CESGA

Infraestructuras Científicas y Técnicas Singulares

Quantum Computing

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Lecture 2

- QPU
- Topologies of QPU
- Programming
- Simulators.
- Introduction to ProjectQ
- My first program with ProjectQ .

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Universal Quantum Computer. Quantum Gates

ONE QUBIT GATES

Hadamard	H	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$
Pauli-X	X	$\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}$
Pauli-Y	Y	$\begin{bmatrix}0 & -i\\ i & 0\end{bmatrix}$
Pauli-Z	Z	$\begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}$
Phase	S	$\begin{bmatrix}1 & 0\\ 0 & i\end{bmatrix}$
$\pi/8$	T	$\begin{bmatrix}1 & 0\\ 0 & e^{i\pi/4}\end{bmatrix}$

TWO QUBIT GATES

controlled-NOT

$$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{bmatrix}$$

swap

$$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

measurement — Projection onto $|0\rangle$ and $|1\rangle$

(H,S,T,CNOT) = Universal Quantum Gates: can approximate ANY unitary operation

From: Nielsen, M., & Chuang, I. (n.d.). Quantum computation and Quantum information.

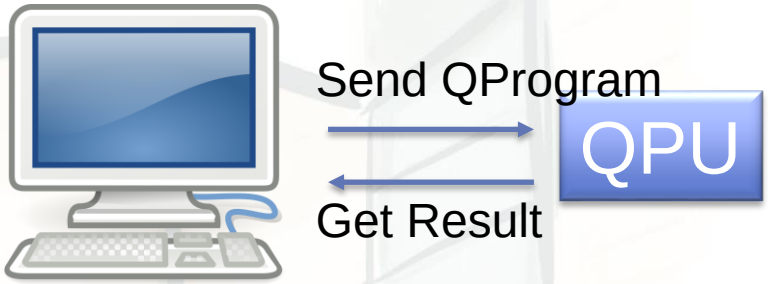
Universal Quantum Computer. QRAM || QPU

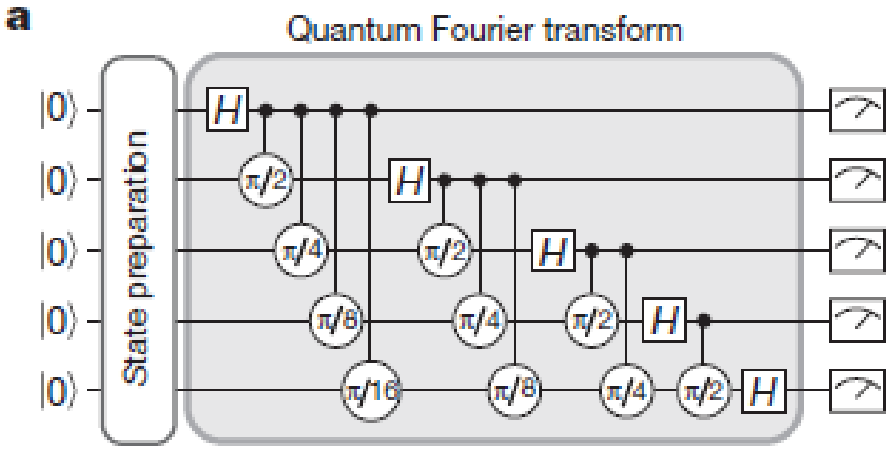
✓ Quantum register initialized to |0> for a finite bit string 0 (n bits = nqubits)

✓ Manipulated by a set of primitives one or two qubit unitary operations (quantum gates)

✓ Measured into a classical bases labeled as a bit string of length n.

✓ A program is provided by a set of gates to be applied onto QuBits.



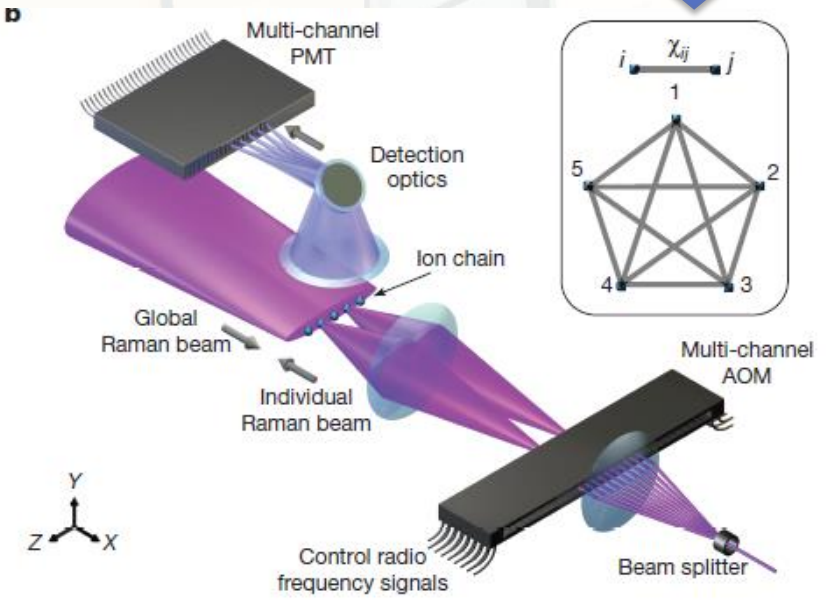


Knill, E. (1996). *Conventions for quantum pseudocode. LANL report LAUR-96-2724 &* Knill, E. (1996). *Quantum Randomness and Nondeterminism, LABL report LAUR-96-2186. Archiv:quant-ph/9610012*

Ion Trap (I)

- $^{171}Yb^{+}$ trapped ions
- Information stored in the hyperfine 'clock' states:
  - $|0> \equiv |F = 0;\ m_F = 0>$
  - $|1> \equiv |F = 1;\ m_F = 0>\ of\ the\ {}^2S_{1/2}$ electronic ground level
  - F , m_F quantum numbers associated to total atomic angular momentum and its projection along the quantization axes defined by an applied magnetic field of 5.2G
  - **Coherence time > 0.5s**
- Confined in a linear radio-frequency Paul trap
- Laser-cooled
- 5 μm for 5 qubits

All-with-All



Debnath, S., Linke, N. M., Figgatt, C., Landsman, K. A., Wright, K., & Monroe, C. (2016). Demonstration of a small programmable quantum computer with atomic qubits. *Nature*, *536*(7614), 63–66. http://doi.org/10.1038/nature18648

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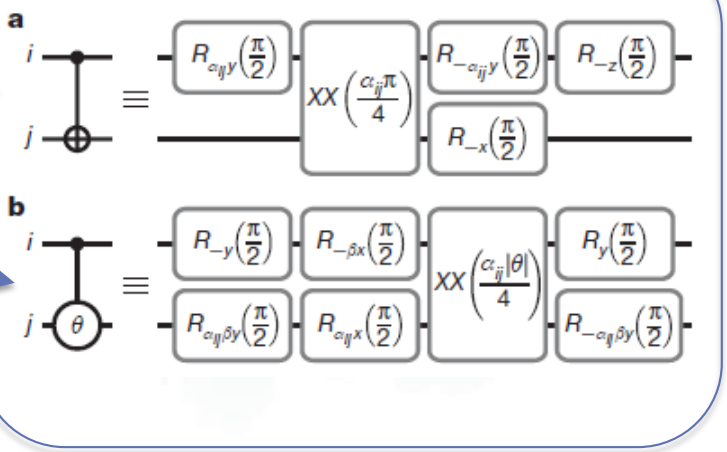
Ion Trap (II): Universal Gates

- Implemented gates (using Raman transition):
  - single qubit $R_\varphi(\theta) = R(\theta, \varphi)$
  - two − qubits XX
- Universal Gates derived as:
  - $H = R_x(-\pi)R_y\left(\frac{\pi}{2}\right)$
  - $\mathrm{Z} = R_y(-\pi/2)R_x(\theta)R_y\left(\frac{\pi}{2}\right)$
  - Controlled-NOT (CNOT)
  - Controlled-Phase (cP)

$$R(\theta, \phi) := \begin{pmatrix} \cos\frac{\theta}{2} & -\mathrm{i}e^{-\mathrm{i}\phi}\sin\frac{\theta}{2} \\ -\mathrm{i}e^{\mathrm{i}\phi}\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{pmatrix}$$

$$XX(\chi_{ij}) = \begin{bmatrix} \cos(\chi_{ij}) & 0 & 0 & -i\sin(\chi_{ij}) \\ 0 & \cos(\chi_{ij}) & -i\sin(\chi_{ij}) & 0 \\ 0 & -i\sin(\chi_{ij}) & \cos(\chi_{ij}) & 0 \\ -i\sin(\chi_{ij}) & 0 & 0 & \cos(\chi_{ij}) \end{bmatrix}$$



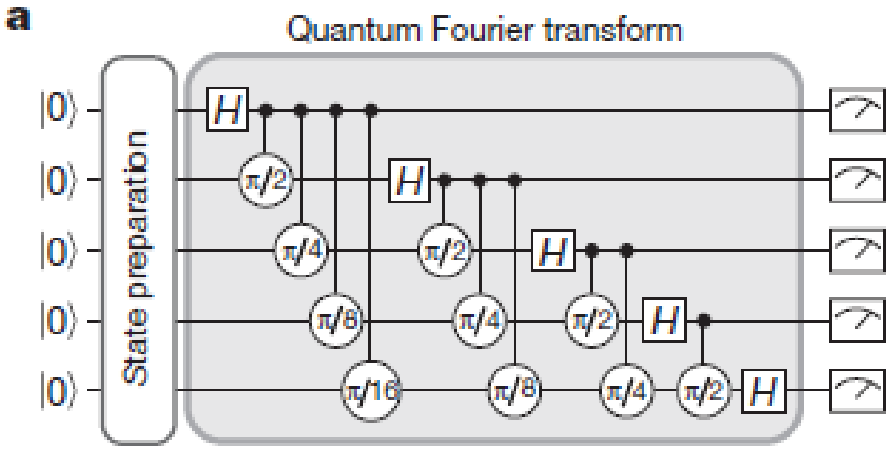
Debnath, S., Linke, N. M., Figgatt, C., Landsman, K. A., Wright, K., & Monroe, C. (2016). Demonstration of a small programmable quantum computer with atomic qubits. *Nature*, *536*(7614), 63–66. http://doi.org/10.1038/nature18648

Ion Trap (III): QFT(5)

- State preparation (single qubits rotations)

QFT Ideal Gates: 15

- Total gates[1]:
  - 5 H = 10 R
  - 10 CP = 10 (6R + 1 X)
  - Total = 80 gates
- Optimised Version [2]:
  - 22 single-qubit gates
  - 10 two-qubits gates
  - Total: 32 gates
  - Time: 2669 μs



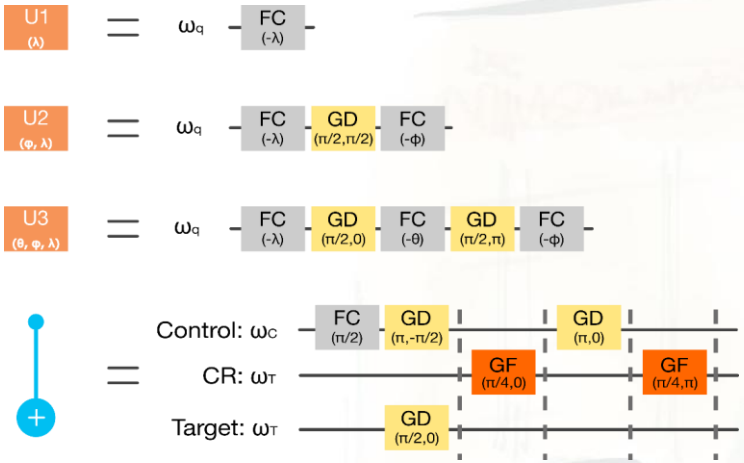
[1] Debnath, S., Linke, N. M., Figgatt, C., Landsman, K. A., Wright, K., & Monroe, C. (2016). Demonstration of a small programmable quantum computer with atomic qubits. *Nature*, *536*(7614), 63–66. http://doi.org/10.1038/nature18648

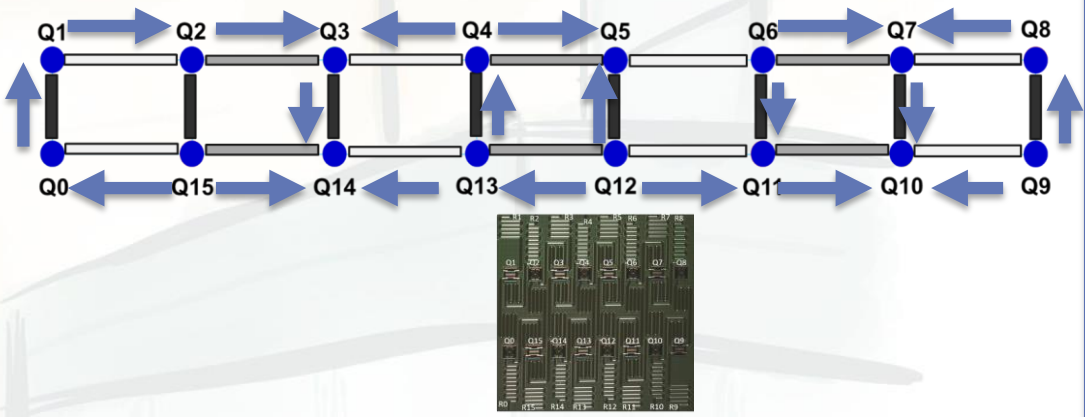
[2] Maslov, D. (2017). Basic circuit compilation techniques for an ion-trap quantum machine. *New Journal of Physics*, *19*(2), 23035. http://doi.org/10.1088/1367-2630/aa5e47

IBM QX

Hardware Gates:

- Frame Change (FC, 0ns),
- Gaussian Derivative (GD, 80ns) ,
- Gaussian Flattop (GF, 170-384ns)
- Buffer after each pulse:10ns





https://github.com/QISKit/ibmqx-backend-information/tree/master/backends/ibmqx3

Limits on:

- Available gates,
- Different times for each operations
- Restrictions on 2 qubits operations
- Restrictions on measurement

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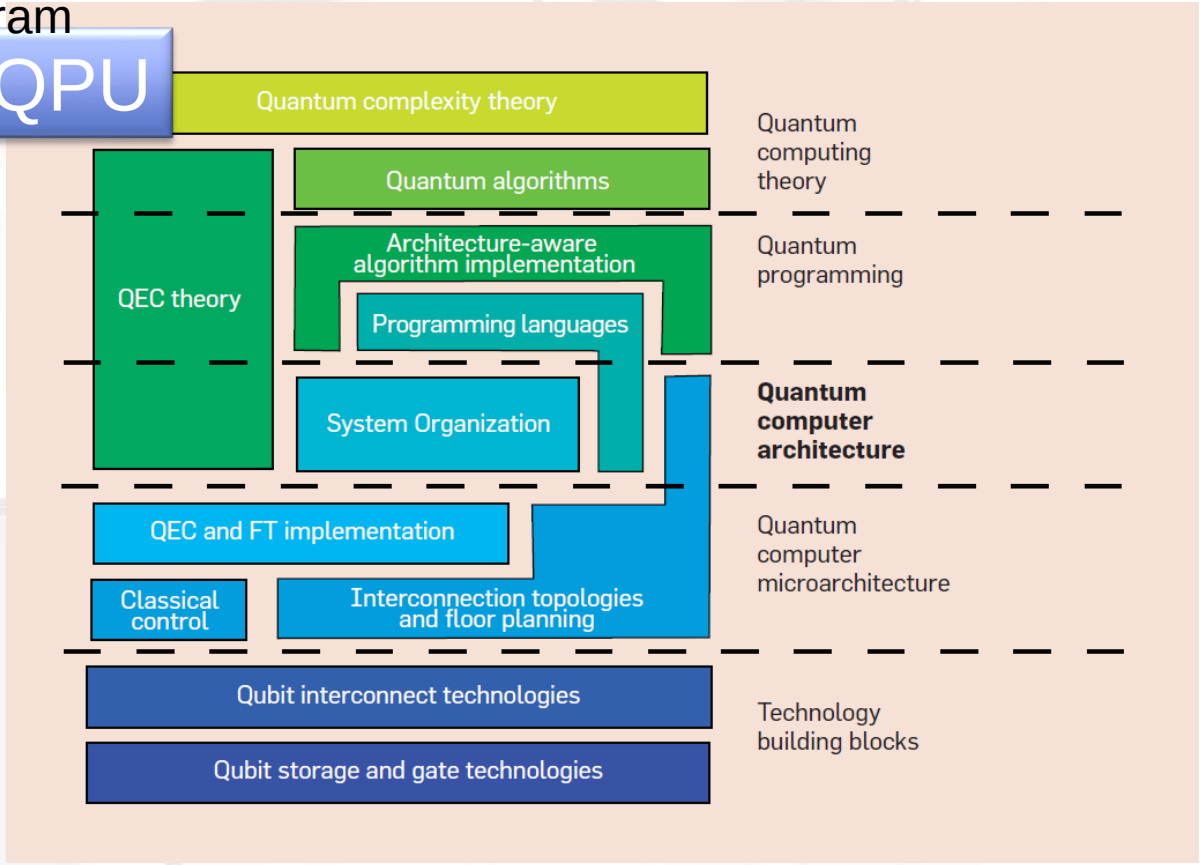
Quantum Computing Architecture

Send QProgram

Get Result

QPU



Van Meter, R., & Horsman, C. (2013). A blueprint for building a quantum computer. *Communications of the ACM*, *56*(10), 84. http://doi.org/10.1145/2494568

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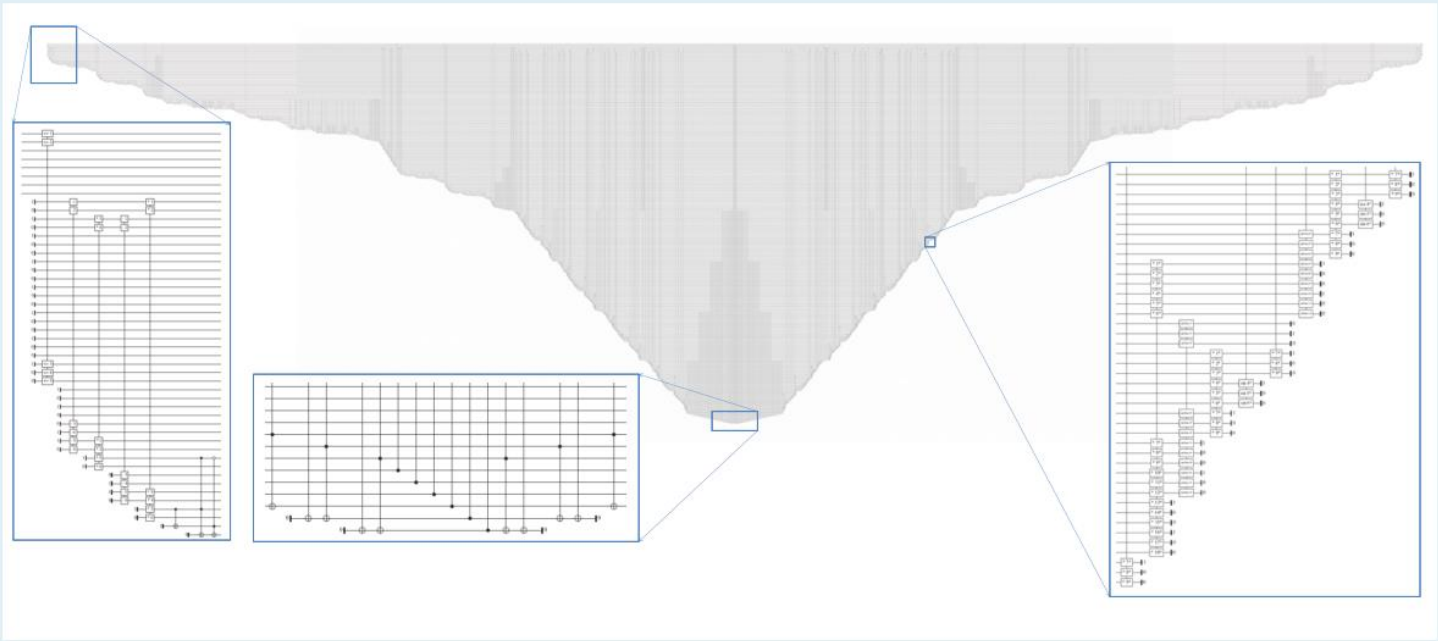
Quantum Algorithm

Figure 17. The `calcRweights` circuit.



Smith, J. M. (2015). Programming the Quantum Future. Communications of the ACM, 58(8), 52–61. http://doi.org/10.1145/2699415

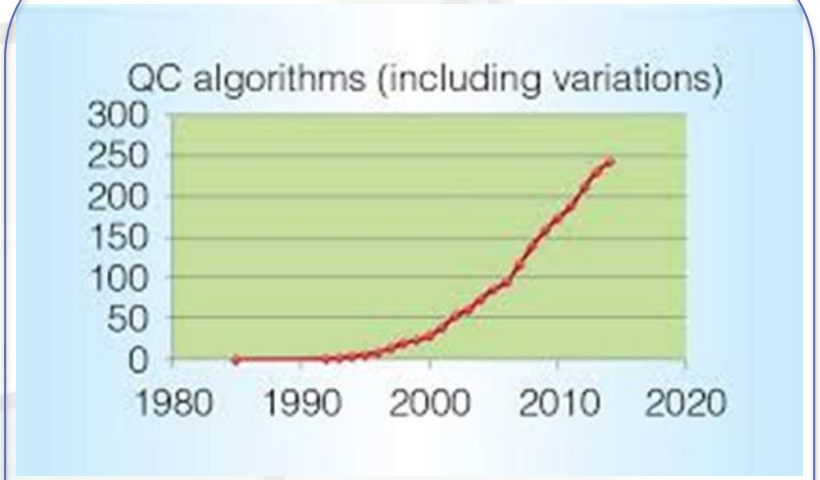
Quantum Algorithm

- A sequence of gates applied on a set of qubits

- Some well-known techniques:
  - Amplify amplitude (Grover's)
  - Estimate phase

- More than 400 quantum algorithm papers on Quantum Zoo

- Many are <u>unitary transformation on n-qubits plus measurement</u>
  - <u>How to make them as a set of universal gates?</u>



Quantum Zoo website

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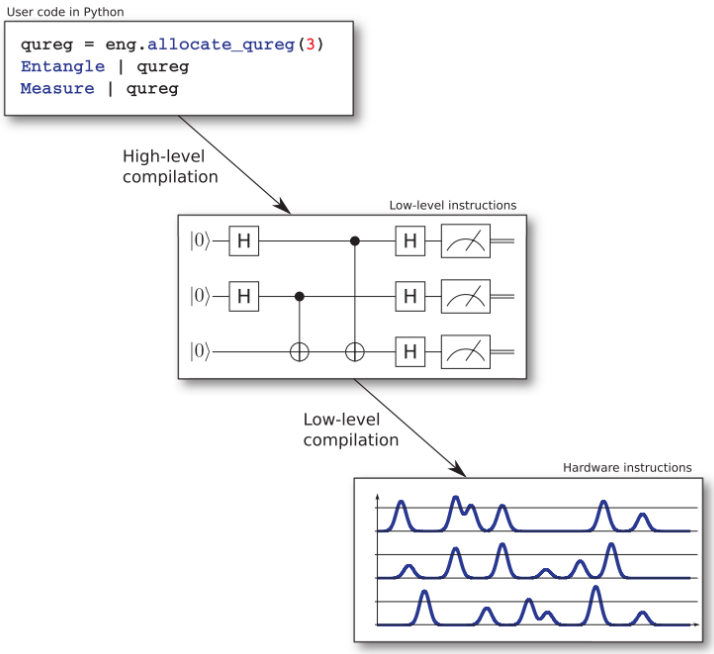
Quantum Programing

- Define one or several quantum registers
- Apply high level methods, a set of gates or general unitary transformations
- Decompose them in basic gates
- Transform to real operations of the QPU
- Or for simulators



Steiger, D. S., Häner, T., & Troyer, M. (2016). ProjectQ: An Open Source Software Framework for Quantum Computing. Retrieved from http://arxiv.org/abs/1612.08091

Modern Quantum Languages (I)

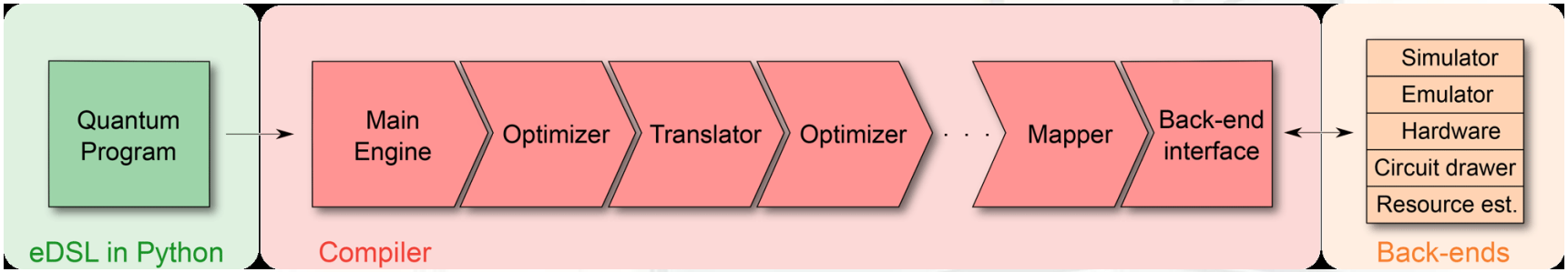
	Core Language	Unlimited Qubits	Simulator	Optimizer/ decomp.	CESGA
ProjectQ	Python/C	●	●	●	●
LIQUi|>	F#	● (*)	●	●	
Quipper	HasKell	●	●	●	
ScaffCC	Scaffold	●	QX	●	
Microsoft Quantum Development Kit (2018)	Q#	● (**)	●	●	
QisKit	Python	●	●		●
Xacc	C++/python	●	TNQVM	●	

(*) At least in the public versión
(**) 30 locally, 40 in Azure

Modern Quantum Languages (II)

	Core Language	Unlimited Qubits	Simulator	Optimizer/ decomp.	CESGA
Quest	Python/C				
Circ (Google)	Python			??	
Quil (Rigetti)	Python			??	

ProjectQ



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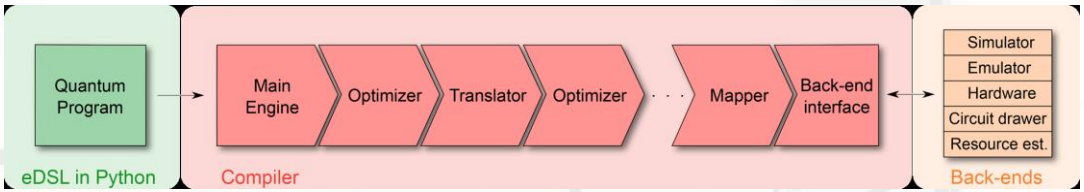
ProjectQ. Compiler Engines



MainEngine	The MainEngine class provides all functionality of the main compiler engine.
CommandModifier	CommandModifier is a compiler engine which applies a function to all incoming commands, sending on the resulting command instead of the original one.
IBMCNOTMapper	CNOT mapper for the IBM backend.
ManualMapper	Manual Mapper which adds QubitPlacementTags to Allocate gate commands according to a user-specified mapping.
LocalOptimizer	LocalOptimizer is a compiler engine which optimizes locally (merging rotations, cancelling gates with their inverse) in a local window of user-defined size.
AutoReplacer	The AutoReplacer is a compiler engine which uses *engine.is_available* in order to determine which commands need to be replaced/decomposed/compiled further.
TagRemover	TagRemover is a compiler engine which removes temporary command tags.

```
eng = MainEngine(backend=Simulator(),
                 engine_list =[AutoReplacer(rule_set), TagRemover(), LocalOptimizer(3) ])
```

More at http://projectq.readthedocs.io/en/latest/projectq.cengines.html

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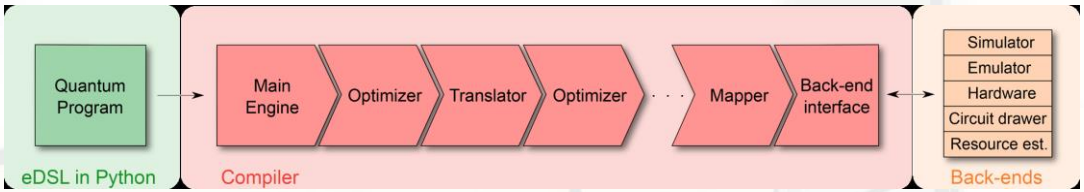
ProjectQ. Backends

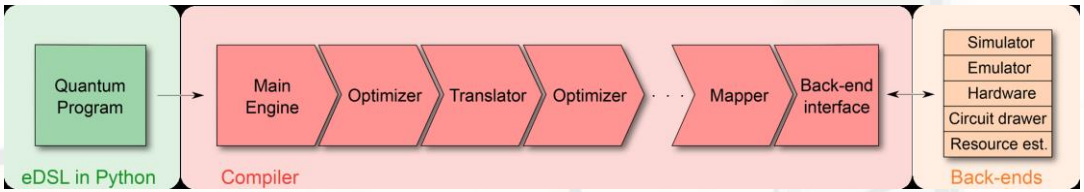


CommandPrinter	CommandPrinter is a compiler engine which prints commands to stdout prior to sending them on to the next compiler engine.
CircuitDrawer	CircuitDrawer is a compiler engine which generates TikZ code for drawing quantum circuits.
Simulator	Simulator is a compiler engine which simulates a quantum computer using C++-based kernels.
ClassicalSimulator	A simple introspective simulator that only permits classical operations.
ResourceCounter	ResourceCounter is a compiler engine which counts the number of gates and max.
IBMBackend	The IBM Backend class, which stores the circuit, transforms it to JSON QASM, and sends the circuit through the IBM API.

More at http://projectq.readthedocs.io/en/latest/projectq.backends.html

Steiger, D. S., Häner, T., & Troyer, M. (2016). ProjectQ: An Open Source Software Framework for Quantum Computing. Retrieved from http://arxiv.org/abs/1612.08091

ProjectQ. Setups



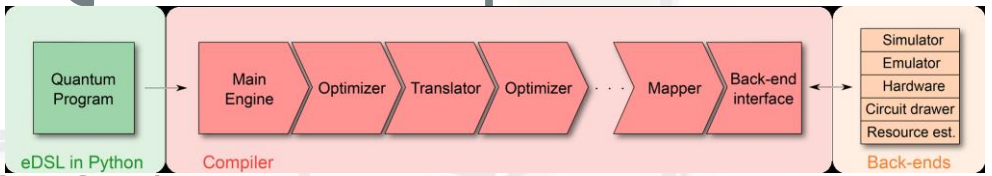
- The setups package contains a collection of setups which can be loaded by the MainEngine.
- Each setup then loads its own set of decomposition rules and default compiler engines.
- MainEngine(setup=projectq.setups.ibm)

default	Defines the default setup which provides an *engine_list* for the *MainEngine*
ibm	Defines a setup useful for the IBM QE chip with 5 qubits.
ibm16	Defines a setup useful for the IBM QE chip with 16 qubits.

More at http://projectq.readthedocs.io/en/latest/projectq.setups.html

Steiger, D. S., Häner, T., & Troyer, M. (2016). ProjectQ: An Open Source Software Framework for Quantum Computing. Retrieved from http://arxiv.org/abs/1612.08091

ProjectQ. eDSL. Operations



- All common gates: X, Y, Z, T, S, CNOT, SWAP, etc.
- Additional useful gates: Rx, Ry, Rz, R, Ph, Toffoli (ControledControledNOT/ ControledControledX)
- Advanced operations:
  - Quantum Fourier Transform, QFT
  - Hamiltonian Time Evolution, TimeEvolution
  - A set of gates to be applied on a set of qubits, QubitOperator
  - Create an entangled state: Entangle
- Methods to create multi-qubit controlled gates, ControledGate
- Measurement: Measure

- Sintax: <Operation> | <qubits>.
- Example: H | qureg[0]

More at http://projectq.readthedocs.io/en/latest/projectq.ops.html

Qiskit

https://qiskit.org/documentation/the_elements.html

Qiskit

- All common gates: X, Y, Z, T, S, CNOT, SWAP, etc.
- Additional useful gates: Rx, Ry, Rz, R, Toffoli
- Specific gates for IBM hardware:u1,cu1,u2,cu2,u3,cu3
- Advanced operations:
  - Quantum Fourier Transform, QFT
  - Hamiltonian Time Evolution, TimeEvolution
  - A set of gates to be applied on a set of qubits, Operator
- Methods to create multi-qubit controlled gates
- Measurement: Measure

- Sintax: gates are methods of the circuit class:
- Example: circuit.h(0) means add a H gate to qubit 0

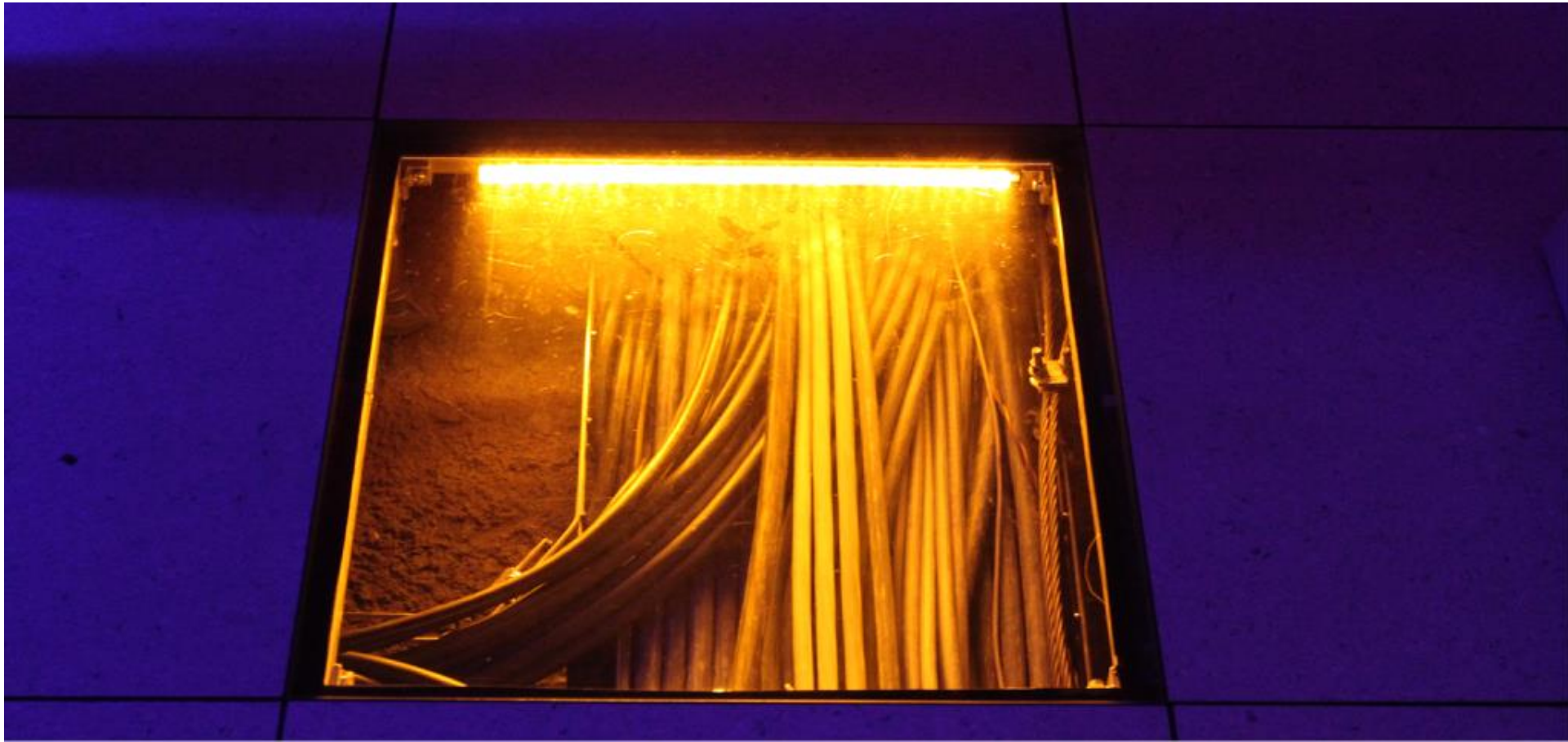
More at http://projectq.readthedocs.io/en/latest/projectq.ops.html

Qiskit. Backends

- AER.
  - Local simulator
  - Login not needed
  - Three simulators:
    - Unitary_simulator: produces the result operator of a circuit
    - Statevector_simulator: One shot simulator that returns the state vector
    - Qasm_simulator: simulates the real hardware including noise. Return the set of simulated measurements.
- Real backends:
  - Allow execution of circuits on real noisy hardware or advanced simulator
  - Need login
  - Remote execution using queues

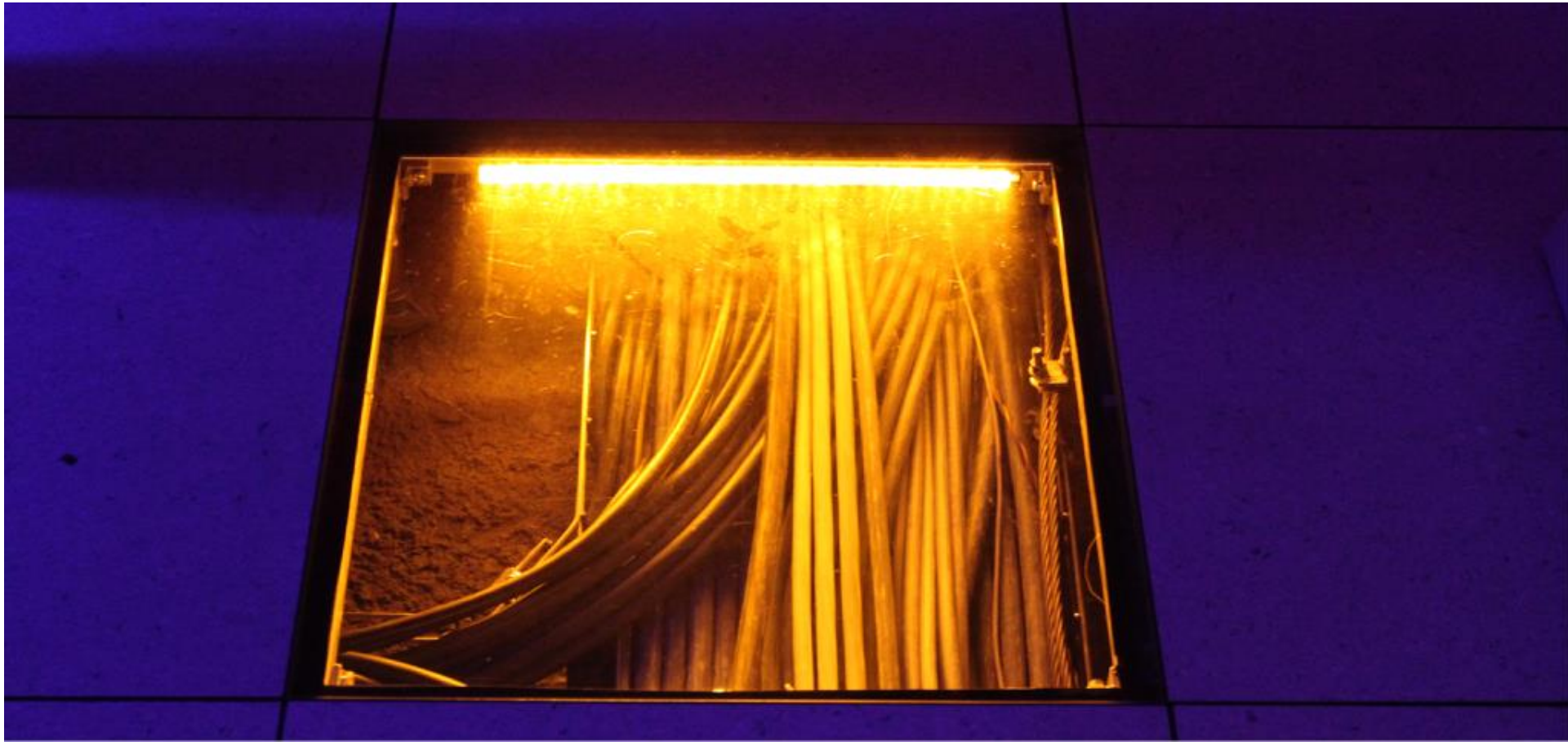
Exercise: My First ProjectQ Program

OPEN PROJECTQ/DENSE_CODING NOTEBOOK



Exercise: My First Qiskit Program

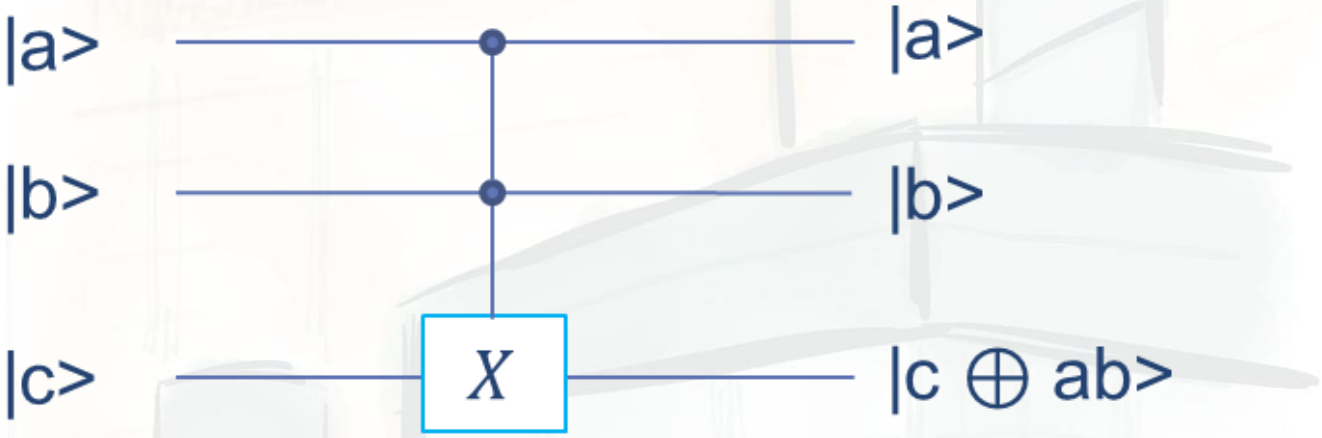
OPEN QISKIT/DENSE_CODING NOTEBOOK



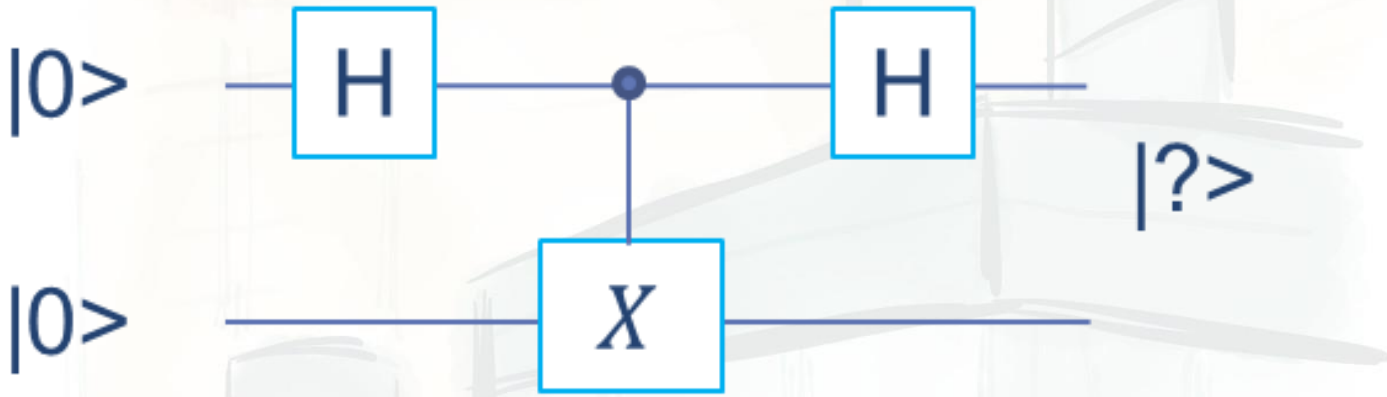
Some Basic Concepts with 2 qubits

Phase Kickback

Toffoli Gate



Inverse Gate?

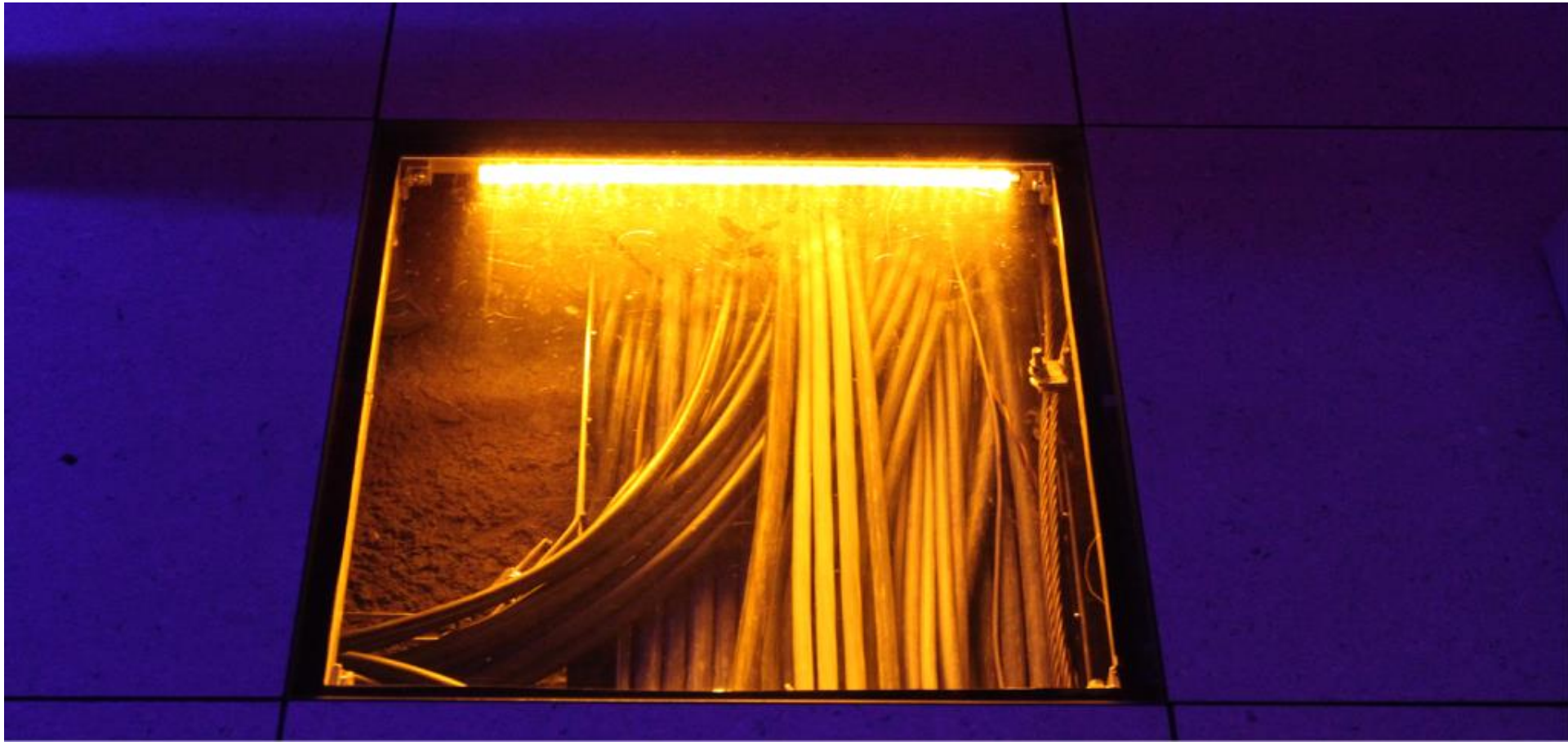


Exercise: Some Basic Gates with ProjectQ

OPEN PROJECTQ/SOME_BASICS NOTEBOOK

Exercise: Some Basic Gates with Qiskit

OPEN QISKIT/SOME_BASICS NOTEBOOK

CESGA

Thanks!
Questions?