Introduction to ProjectQ

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Outline

The ProjectQ framework

What is ProjectQ?

ProjectQ is an open-source software framework for quantum computing.

It aims at providing tools which facilitate inventing, implementing, testing, debugging, and running quantum algorithms using either classical hardware or actual quantum devices.

Important URLs:

Main website	`http://projectq.ch`
GitHub	`https://github.com/ProjectQ-Framework/ProjectQ`
Documentation	`https://projectq.readthedocs.io/en/latest/index.html`

ProjectQ: Design goals

ProjectQ was designed with four main goals

1. Open & Free: ProjectQ is released under the Apache 2 license
2. Simple learning curve: It is implemented in Python and has an intuitive syntax
3. Easily extensible: Anyone can contribute to the compiler, the embedded domain-specific language, and libraries
4. Code quality: Code reviews, continuous integration testing (unit and functional tests)

Citing ProjectQ

Think about citing the following papers

D. S. Steiger, T. Häner, and M. Troyer. "ProjectQ: An Open Source Software Framework for Quantum Computing". In: (Dec. 2016). DOI: 10.22331/q-2018-01-31-49. arXiv: 1612.08091. URL: https://arxiv.org/abs/1612.08091

T. Häner et al. "A Software Methodology for Compiling Quantum Programs". In: (Apr. 2016). DOI: 10.1088/2058-9565/aaa5cc. arXiv: 1604.01401. URL: http://arxiv.org/abs/1604.01401

ProjectQ in details

ProjectQ's syntax

Physics

$$A\left|000\right\rangle \equiv A\left(\left|0\right\rangle \otimes \left|0\right\rangle \otimes \left|0\right\rangle\right)$$

ProjectQ

```
A | qubits
```

eDSL in Python

```
1  from projectq import MainEngine
2  from projectq.ops import H, Measure
3
4  eng = MainEngine()
5  qubit = eng.allocate_qubit()
6
7  H | qubit
8  Measure | qubit
9
10 eng.flush()
11 print("Measured {}".format(int(qubit)))
```

```
> python3 test.py
Measured 1
```


Imports

There are three main sub-modules to ProjectQ

```
1  import projectq.backends # contains all known back-ends
2  import projectq.cengines # contains compiler engines
3  import projectq.ops      # contains most quantum gates and operations
4  import projectq.meta     # contains 'meta' operations
```

But there are actually a few more:

```
1  import projectq.setups
2  import projectq.libs
3  import projectq.types
```


Allocating qubits

The `MainEngine` contains two methods to create qubits:

- `eng.allocate_qubit()` for a single qubit
- `eng.allocate_qureg(N)` for a list of N qubits (also known as a quantum register)

For ProjectQ, quantum registers are nothing more than lists of qubits

```
1  qureg = eng.allocate_qureg(10)
2  qubit_8 = qureg[7]
```

Per convention, qubit allocated using ProjectQ start in the $|0\rangle$ state.

Allocating qubits (contd.)

Once a qubit has been measured, you can access its value by converting it to an `int` or `bool`:

```
1  measured = int(qubit)
```

If a qubit was not already measured when you try to convert it to an `bool` or `int`, an exception will be thrown:

```
> python3 test.py
RuntimeError: Error: Qubit has not been measured / uncomputed! \
  There is most likely a bug in your code.
raised in:
'  File ".../backends/_sim/_simulator.py", line 385, in _handle'
'    self._simulator.deallocate_qubit(ID)'
```

Deallocating qubits

Qubit are *automatically* deallocated once they go out of scope.

You can however deallocate a qubit manually by using either syntax:

```
del qubit
qubit.__del__()
```

For quantum registers:

```
del qureg # deletes all qubits in register
```

Important

Qubit may only be de-allocated when in a classical state

Single-qubit gates

Basic single-qubit quantum gates can be used as-is.

X, NOT	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$	**S**	$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$	**Rx**	$\begin{bmatrix} \cos(\alpha/2) & -i\sin(\alpha/2) \\ -i\sin(\alpha/2) & \cos(\alpha/2) \end{bmatrix}$	**R**	$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\alpha} \end{bmatrix}$
Y	$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$	**T**	$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$	**Ry**	$\begin{bmatrix} \cos(\alpha/2) & -\sin(\alpha/2) \\ \sin(\alpha/2) & \cos(\alpha/2) \end{bmatrix}$	**Ph**	$\begin{bmatrix} e^{i\alpha} & 0 \\ 0 & e^{i\alpha} \end{bmatrix}$
Z	$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$			**Rz**	$\begin{bmatrix} e^{-i\alpha/2} & 0 \\ 0 & e^{i\alpha/2} \end{bmatrix}$		

```
from projectq.ops import (X, NOT, Y, Z, S, T, H,
                          Rx, Ry, Rz, Ph, R)
X | qubit
Rx(1.0) | qubit
```


Other standard gates

```
from projectq.ops import CNOT, CZ, Toffoli, Swap, Barrier, Measure

CNOT | (ctrl, tgt)
CZ | (ctrl, tgt)
Toffoli | (ctrl1, ctrl2, tgt) # (CCNOT gate)

Swap | (qubit0, qubit1)

Barrier | qubit
Measure | qubit
```

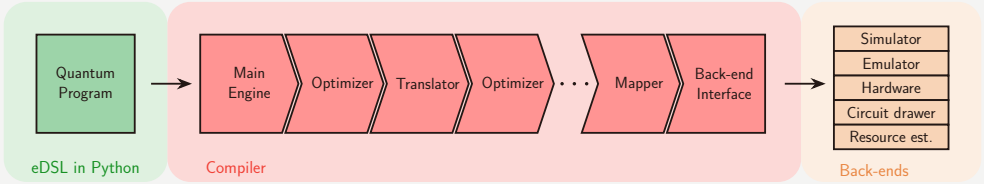

eDSL in Python (again)

```
from projectq import MainEngine
from projectq.ops import H, Measure

eng = MainEngine()  # create a default compiler
qubit = eng.allocate_qubit()  # allocate 1 qubit

H | qubit  # apply a Hadamard gate
Measure | qubit  # measure the qubit

eng.flush()  # flush all gates (and execute measurements)
print("Measured {}".format(int(qubit)))  # output measurement result
```

Flushing command list

ProjectQ does *not* execute instructions immediately.

Teaser from tomorrow:



Main message

Some of the compiler engines may cache instructions. Therefore, use:
`eng.flush()`

Beyond simple gates

ProjectQ supports some *meta*-operations:

- Tensor gates (going from single to N-qubit gates)
- Control
- Dagger
- Loop
- Compute/Uncompute

Control and tensor gates

```
1  from projectq.ops import (X, Measure,
2                            All, Tensor, C)
3
4  All(Measure) | qureg          # Measure all qubits in 'qureg'
5  Tensor(Measure) | qureg       # Same as above
6
7  C(X) | (ctrl, tgt)            # equivalent to CNOT(ctrl, tgt)
8  C(X, 2) | (ctrl1, ctrl2, tgt) # equivalent to Toffoli(c1, c2, tgt)
```

2-qubit Bell state

```python
from projectq import MainEngine
from projectq.ops import All, Measure, CNOT, C, X, H

eng = MainEngine()
qureg = eng.allocate_qureg(2)

H | qureg[0]
CNOT | (qureg[0], qureg[1]) # same as C(X) | (qureg[0], qureg[1])
All(Measure) | qureg

eng.flush()
print("Measured {}".format([int(qubit) for qubit in qureg]))
# Should print either '[0, 0]' or '[1, 1]' with 0.5 probability
```


General Bell state

```python
from projectq import MainEngine
from projectq.ops import All, Measure, CNOT, H

N = 10
eng = MainEngine()
qureg = eng.allocate_qureg(N)

H | qureg[0]
for qb in qureg[1:]:
    CNOT | (qureg[0], qb)
All(Measure) | qureg

eng.flush()
print("Measured {}".format([int(qubit) for qubit in qureg]))
```


Control with N > 1

Imagine you are in the following situation:

```python
from projectq import MainEngine
from projectq.ops import H, X, All, C

eng = MainEngine()
ctrl = eng.allocate_qureg(5)
qureg = eng.allocate_qureg(4)
```

How to perform some gates controlled on all qubits in `ctrl` ?

Control with N > 1 (contd.)

Bad solution:

```python
from projectq import MainEngine
from projectq.ops import H, X, All, C

eng = MainEngine()
ctrl = eng.allocate_qureg(5)
qureg = eng.allocate_qureg(4)

# Idea 1
C(H, 5) | (ctrl[0], ctrl[1], ctrl[2], ctrl[3], ctrl[4], qureg[0])
# Idea 2
C(H, 5) | (*ctrl, qureg[0])
```

Not recommended!

Control with N > 1 (contdd.)

Better solution:

```
from projectq import MainEngine
from projectq.meta import Control
from projectq.ops import H, X, All, C

eng = MainEngine()
ctrl = eng.allocate_qureg(5)
qureg = eng.allocate_qureg(4)

with Control(eng, ctrl):
    H | qureg[0]
    X | qureg[1]
```


General Bell state (revisited)

```
from projectq import MainEngine
from projectq.meta import Control
from projectq.ops import All, Measure, X, H

N = 10
eng = MainEngine()
qureg = eng.allocate_qureg(N)

H | qureg[0]
with Control(eng, qureg[0]):
    All(X) | qureg[1:]
All(Measure) | qureg
eng.flush()
print("Measured {}".format([int(qubit) for qubit in qureg]))
```


Inverting gates

Bad solution:

```
from projectq import MainEngine
from projectq.ops import Rx, get_inverse

eng = MainEngine()
qureg = eng.allocate_qureg(2)

# ...
get_inverse(Rx(1.0)) | qureg[0]
get_inverse(Rx(2.0)) | qureg[1]
```

Not recommended!

Control with N > 1 (contdd.)

Better solution:

```
from projectq import MainEngine
from projectq.meta import Dagger
from projectq.ops import Rx

eng = MainEngine()
qureg = eng.allocate_qureg(2)

with Dagger(eng):
    Rx(1.0) | qureg[0]
    Rx(1.0) | qureg[1]
```

Implementing loops

```
from projectq import MainEngine
from projectq.meta import Loop

N = 5; N_iter = 10
eng = MainEngine()
qureg = eng.allocate_qureg(N)

# Normal Python loop
for _ in range(N_iter):
    # do something

# ProjectQ loop
with Loop(eng, N_iter):
    # do something
```


Compute/Uncompute pattern

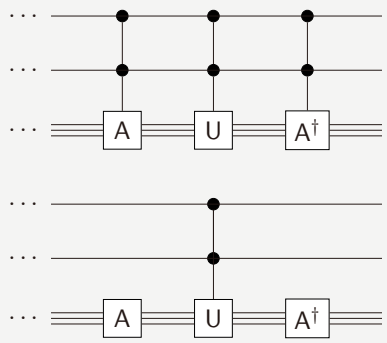
```
from projectq import MainEngine
from projectq.ops import H, X
from projectq.meta import Compute, Uncompute

N = 5
eng = MainEngine()
qureg = eng.allocate_qureg(N)

# ProjectQ loop
with Compute(eng, N_iter):
    All(H) | qureg
All(X) | qureg[0::2]
Uncompute(eng)
```


Compute/Uncompute pattern (contd.)

```
# ...

# ProjectQ loop
with Compute(eng):
    # some computations here

# more computations here

with CustomUncompute(eng):
    # do 'better' Uncompute here
```


Benefits of code annotations

More context for the compiler → better chances for optimizations!




```
C(A)  | (ctrl, qubit)
C(U)  | (ctrl, qubit
C(iA) | (ctrl, qubit)
```

```
with Control(eng, ctrl):
    with Compute(eng):
        A  | qubit
    U | qubit
    Uncompute(eng)
```

Quick words about Backends

Default backend

By default, the MainEngine uses the simulator/emulator backend:

```
1 from projectq import MainEngine
2 from projectq.backends import Simulator
3
4 eng = MainEngine(backend=Simulator())
```

Available backends:

- Simulator
- ResourceCounter
- CommandPrinter
- CircuitDrawer
- IBMBackend

ResourceCounter

```
1 from projectq import MainEngine
2 from projectq.backends \
3     import ResourceCounter
4
5 backend = ResourceCounter()
6 eng = MainEngine(backend=backend)
7 # ... do something
8 print(backend)
```

```
> python3 test.py
Gate class counts:
    AllocateQubitGate : 1
    HGate : 1
    MeasureGate : 1

Gate counts:
    Allocate : 1
    H : 1
    Measure : 1

Max. width (number of qubits) : 1.
```


CommandPrinter

```
1 from projectq import MainEngine
2 from projectq.backends import CommandPrinter
3
4 eng = MainEngine(backend=CommandPrinter(accept_input=True,
5                                         default_measure=False,
6                                         in_place=False))
7 # ... do something
```

```
> python3 test.py
Allocate | Qureg[0]
H | Qureg[0]
Measure | Qureg[0]
Input measurement result (0 or 1) for qubit 0: 0
```

CircuitDrawer

```python
from projectq import MainEngine
from projectq.backends import CircuitDrawer

backend = CircuitDrawer()
eng = MainEngine(
    backend=CircuitDrawer(
        accept_input=False,
        default_measure=0)

# ... do something

with open('/tmp/circuit.tex', 'w') as fd:
    fd.write(backend.get_latex())
```

IBMBackend

Submit circuits directly to the IBM Quantum Experience

```python
from projectq.backends import IBMBackend

backend = IBMBackend(use_hardware=False,
                     num_runs=1024,
                     verbose=False,
                     user=None,
                     password=None,
                     device='ibmqx4',
                     num_retries=3000,
                     interval=1,
                     retrieve_execution=None)
```


Summary

What we've seen so far

- Qubit allocation/deallocation (`eng.allocate_XXX(...)`)
- Single-qubit gates (`X | qureg`, `H`, `Rx(1.0)`, `...`)
- Measurements (`Measure | qubit`)
- Tensor gate application (`All(Measure) | qureg`)
- *Meta*-operations
  - Control (`with Control(eng, ctrl_qubits)`)
  - Dagger (`with Dagger(eng, ctrl_qubits)`)
  - Loop (`with Loop(eng, N_iter)`)
  - Compute/Uncompute (`with Compute(eng)`)
- Backend choices (`Simulator()`, `ResourceCounter()`, `CommandPrinter()`, `...`)

Installation

Quick install for users

Simplest method:

```
python3 -m pip install --user projectq
```

Or if you're using a `virtualenv`:

```
. path/to/virtualenv/bin/activate
python3 -m pip install projectq
```

Might want to change the C++ compiler:

```
CXX=g++-9 python3 -m pip install -e .
```


Quick install for developers

Checkout the repository

```
git clone https://github.com/ProjectQ-Framework/ProjectQ.git
```

Install *in-place*:

```
python3 -m pip install -e .
```


Ubuntu/Debian

1. Install the required build tools:

   ```
   sudo apt-get install build-essential
   ```

2. Install Python 3 and the package manager `pip`

   ```
   sudo apt-get install python3 python3-pip
   ```

3. Install ProjectQ

   ```
   python3 -m pip install --user projectq
   ```

Windows

Download and install the latest Python distribution:

64bits: `https://www.python.org/ftp/python/3.7.3/python-3.7.3-amd64.exe`

32bits: `https://www.python.org/ftp/python/3.7.3/python-3.7.3.exe`

Install the compiler and associated libraries. Either of

With Visual Studio `https://visualstudio.microsoft.com/`

Without Visual Studio

Visual C++ Build Tools `http://chürzer.ch/visual-cpp-build-tools`

Microsoft Windows SDK `http://chürzer.ch/windows-10-sdk`

Open a `cmd.exe` window:

```
> python3 -m pip install --user projectq
```


Mac OSX

Download and install XCode
`https://itunes.apple.com/ch/app/xcode/id497799835`

In a Terminal windows enter:

```
> xcode-select --install
```

Try with the Apple version of `clang`:

```
> sudo python3 -m pip install projectq
```


Mac OSX (contd.)

If it fails, install Homebrew

```
> /usr/bin/ruby -e "`curl -fsSL https://git.io/pVOl`"
```

Install the required programs and libraries

```
> brew install python3 llvm
```

Compile and install ProjectQ

```
> CXX=/usr/local/opt/llvm/bin/clang++ python3 -m pip install projectq
```


Small test program

```
1  from projectq import MainEngine
2  from projectq.ops import H
3
4  eng = MainEngine()
5  qubit = eng.allocate_qubit()
6  H | qubit
7
8  Measure | qubit
9  eng.flush()
10
11 print('Measured: {}'.format(int(qubit)))
```

Shortened URLs

Windows:

- Python
  - 64bits: `https://www.python.org/ftp/python/3.7.3/python-3.7.3-amd64.exe`
  - 32bits: `https://www.python.org/ftp/python/3.7.3/python-3.7.3.exe`
- Visual Studio

  `https://visualstudio.microsoft.com/`
- Visual C++ Build Tools

  `https://visualstudio.microsoft.com/en/visual-cpp-build-tools/`
- Microsoft Windows SDK

  `https://developer.microsoft.com/en-us/windows/downloads/windows-10-sdk`

Mac OSX:

- Homebrew:

  `https://raw.githubusercontent.com/Homebrew/install/master/install`

Thank you for your attention

Any questions?

Time for a break!