Quantum Computing in NLP

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Quantum Computing overview and Math

Overview

- Quantum computing represents a new paradigm in computation that utilizes the fundamental principles of quantum mechanics to perform calculations.
- promise of quantum computation lies in the possibility of efficiently performing a handful of tasks such as prime factorization, quantum simulation, search, optimization, and algebraic programs such as machine learning.
- The strength of QC comes in its capability of it being able to represent float numbers upto virtually infinite precision. (inherently analog nature)

Dirac Notation

Let's assume we live in a 2D world

1. Zero

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

2. One

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

Tensor product

$$\begin{pmatrix} x_0 \\ x_1 \end{pmatrix} * \begin{pmatrix} y_0 \\ y_1 \end{pmatrix} = \begin{pmatrix} x_0 * \begin{pmatrix} y_0 \\ y_1 \end{pmatrix} \\ \\ x_1 * \begin{pmatrix} y_0 \\ y_1 \end{pmatrix} \end{pmatrix} = \begin{pmatrix} x_0 y_0 \\ x_0 y_1 \\ x_1 y_0 \\ x_1 y_1 \end{pmatrix}$$

Operations on 1 bit

1. Identity
2. Negation
3. Set - 0
4. Set - 1

1. Identity

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

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

2. Negation

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

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

3. Set - 0

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

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

4. Set - 1

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

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

Conditional Not Gate

- MSB: Control bit
- LSB: Target bit

$$CNot := \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Bit Flip Operation

Definition:

$$X := \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

Example:

$$X(\begin{pmatrix} 0 \\ 1 \end{pmatrix}) = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

Quantum bit (Qubit)

- Def:

  $\binom{a}{b}$ is a Qubit if **$||a||^2 + ||b||^2 = 1$**, Where a & b are complex numbers.
- Cbit is a special case of Qubit
- Example:

$$\begin{pmatrix} \frac{1}{2} \\ \frac{\sqrt{3}}{4} \end{pmatrix} \quad \begin{pmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{pmatrix} \quad \begin{pmatrix} -1 \\ 0 \end{pmatrix}$$

Super Position

- The Qubit is not 0 or 1, but it's the squared sum of it comes out to be 1.
  - Does not mean they are 0 & 1 at the same time?
  - This is called “**Superposition**” (Schrödinger’s cat!)

Hadamard Product

Definition:

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

Example:

$$H(\begin{pmatrix} 0 \\ 1 \end{pmatrix}) = \begin{pmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{pmatrix}$$

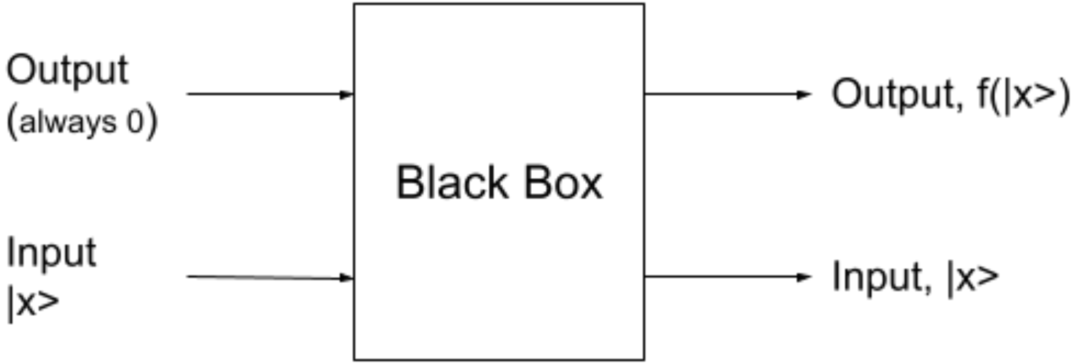
Collapsing

- When we "observe" the qbit, it is "collapses" to either 0 or 1 (Not automatically)
- As we understand onl the classical reality, we make this bit collapse to either 0 or 1 at the end of computation!
- Simplest collapsing circuit can be probability based one,
    - $\begin{pmatrix} a \\ b \end{pmatrix}$ Has $\mathbf{a}^2$ probability of collapsing to 0, and $\mathbf{b}^2$ of collapsing to 1

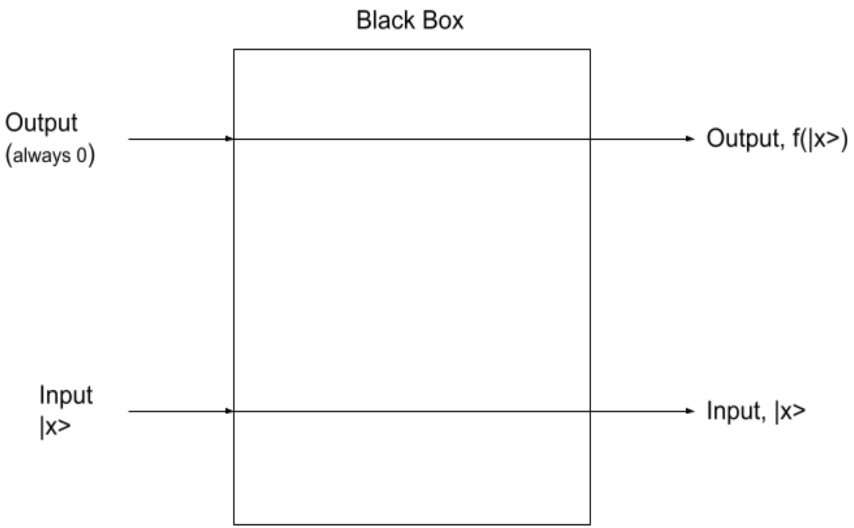
Classical QC problem:
Deutsche Oracle problem

2-wire model

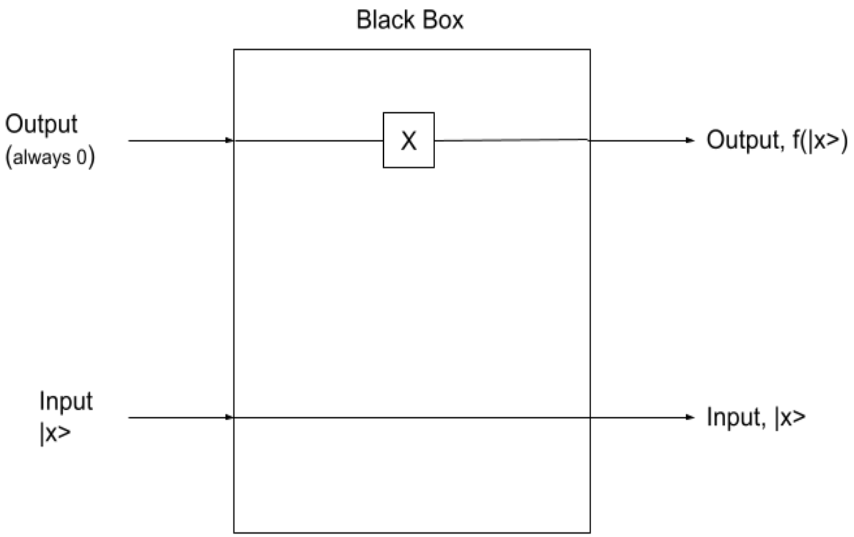
To make any operation reversible!



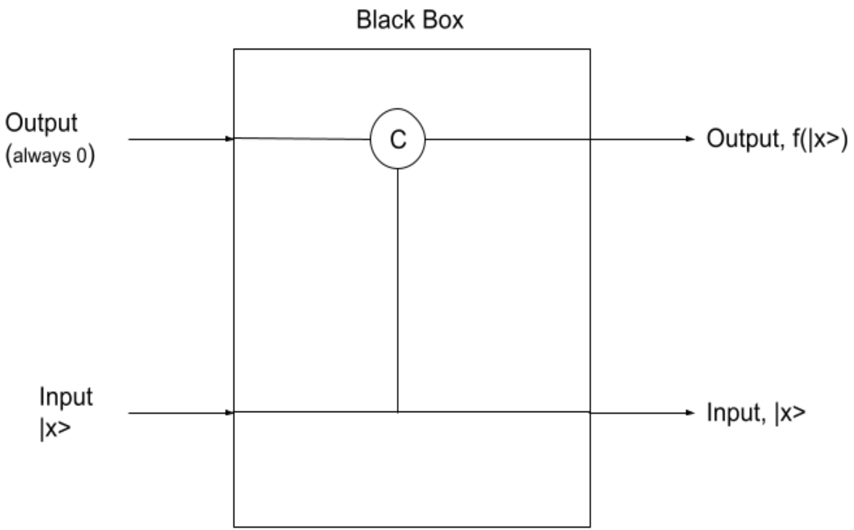
Output-0



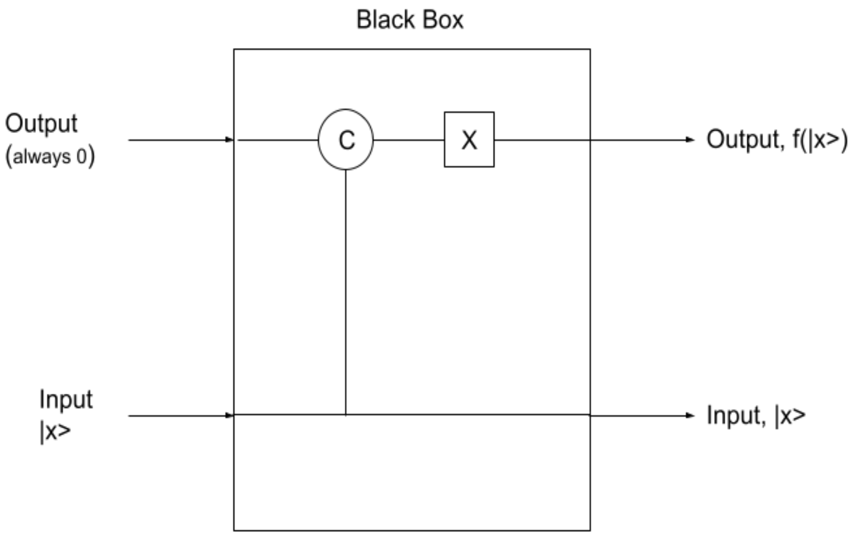
Output-1



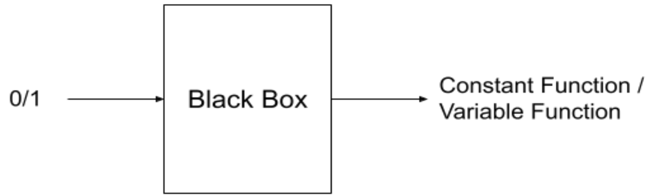
Identity



Negation

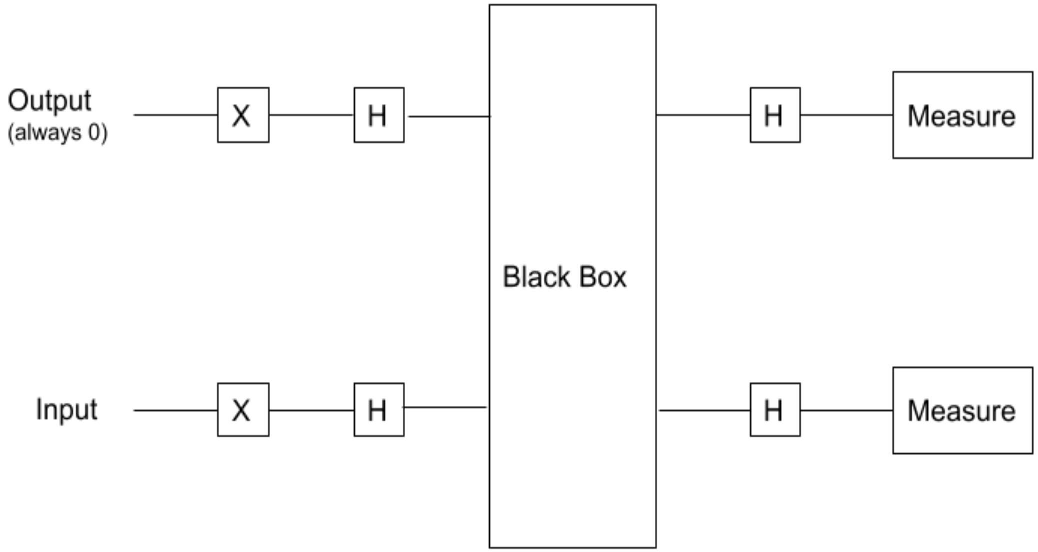


Deutsche Oracle Problem

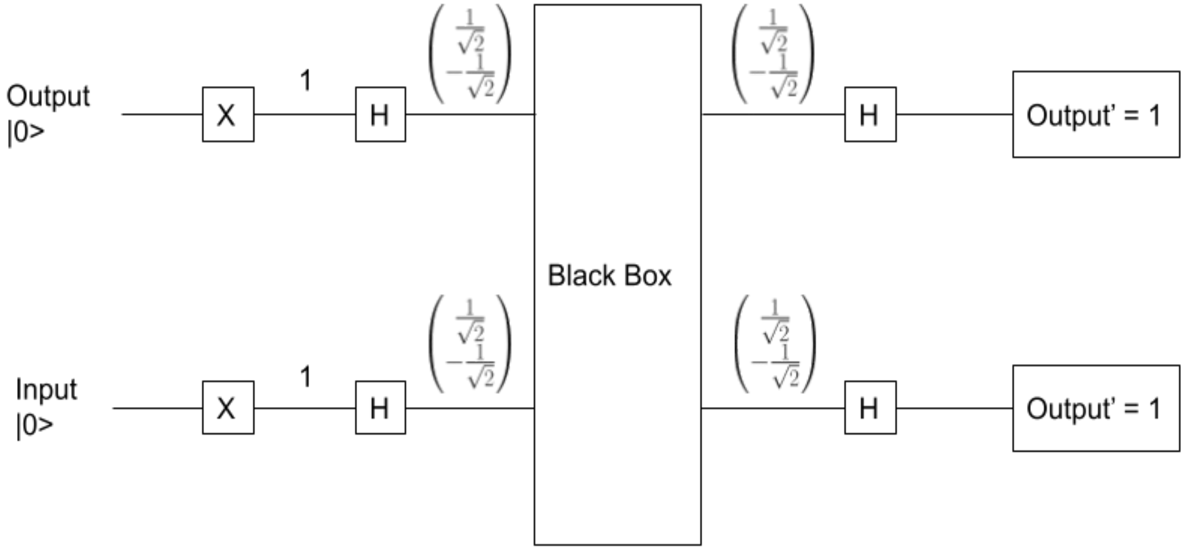


- There’s a black box where there can be one of the following functions
  - Set 1, set 0, negation, identity
  - Black box has to return if the function inside is constant or variable
- Rule:
  - You can only feed the query & record the output
- How many times human has to repeat the above experiment to solve the problem?
  - Human would take 2 attempts!
  - Quantum computer would take only 1!!

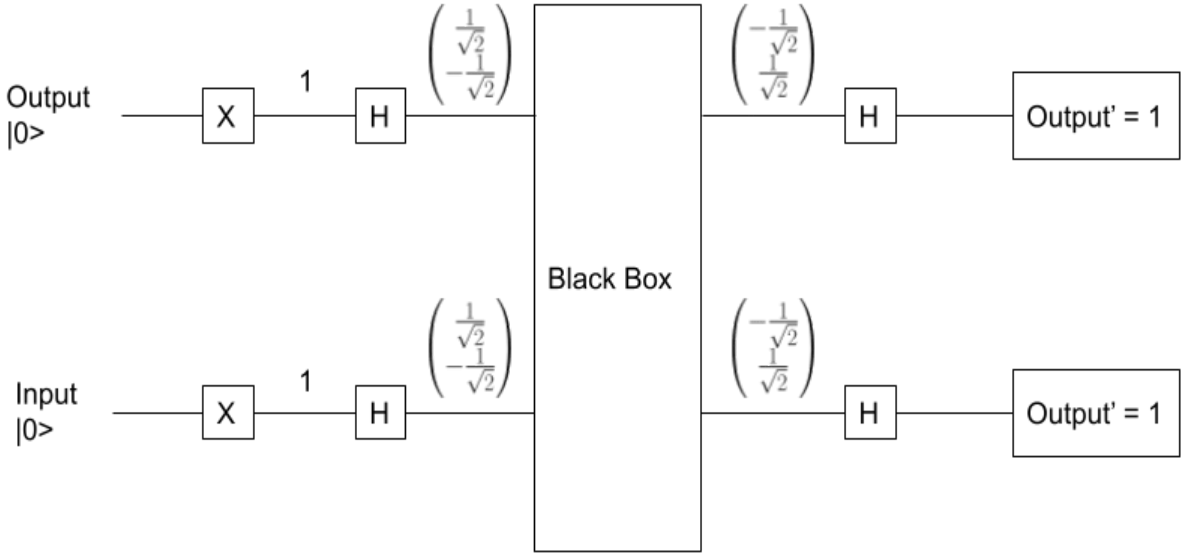
Circuit Diagram



Set - 0

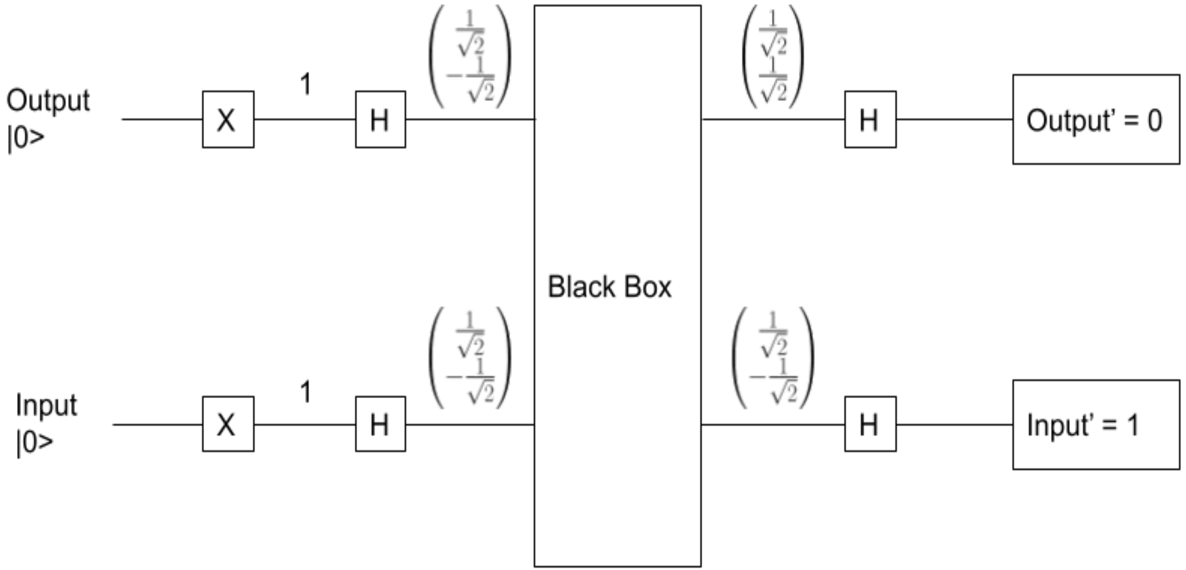


Set - 1



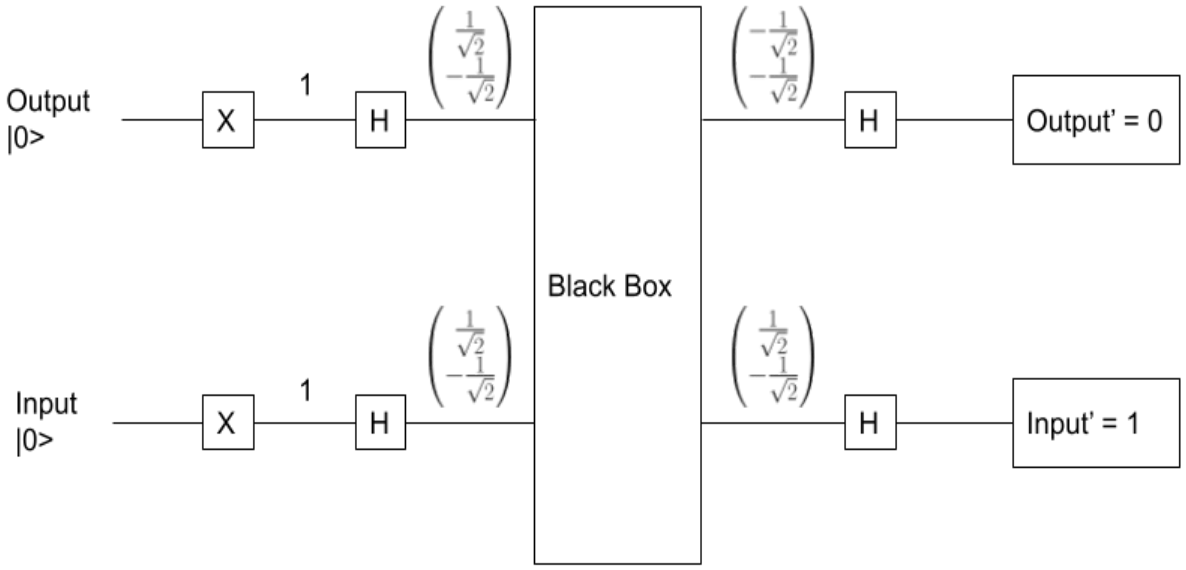
Output
|0>
X
1
H
$\begin{pmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{pmatrix}$
Black Box
$\begin{pmatrix} -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{pmatrix}$
H
Output' = 1
Input
|0>
X
1
H
$\begin{pmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{pmatrix}$
$\begin{pmatrix} -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{pmatrix}$
H
Output' = 1

Identity



Output
|0>
X
1
H
$\begin{pmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{pmatrix}$
Black Box
$\begin{pmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{pmatrix}$
H
Output' = 0
Input
|0>
X
1
H
$\begin{pmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{pmatrix}$
$\begin{pmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{pmatrix}$
H
Input' = 1

Negation

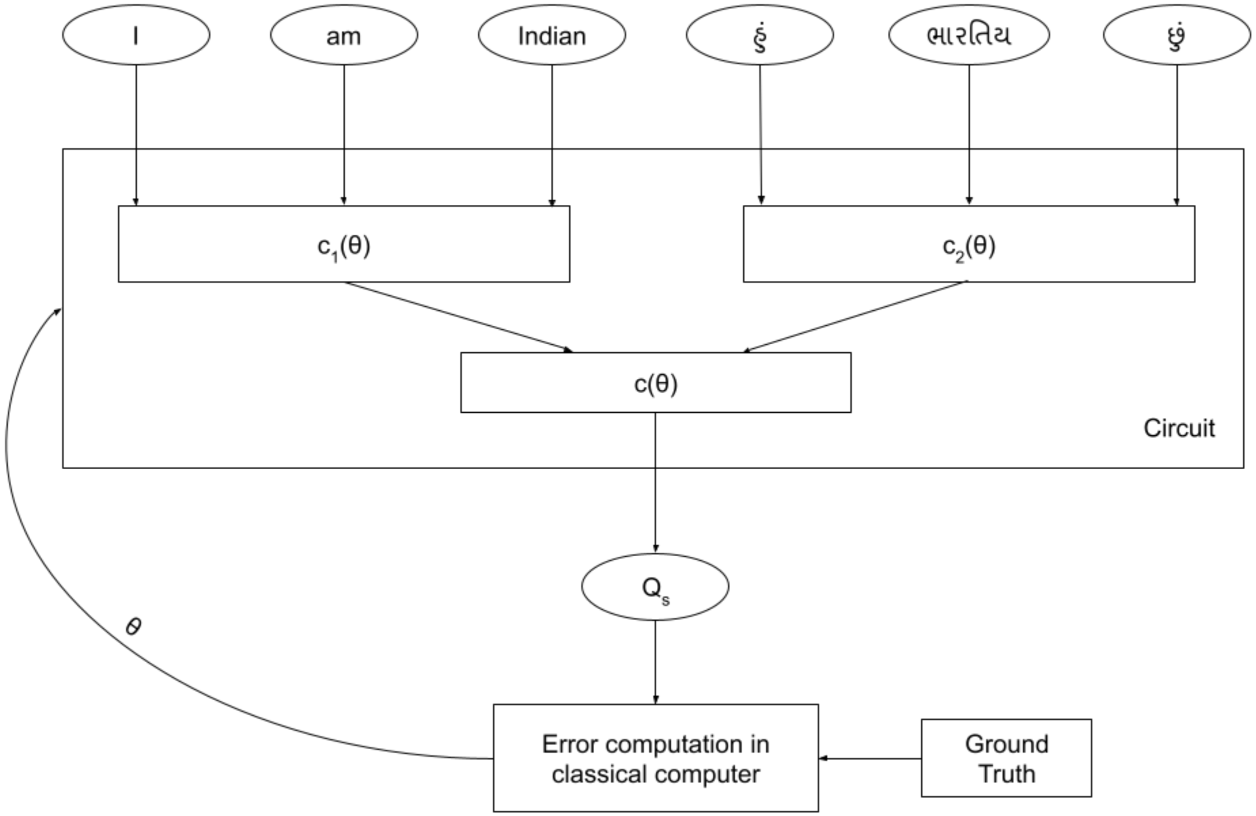


Output
|0>
X
1
H
$\begin{pmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{pmatrix}$
Black Box
$\begin{pmatrix} -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{pmatrix}$
H
Output' = 0
Input
|0>
X
1
H
$\begin{pmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{pmatrix}$
$\begin{pmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{pmatrix}$
H
Input' = 1

Results

Input	Constant Function	Variable Function
0	|11>	|01>
1	|10>	|11>

QT: QUANTUM TRANSFORMER!



Θ : Parameter

Q_s : Quantum State

$C_1(\theta)$, $C_2(\theta)$, $C(\theta)$: Quantum circuit having reversible functions

QT Training

Algorithm: Training

$Input_{source}$ <- Quantum representation of source input tokens

$Input_{Target}$ <- Quantum representation of target input tokens

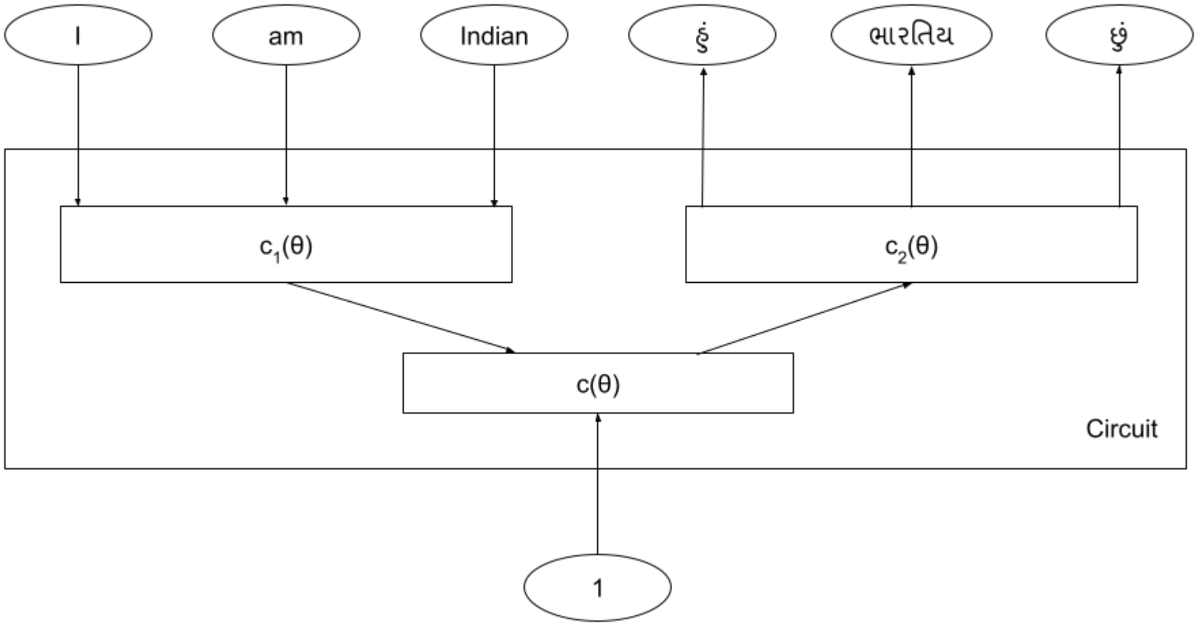
For (epochs) :

$Q_s = C_{(\theta)} \left(C_{(\theta)1}(Input_{source}) , C_{(\theta)2} (Input_{Target}) \right)$

R_s = collapseCircuit (Q_s)

Θ = lossFunction (R_s , groundTruth)

epochs --



QT Inference

Θ : Parameter

Q_s : Quantum State

$C_1(\theta)$, $C_2(\theta)$, $C(\theta)$: Quantum circuit having reversible functions

Algorithm: Inference

$Input_{source}$ <- Quantum representation of source input tokens

$Output = C_{(\theta)2}\ (\ C_{(\theta)1}(\ Input_{source}\ )\ ,\ 1\ )$


Food
Games
Noise
Thank you

References

Microsoft Research Talk:

Medium:
https://medium.com/cambridge-quantum-computing/quantum-natural-language-processing-748d6f27b31d

Thank you