Introduction to Quantum Computing

K. Grover

Outline

Disclaimer

I am STILL not an expert on quantum stuff.

History and Motivation

History of Quantum Mechanics

- It all started in late 19th and early 20th century.

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- Most theories in classical physics can be derived from quantum mechanics as an approximation valid at large (macroscopic) scale.

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2021 USTC proved quantum supremacy. Boson sampling with 76 photos. (20 seconds vs 600 million years)

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- Use Shor's algorithm.
- Use Grover's algorithm.
- Simulate quantum mechanical systems. Speed up biological research by giving new insights on proteins.

Classical vs Quantum Computing

Representing bits as vectors

- Dirac delta notation:

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

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- What are the operations on a single bit?

Operations on a single bit

- Identity:

$$\begin{tikzcd} 0 \arrow[r] & 0 \\ 1 \arrow[r] & 1 \end{tikzcd}$$

- Negation:

$$\begin{tikzcd} 0 \arrow[dr] & 0 \\ 1 \arrow[ur] & 1 \end{tikzcd}$$

- Constant 0:

$$\begin{tikzcd} 0 \arrow[r] & 0 \\ 1 \arrow[ur] & 1 \end{tikzcd}$$

- Constant 1:

$$\begin{tikzcd} 0 \arrow[dr] & 0 \\ 1 \arrow[r] & 1 \end{tikzcd}$$

Operations on a single bit using matrices

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2 bits

$$|00\rangle = |0\rangle \otimes |0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \otimes \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \begin{pmatrix} 1 \\ 0 \end{pmatrix} \\ 0 \begin{pmatrix} 1 \\ 0 \end{pmatrix} \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} = |0\rangle$$

2 bits

$$|00\rangle = |0\rangle \otimes |0\rangle = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} = |0\rangle \qquad |01\rangle = |0\rangle \otimes |1\rangle = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} = |1\rangle$$

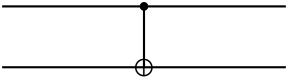
$$|10\rangle = |1\rangle \otimes |0\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} = |2\rangle \qquad |11\rangle = |1\rangle \otimes |1\rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} = |3\rangle$$

Operations on 2 bits

CNOT operation:

$$|00\rangle \to |00\rangle$$
$$|01\rangle \to |01\rangle$$
$$|10\rangle \to |11\rangle$$
$$|11\rangle \to |10\rangle$$

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



n bits

$$|010\ldots01\rangle = |i\rangle = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 1 \\ \vdots \\ 0 \\ 0 \end{pmatrix} \begin{matrix} \\ \\ \\ \leftarrow (i-1)\text{th index} \\ \\ \\ \\ \end{matrix}$$

Qubits

$$\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \alpha \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \beta \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \alpha|0\rangle + \beta|1\rangle$$

$$|\alpha|^2 + |\beta|^2 = 1$$

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Some examples: $\begin{pmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \frac{\sqrt{3}}{2} \\ \frac{1}{2} \end{pmatrix} \begin{pmatrix} -\frac{\sqrt{3}}{2}\iota \\ \frac{1}{2}\iota \end{pmatrix}$

Qubits

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- Polarization of a photon.
- Current in a supercondutor.
- Spin of an electron.
- Collection of anyons.

n Qubits

$$\begin{pmatrix}\alpha_{11}\\ \alpha_{12}\end{pmatrix}\otimes\begin{pmatrix}\alpha_{21}\\ \alpha_{22}\end{pmatrix}\otimes\cdots\otimes\begin{pmatrix}\alpha_{n1}\\ \alpha_{n2}\end{pmatrix}=\begin{pmatrix}\beta_0\\ \beta_1\\ \vdots\\ \beta_{2^n-1}\end{pmatrix}$$

$$\begin{pmatrix}\gamma_0\\ \gamma_1\\ \vdots\\ \gamma_{2^n-1}\end{pmatrix}\neq\begin{pmatrix}\delta_{11}\\ \delta_{12}\end{pmatrix}\otimes\begin{pmatrix}\delta_{21}\\ \delta_{22}\end{pmatrix}\otimes\cdots\otimes\begin{pmatrix}\delta_{n1}\\ \delta_{n2}\end{pmatrix}$$

Recap

- History and Motivation.

Quantum Supremacy.

Recap

- History and Motivation.
- Dirac delta notation for representing cbits and qubits.

$$\begin{pmatrix} \alpha \\ \beta \end{pmatrix} \equiv e^{\iota\phi} \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

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- History and Motivation.
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- Superposition.

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Recap

- History and Motivation.
- Dirac delta notation for representing cbits and qubits.
- Superposition.
- Tensor product for multiple qubits.

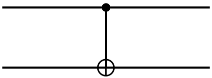
$$\begin{pmatrix}\alpha\\\beta\end{pmatrix} \otimes \begin{pmatrix}\gamma\\\delta\end{pmatrix} = \begin{pmatrix}\alpha\begin{pmatrix}\gamma\\\delta\end{pmatrix}\\\beta\begin{pmatrix}\gamma\\\delta\end{pmatrix}\end{pmatrix}$$

$$= \begin{pmatrix}\alpha\gamma\\\alpha\delta\\\beta\gamma\\\beta\delta\end{pmatrix}$$

Recap

- History and Motivation.
- Dirac delta notation for representing cbits and qubits.
- Superposition.
- Tensor product for multiple qubits.
- Only reversible operations in QC e.g CNOT.

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



A small example

Hadamard Gate

$$H|0\rangle = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{pmatrix} = |+\rangle$$

$$H|+\rangle = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} = |0\rangle$$

A state machine example

1 Qubit and only "bit-flip" and "hadamard" operator.

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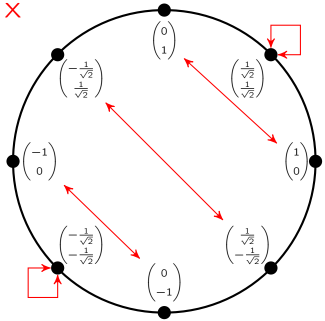

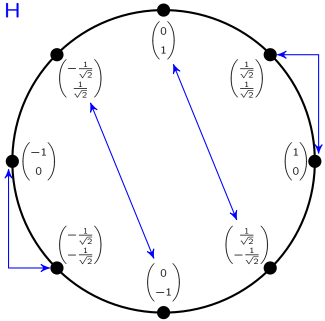

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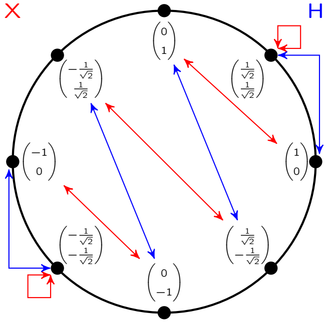

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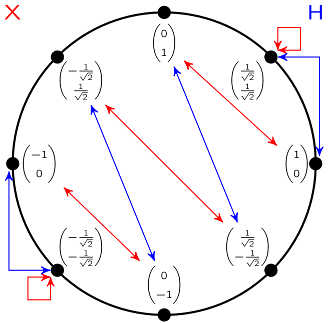
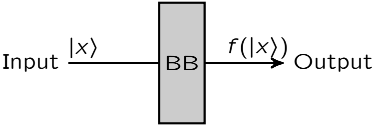


$$\begin{pmatrix}1\\0\end{pmatrix} \text{ --- } \boxed{X} \text{ - } \boxed{H} \text{ - } \boxed{X} \text{ - } \boxed{H} \text{ - } \boxed{X} \text{ --- } \begin{pmatrix}-1\\0\end{pmatrix}$$

Quantum > Classical

Deutsch Oracle problem

How many queries to find the one-bit operation?



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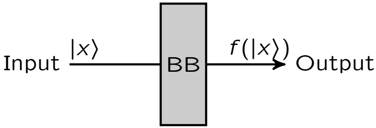

How many queries to find if the one-bit operation was a constant function or not?

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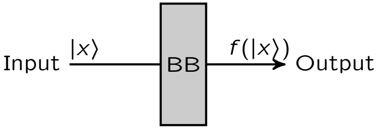

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How to do it in a single query?

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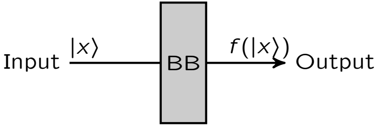

How many queries to find if the one-bit operation was a constant function or not?

How to do it in a single query?
Let's take a look at how these operations look on a quantum computer.

Non-reversible computing on quantum computer

Identify input by looking at the output.

Non-reversible computing on quantum computer

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Output the input also.

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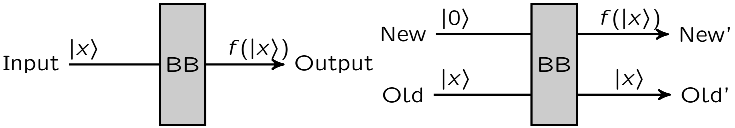
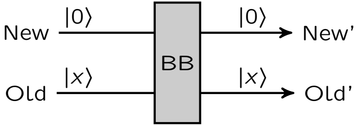
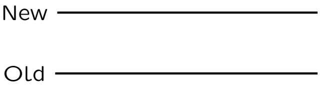
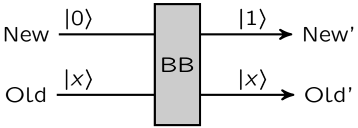


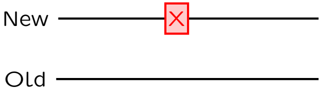
Constant-0



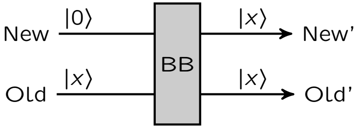


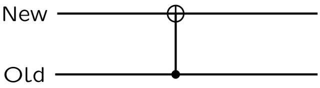
Constant-1



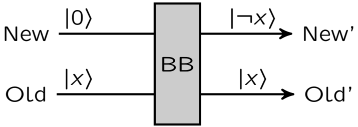


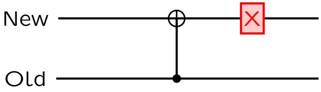
Identity



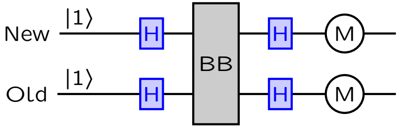


Negation


New
$|0\rangle$
Old
$|x\rangle$
BB
$|\neg x\rangle$
New'
$|x\rangle$
Old'


New
Old

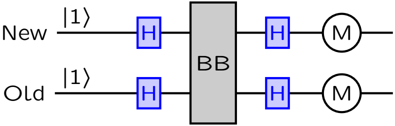
Deutsch oracle problem

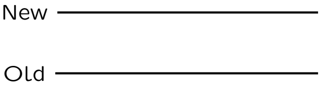


Output: $|11\rangle \rightarrow$ Constant operation
$|01\rangle \rightarrow$ Variable operation

Notation: $|old, new\rangle$

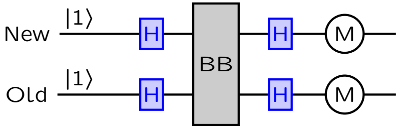
Constant 0

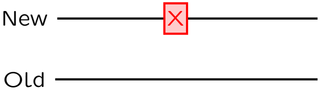




Output: $|11\rangle$

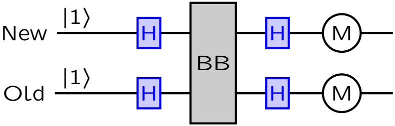
Constant 1

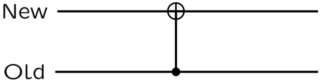




Output: $|11\rangle$

Identity



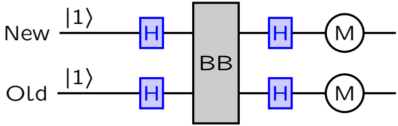


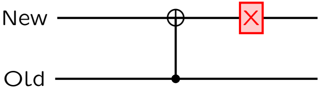
Output: $|01\rangle$

Identity

$$C\left(\begin{pmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{pmatrix} \otimes \begin{pmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{pmatrix}\right) = C \begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \\ -\frac{1}{2} \\ \frac{1}{2} \end{pmatrix} = \begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \\ \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{pmatrix} \otimes \begin{pmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{pmatrix}$$

Negation

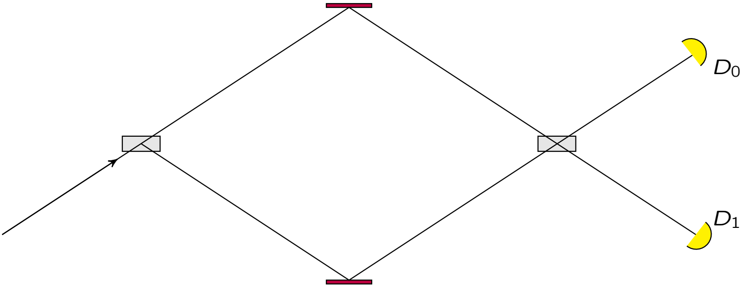




Output: $|01\rangle$

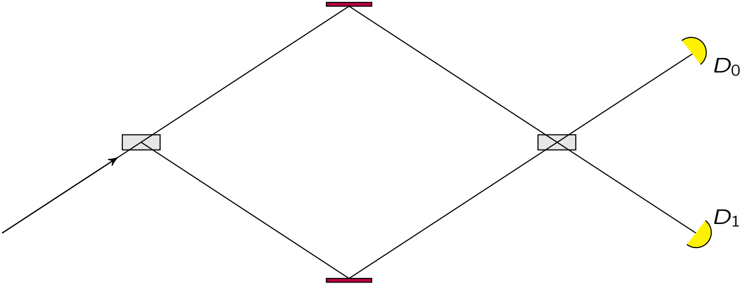
Cool Things

Mach-Zehnder Interferometer



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

Mach-Zehnder Interferometer



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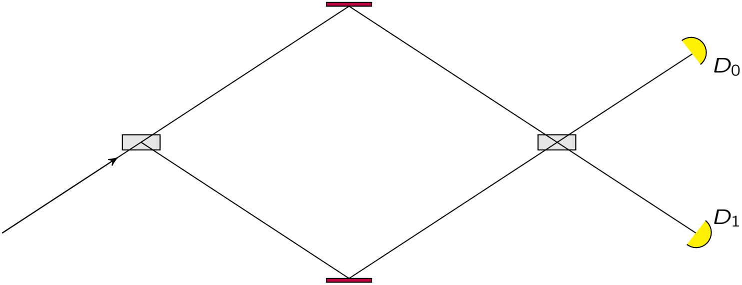
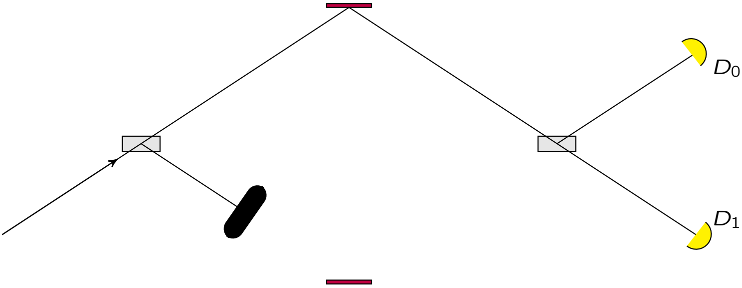
Mach-Zehnder Interferometer



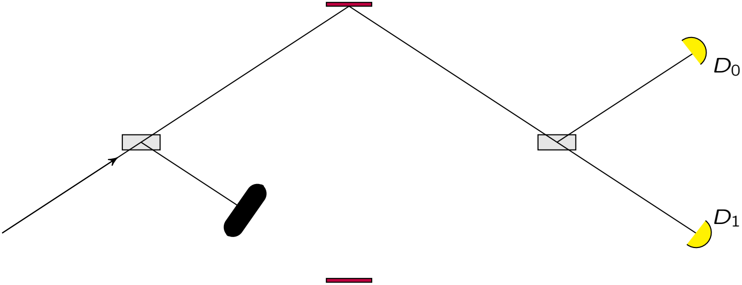
$$\begin{pmatrix} -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{pmatrix} = \begin{pmatrix} -1 \\ 0 \end{pmatrix}$$

Mach-Zehnder Interferometer



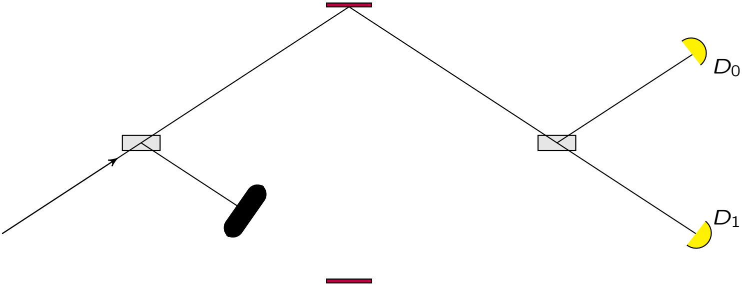
$$\begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Mach-Zehnder Interferometer



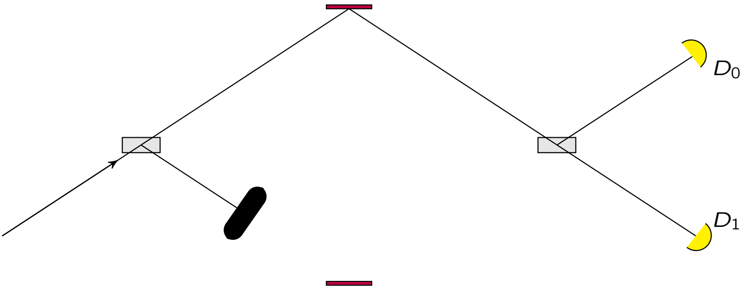
$$\begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{pmatrix}$$

Mach-Zehnder Interferometer



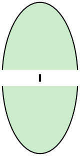
$$\begin{pmatrix} \frac{1}{\sqrt{2}} \\ 0 \end{pmatrix}$$

Mach-Zehnder Interferometer

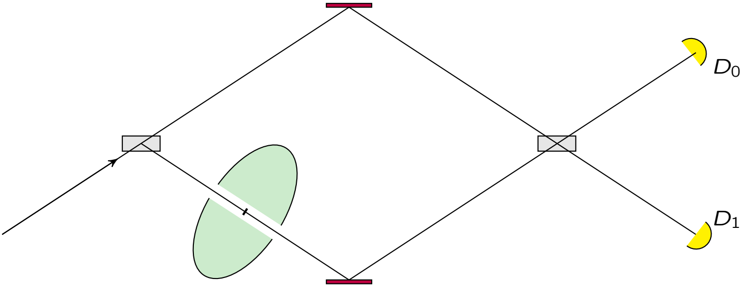


$$\begin{pmatrix} -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{2}} \\ 0 \end{pmatrix} = \begin{pmatrix} -\frac{1}{2} \\ \frac{1}{2} \end{pmatrix}$$

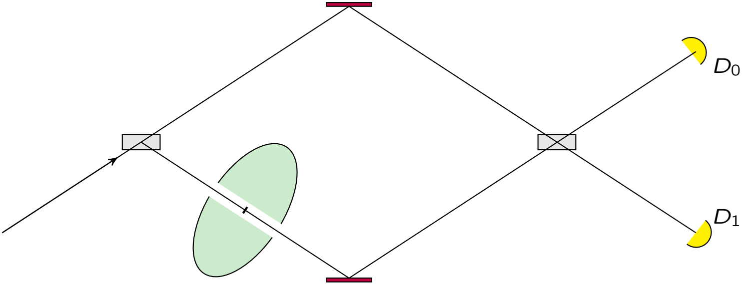
Elitzur-Vaidman Bombs



Bomb doesn't work



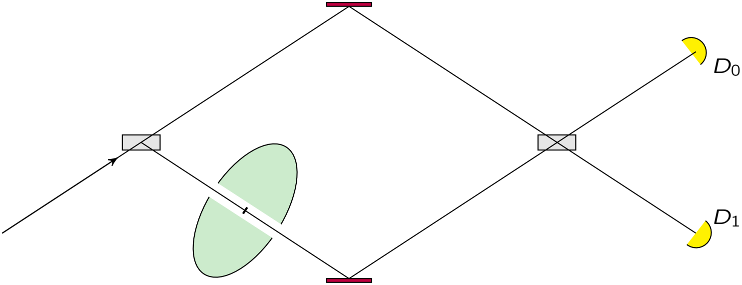
Bomb works



$\mathcal{P}$(Photon detected at bomb) $= \frac{1}{2}$

Bomb explodes (Works)

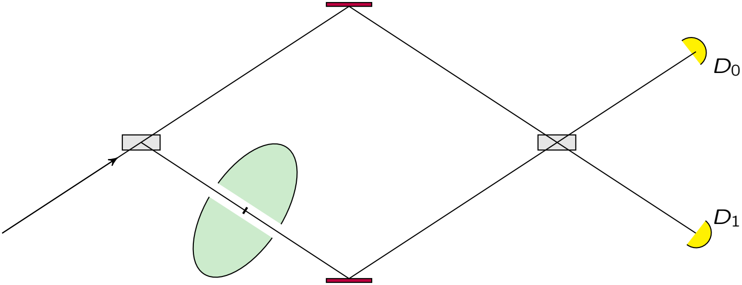
Bomb works



$\mathcal{P}$(Photon detected at bomb) $= \frac{1}{2}$ Bomb explodes (Works)

$\mathcal{P}$(Photon detected at D_0) $= \frac{1}{4}$ Bomb doesn't explode (Don't know)

Bomb works



$\mathcal{P}$(Photon detected at bomb) $= \frac{1}{2}$	Bomb explodes (Works)
$\mathcal{P}$(Photon detected at D_0) $= \frac{1}{4}$	Bomb doesn't explode (Don't know)
$\mathcal{P}$(Photon detected at D_1) $= \frac{1}{4}$	Bomb doesn't explode (Works)

Quantum Entanglement

- If we cannot factor two bits, they are said to be **entangled**.

Quantum Entanglement

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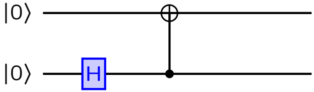
e.g. $$\begin{pmatrix} \frac{1}{\sqrt{2}} \\ 0 \\ 0 \\ \frac{1}{\sqrt{2}} \end{pmatrix} = \begin{pmatrix} a \\ b \end{pmatrix} \otimes \begin{pmatrix} c \\ d \end{pmatrix}$$

$$\begin{aligned} ac &= \frac{1}{\sqrt{2}} \\ ad &= 0 \\ bc &= 0 \\ bd &= \frac{1}{\sqrt{2}} \end{aligned}$$

Quantum Entanglement



$$CH_1\left(\begin{pmatrix}1\\0\end{pmatrix}\otimes\begin{pmatrix}1\\0\end{pmatrix}\right)=C\left(\begin{pmatrix}\frac{1}{\sqrt{2}}\\\frac{1}{\sqrt{2}}\end{pmatrix}\otimes\begin{pmatrix}1\\0\end{pmatrix}\right)=C\begin{pmatrix}\frac{1}{\sqrt{2}}\\0\\\frac{1}{\sqrt{2}}\\0\end{pmatrix}$$

Spooky action at a distance!

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- Einstein, Podolsky and Rosen gave the idea of Quantum entanglement.

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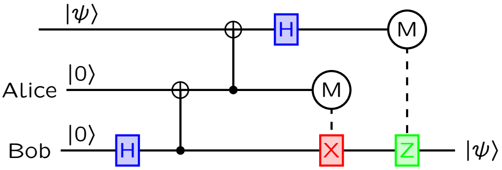
- Principle of locality would be violated.

Spooky action at a distance!

- Einstein, Podolsky and Rosen gave the idea of Quantum entanglement.
- Principle of locality would be violated.
- Experiments show that Quantum entanglement happens.

Quantum Teleportation

Transferring (state of) a qubit from one location to other.



Quantum Teleportation

- No cloning theorem.
- Not faster than light.

Next time?

- Better understanding of quantum state machines.
- Verification of quantum systems.
- What can we do?

Sources:

- Youtube video titled "Quantum computing for computer scientists" by Microsoft Research.
- John Preskill's (Caltech) lectures on quantum computing.
- Model Checking Quantum Systems by M. Ying and Y. Feng.
- A lot of other youtube videos and wikipedia pages on quantum stuff.