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ECOLE CONJOINTE GT IQ , GT2L et EU/ME

Approches Quantiques pour une nouvelle recherche opérationnelle !?

Montpellier du 2-5 Novembre 2021

Your first steps into IBM Quantum Computing

IBM Client Center Montpellier

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Part 1

Guided tour of the IBM Quantum devices,

and Quantum « Hello World! »

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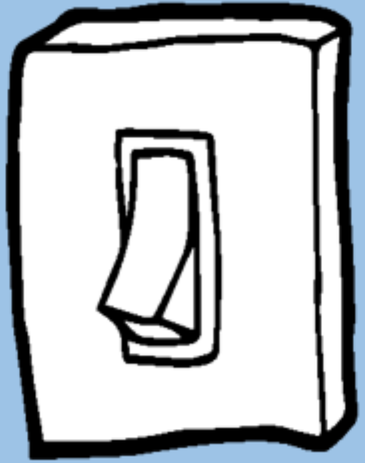
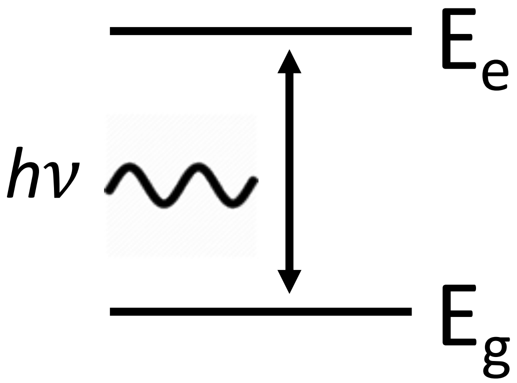


1

classical bit

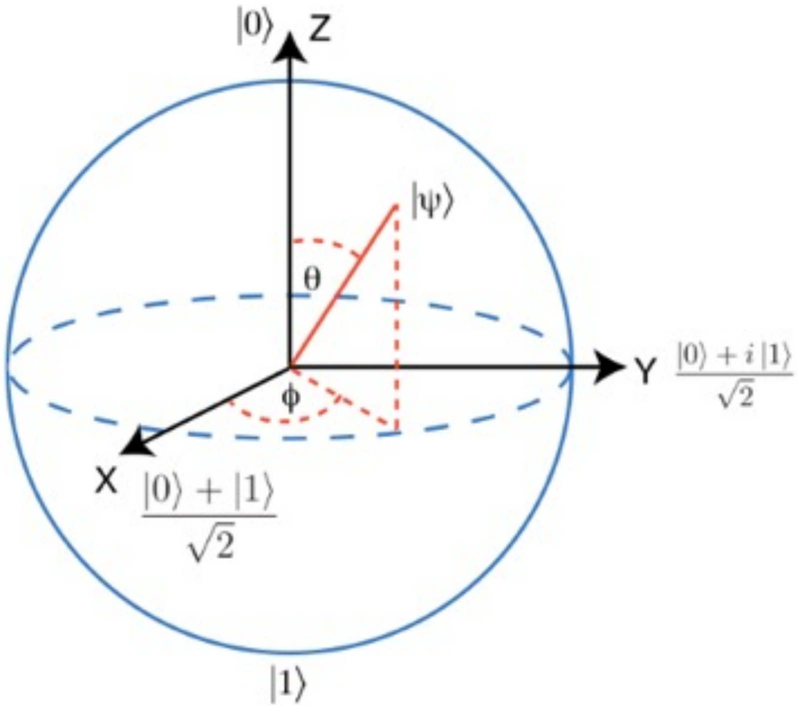
qubit : quantum bit



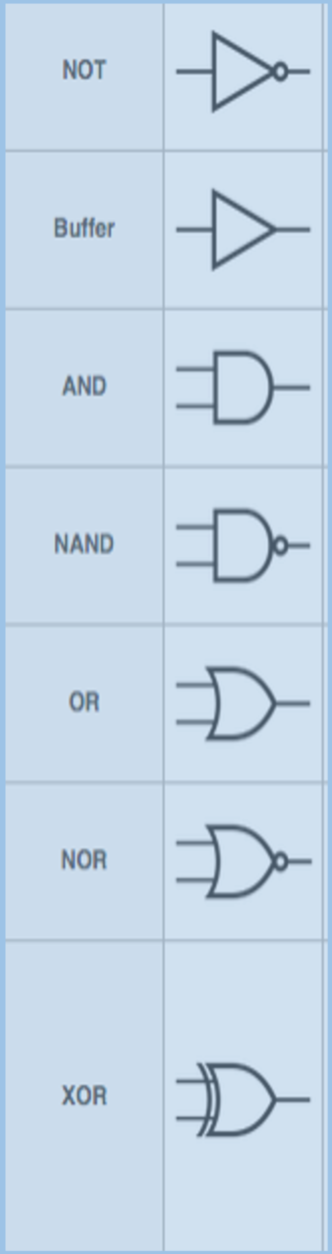
$$|e\rangle \sim |1\rangle$$

$$|g\rangle \sim |0\rangle$$

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$



The Bloch sphere



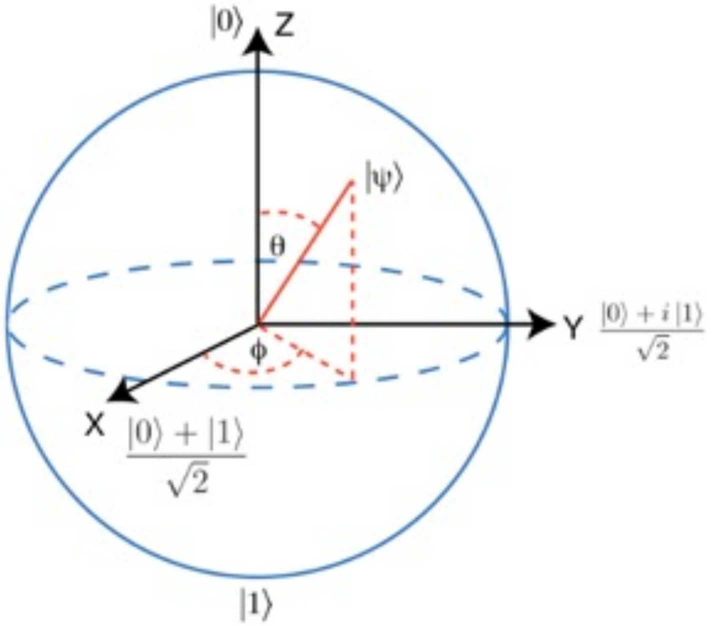
Controlling a qubit

« PAULI » Operators

rotation around x axis	⊕	$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$	qc.x(qr[n])	RX	$\begin{pmatrix} \cos\frac{\theta}{2} & -i\sin\frac{\theta}{2} \\ -i\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{pmatrix}$
rotation around y axis	Y	$\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$	qc.y(qr[n])	RY	$\begin{pmatrix} \cos\frac{\theta}{2} & -\sin\frac{\theta}{2} \\ \sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{pmatrix}$
rotation around z axis	Z	$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$	qc.z(qr[n])	RZ	$\begin{pmatrix} e^{-i\frac{\theta}{2}} & 0 \\ 0 & e^{i\frac{\theta}{2}} \end{pmatrix}$
Identity	I	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$	qc.id(qr[n])		

Bloch Sphere

$$|\psi\rangle = \cos\frac{\theta}{2}\,|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}\,|1\rangle$$



superposition
(X+Z)
Hadamard gate

H $\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$ qc.h(qr[n])

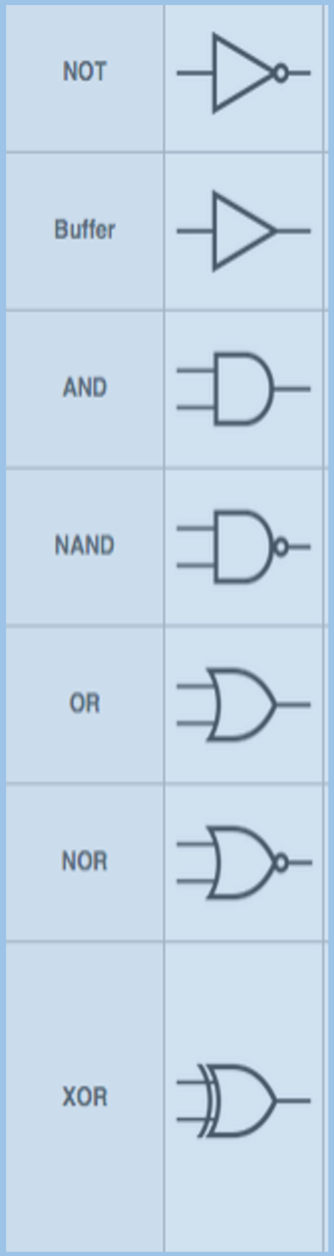
More operators are available from qiskit (S, T, swap, cswap, ccx, cz, …)

CNOT : flips target qubit according to control qubit state.

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

measurement

measures quantum state in quantum register into classical register (0/1)



classical operators

quantum operators :

H operator (Hadamard)

$$|0\rangle \xrightarrow{\ \boxed{H}\ } \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right)$$

creates equal superposition of states $|0\rangle$ and $|1\rangle$

Control-Not operation

controler →

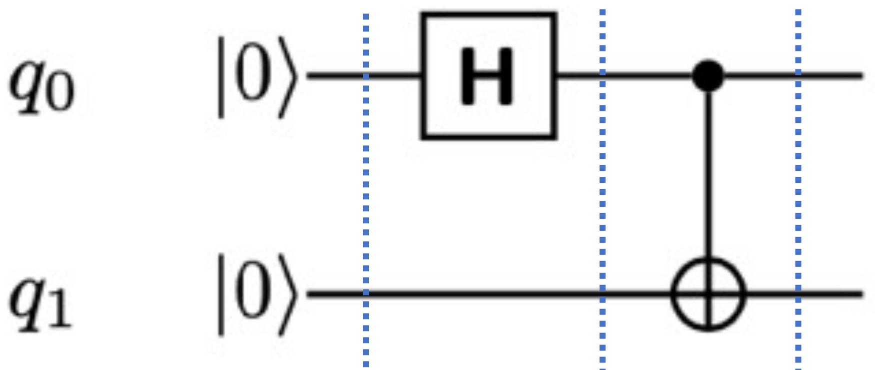
target →

target qubit state is flipped if and only if the control qubit is in state $|1\rangle$

creates quantum entanglement of two qubits

print(’Hello World!’)

Hello World!



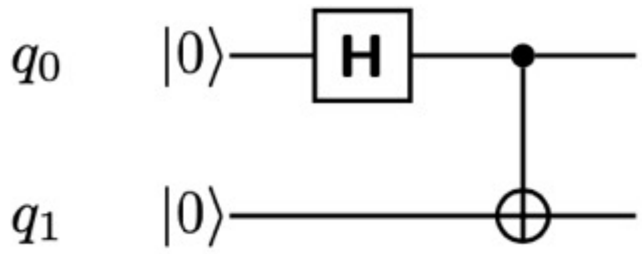
$$|00\rangle$$

$$\frac{1}{\sqrt{2}}(|00\rangle + |10\rangle)$$

$$\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

Hello World! example

Hadamard gate applied to q_0, then Control-Not applied to q_1, controlled by q_0



This produces the « Bell-State »

With words :

System starts in $|00\rangle$ (both q_0 and q_1 in state $|0\rangle$).

Then q_0 goes through Hadamard and gets into equal superposition of $|0\rangle$ and $|1\rangle$.

After q_0 controls q_1, the state of q_1 is in a superposition of $|0\rangle$ & $|1\rangle$, (q_1 stays at $|0\rangle$ when q_0 is $|0\rangle$, and q_1 goes $|1\rangle$ when q_0 is $|1\rangle$).

So : both q_0 and q_1 are in $|0\rangle$ (state $|00\rangle$) or both q_0 and q_1 are in $|1\rangle$ (state $|11\rangle$).

Our system is in equal superposition of $|00\rangle$ and $|11\rangle$.

The two qubits are entangled: if you measure one of the qubits, you immediately know the state of the other.

In between :

System starts in $|00\rangle$,then :

$$H|00\rangle = \frac{1}{\sqrt{2}}(|00\rangle+|10\rangle)$$

Applying CNOT: left part of the sum stays as is, right term goes to $|11\rangle$ resulting state is $\frac{1}{\sqrt{2}}(|00\rangle+|11\rangle)$.

One can easily prove there are no $\boldsymbol{\alpha},\boldsymbol{\beta},\boldsymbol{\gamma},\boldsymbol{\delta}$ such that:

$$(\boldsymbol{\alpha}|0\rangle+\boldsymbol{\beta}|1\rangle)\otimes(\boldsymbol{\gamma}|0\rangle+\boldsymbol{\delta}|1\rangle)=\frac{1}{\sqrt{2}}(|00\rangle+|11\rangle)$$

So, the resulting state is not the product of two quantum states, instead this is an entangled state.

With maths :

Stage 1 (H on q0) :

$$(H\otimes I)|00\rangle =$$

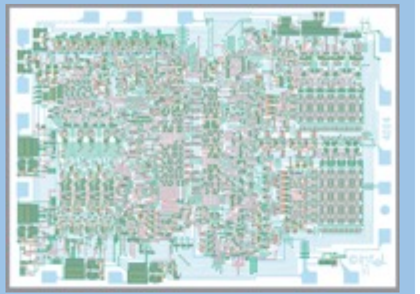
$$\frac{1}{\sqrt{2}}\begin{pmatrix}1 & 0 & 1 & 0\\ 0 & 1 & 0 & 1\\ 1 & 0 & -1 & 0\\ 0 & 1 & 0 & -1\end{pmatrix}\begin{pmatrix}1\\0\\0\\0\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\0\\1\\0\end{pmatrix}$$

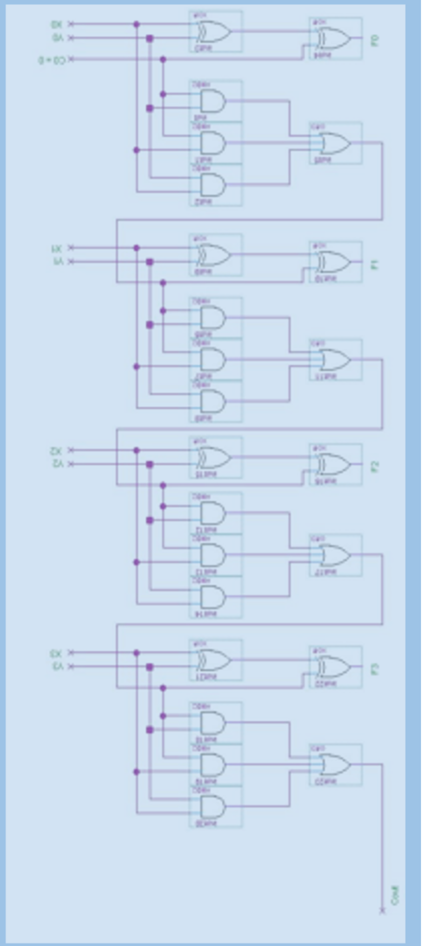
Stage 2: CNOT(0,1)

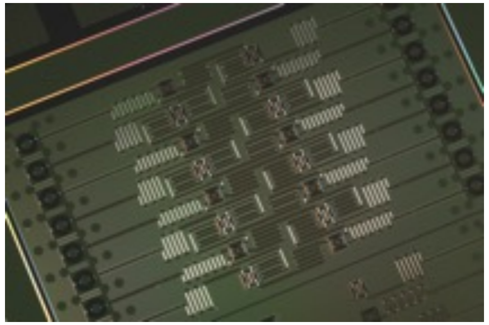
$$\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{pmatrix} \times \frac{1}{\sqrt{2}}\begin{pmatrix}1\\0\\1\\0\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\0\\0\\1\end{pmatrix}$$

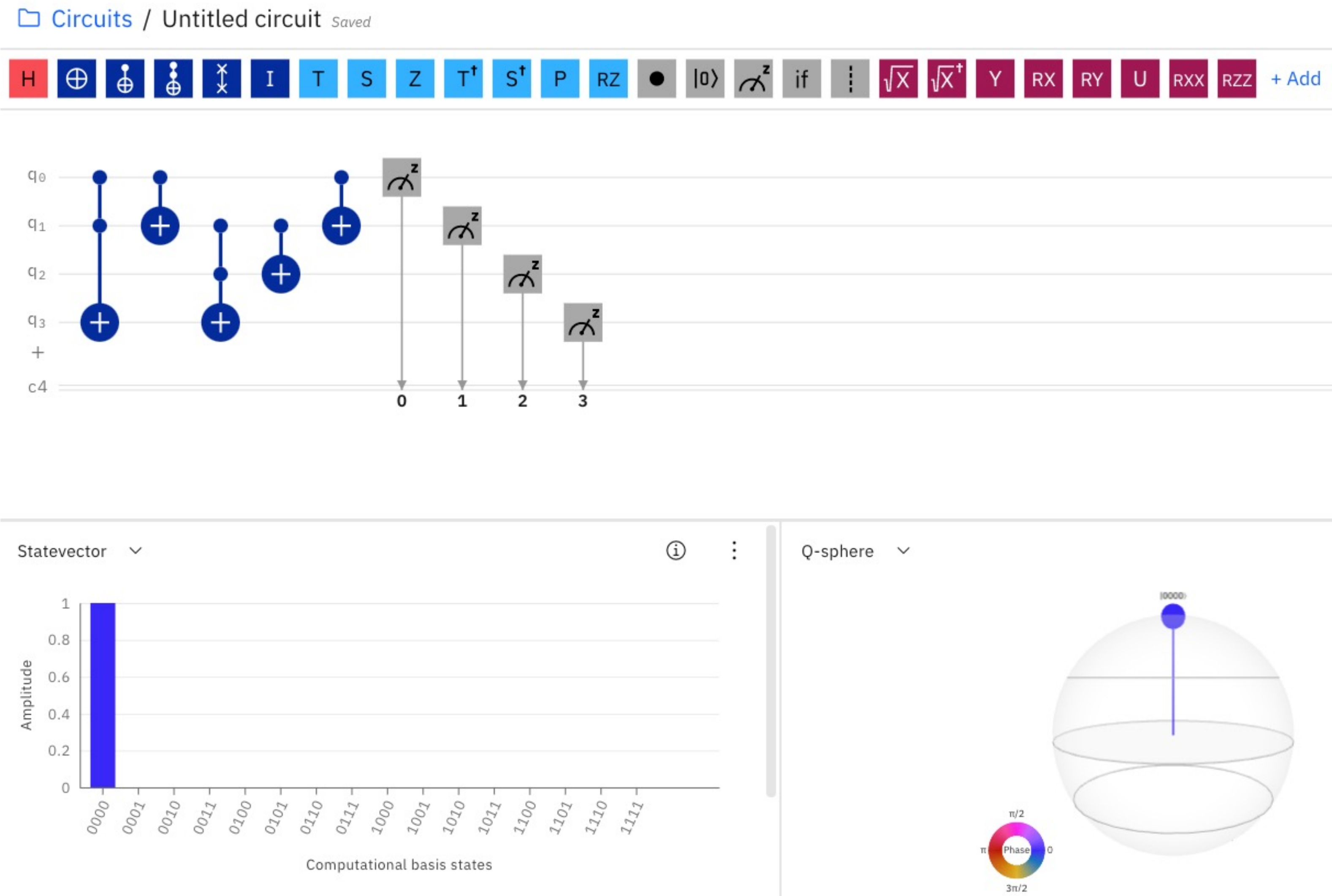
$$= \frac{1}{\sqrt{2}}(|00\rangle+|11\rangle)$$

Quantum Circuit









print('Hello World!')

Demo : Bell state on a quantum machine

Part 2

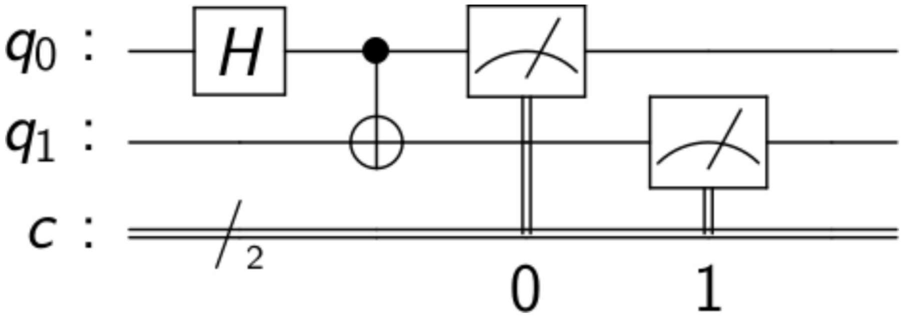
using qiskit library to run quantum program with Python.

print('Hello World!')

Programing

In [1]:
```python
from qiskit import QuantumCircuit, Aer, execute                # imports
backend = Aer.get_backend('qasm_simulator')                    # select a device for execution

qc = QuantumCircuit(2,2)                                       # create a quantum circuit having 2 qubits and 2 cbits

qc.h(0)                                                        # buid the circuit by
qc.cx(0,1)                                                     # adding operators on qubits

qc.measure([0,1],[0,1])                                        # use measurement gates to retrieve results

d = execute(qc,backend).result().get_counts()                  # execute qc on backend and get cumulated results into
print(d)                                                       # a dictionnary
```

```
{'00': 491, '11': 533}
```



print('Hello World!')

Historic Quantum Algorithms

Deutsch	1985	$2 \rightarrow 1$
Bernstein-Vazirani	1992	$N \rightarrow 1$
Deutsch-Josza	1992	$2^{N-1} + 1 \rightarrow 1$
Shor	1994	$e^N \rightarrow (\mathrm{Log}N)^3$
Grover	1996	$N \rightarrow \sqrt{N}$

More and new ones on quantumalgorithmzoo.org/