    32 |  1562    612 |   1012     612 |      -      - |   1012    612      1.71
0.34
QFTAdd16                 32 |  1822    716 |   1168     716 |      -      - |   1186    716      2.90
0.51
QFTAdd32                 64 |  4814   1900 |   3040    1900 |      -      - |   3077   1900     10.31
1.44
```

Simulation

- NVida CUDA-Q
- Optimized quantum circuit simulators
- Simulator Pennylane and plugins
- and many more

Quantum sensing applications

- Atomic clocks.
- Mass ‘Tomography’: magnetometers can detect water pipes (or the like) in walls.
- Energy optimisation
- Navigation and compasses/accelerometers
- Very precise MRI scanners
- Brain scanning
- Many more

Theory: Quantum Sensing([7])

Quantum sensing and quantum basis

	Qubit(s)	Measured quantity(ies)	Typical frequency	
Neutral atoms				
Atomic vapor	Atomic spin	Magnetic field, Rotation, Time/Frequency	DC–10 GHz	
Cold clouds	Atomic spin	Magnetic field, Acceleration, Time/Frequency	DC–10 GHz	
Trapped ion(s)				
	Long-lived electronic state	Time/Frequency Rotation	THz	
	Vibrational mode	Electric field, Force	MHz	
Rydberg atoms				
	Rydberg states	Electric field	DC, GHz	
Solid state spins (ensembles)				
NMR sensors	Nuclear spins	Magnetic field	DC	
NV center ensembles	Electron spins	Magnetic field, Electric field, Temperature, Pressure, Rotation	DC–GHz	
Solid state spins (single spins)				
P donor in Si	Electron spin	Magnetic field	DC–GHz	
Semiconductor quantum dots	Electron spin	Magnetic field, Electric field	DC–GHz	E
Single NV center	Electron spin	Magnetic field, Electric field, Temperature, Pressure, Rotation	DC–GHz	

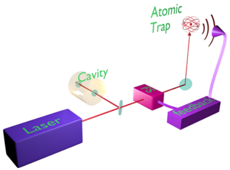
Quantum sensing 2

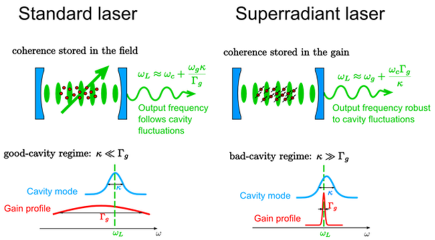
Superconducting circuits			
SQUID	Supercurrent	Magnetic field	DC–10 GHz
Flux qubit	Circulating currents	Magnetic field	DC–10 GHz
Charge qubit	Charge eigenstates	Electric field	DC–10 GHz
Elementary particles			
Muon	Muonic spin	Magnetic field	DC
Neutron	Nuclear spin	Magnetic field, Phonon density, Gravity	DC
Other sensors			
SET	Charge eigenstates	Electric field	DC–100 MHz
Optomechanics	Phonons	Force, Acceleration, Mass, Magnetic field, Voltage	kHz–GHz
Interferometer	Photons, (Atoms, Molecules)	Displacement, Refractive Index	–

Table: Experimental implementations of quantum sensors. SET: single electron transistor, NV: nitrogen-vacancy, status 2017 ([7])

Quantum clock

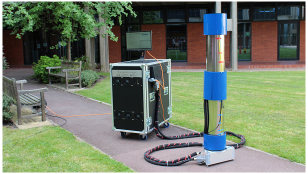
- Technology of quantum clocks to synchronize integrated quantum clock consortium. Prof. Florian Schleck from the University of Amsterdam is involved.

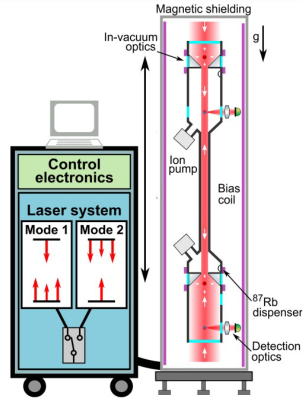




Quantum Gravity sensors

Gravity cartography [8]

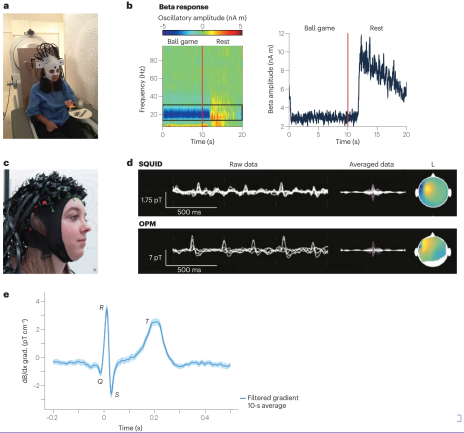




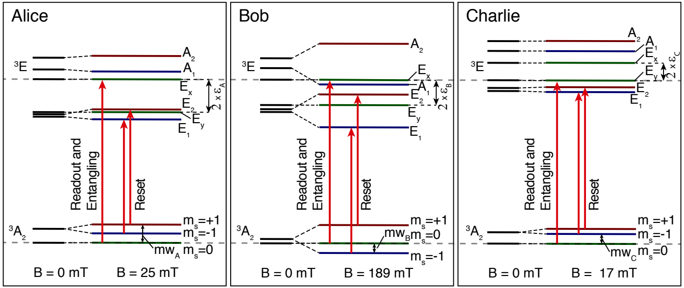
Quantum biology sensors

Non intrusive sensing

- Quantum biology sensors



Quantum internet experiments in Delft ([9]) with a demo ([10])



Quantum technologies for space applications

Cooperation between ESA and EU (see e.g. Policy papers)

- Secure Quantum Communication (QKD via satelite)
- Quantum technology for accurate time and Frequency Transfer (e.g. Navigation)
- Earth Sensing and Observation(e.g. measuring gravity field Earth)
- Fundamental Physics (e.g. Bose-Einstein Condensates)

Quantum technologies for space applications

- 6th Quantum Technology conference, 2023
- Quantum workshop 2024

Quantum theory

1.) Complexity of algorithms

2.) Thermal energy and quantum computation

3.) Foundations based on axioms

Heat production computing

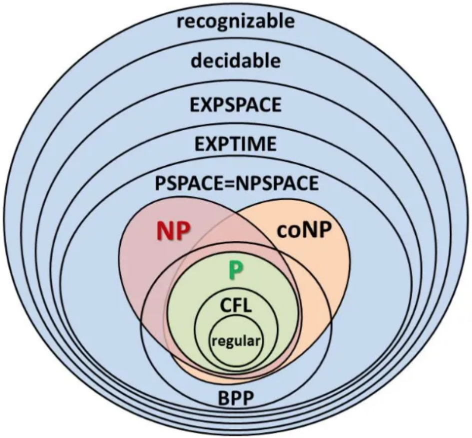
1.) Landauer Principle Stands up to Quantum Test

2.) Breaking Landauer's bound in aspin-encoded quantum computer

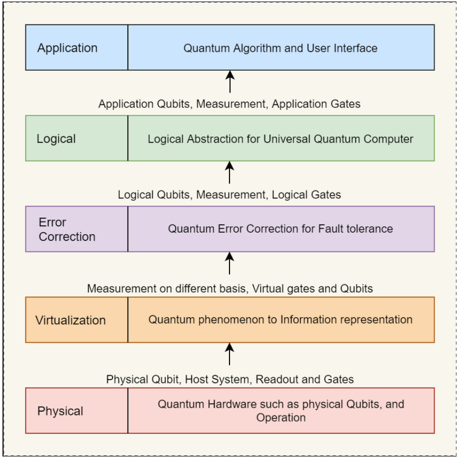
Cooling requires a lot of energy

Classical complexity

Complexity — Classes and Their Limitations

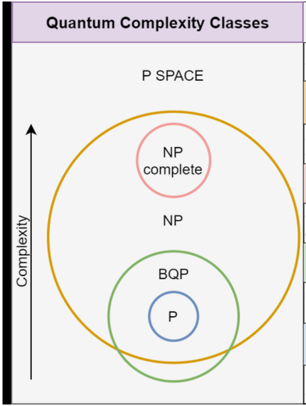


Quantum levels



Quantum Complexity

Quantum Computing Toolkit From Nuts and Bolts to Sack of Tools[11]



Polynomial Space Problem (PSPACE)
Space requirements are polynimial bound e.g. NxN Chess
Non Deterministic Polynomial Time (NP)
Solutions can be guessed and verified in polynomial time e.g. Graph Isomorphism
Non Deterministic Polynomial Time Complete (NP Complete)
Class of problem for which no efficient solution is available e.g. Travelling Sales Person
Bounded-error quantum polynomial time (BQP)
Problems can be efficienltly solved by quantum computer e.g. Factoring Discreet Log
Polynomial Time Solvalbe (P)
Efficiently solved by both quantum and classical computer e.g. Graph Connectivity

Quantum physics axiom 1

Classically, $|x\rangle$ should be polarized $\uparrow$ or $\rightarrow$, if this is the case we expect two outcomes:

1.) If $|x\rangle$ goes through filter, then $|x\rangle$ is $\uparrow$.

2.) If $|x\rangle$ is deflected, then $|x\rangle$ is $\rightarrow$.

Quantum physics axiom 1 continued

Physical States (Choices made by humans to describe quantum mechanics):

$\uparrow = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \qquad \rightarrow = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$ (pure state)

Something of note, these two vectors form a basis for $\mathbb{C}^2$ *and all combinations are:*

$|x\rangle = \alpha \begin{bmatrix} 0 \\ 1 \end{bmatrix} + \beta \begin{bmatrix} 1 \\ 0 \end{bmatrix}$ where $\|\alpha\|^2 + \|\beta\|^2 = 1$ To keep track of this choice, we make the matrix $A = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$ representing vertically polarized filter.

Another note, the eigen-vals of that matrix are $|v\rangle, |h\rangle$.

Quantum physics axiom 2

An observable of a state $|x\rangle$ corresponds to a Hermitian matrix A. $|x\rangle$ is in state $|u\rangle$, an eigen-vect for A with probability $|\langle u|x\rangle|^2$

Definition

Expectation value of A (or mean value) of observable associated to A after measurements with respect to many copies of $|\psi\rangle$ is **the weighted average of the expected outcomes**.

$$\langle A\rangle_\psi = \sum_{i=1}^{n} |\langle u_i|\psi\rangle|^2$$

$$|\psi\rangle = \sum_{i=1}^{n} c_i\,|u_i\rangle \text{ where } u_i \text{ is an e-basis from A}$$

Quantum physics axiom 3

The time dependence of a state is governed by the Schrödinger equation:

$$i\bar{h}\frac{\delta|\psi|}{\delta t} = H\,|\psi\rangle \tag{1}$$

$\bar{h}$ is reduced Planck's constant
H is Hermitian matrix corresponding to energy of the system **Hamiltonian**.
When H is time invariant (constant), the Schrödinger equation becomes:

$$|\psi(t)\rangle = e^{\frac{-itH}{\bar{h}}}\,|\psi(0)\rangle \tag{2}$$

Conclusion

- New developments on quantum hardware in recent years
- Mapping of program to hardware
- Interfacing quantum hardware

Exercises: and ideas for Quantum Stack

- Exercise fundamental Schrödinger equation solution examples and links with Quantum hardware
- Report on Quantum Hardware in Qiskit or Pennylane
- Explore design options in Qiskit metal: Qiskit Metal tutorial examples
- Qiskit notebook on quantum volume

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[10] S. L. N. Hermans, M. Pompili, H. K. C. Beukers, et al. *Qubit teleportation between non-neighboring nodes in a quantum network*. 2021. DOI: 10.48550/ARXIV.2110.11373. URL: https://arxiv.org/abs/2110.11373.

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