TORINO march 2019

FROM BELL'S INEQUALITY TO QUANTUM COMPUTERS

:

THE LONG JOURNEY OF ALICE & BOB

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Physics & Astronomy Department - UNIFI
INFN

FIRENZE

JOURNEY PLAN

- WHERE IT ALL STARTED
- GETTING ORIENTED
- LET'S GO
- MOVE ON
- WHERE ARE WE TODAY
- WHERE TOMORROW

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WHERE IT ALL STARTED

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

WHERE IT ALL STARTED

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WHERE IT ALL STARTED

$$\frac{1}{\sqrt{2}}\left(|0\rangle_A \otimes |0\rangle_B + |1\rangle_A \otimes |1\rangle_B\right)$$

WHERE IT ALL STARTED

Alice

$$\frac{1}{\sqrt{2}}\left(|0\rangle_A \otimes |0\rangle_B + |1\rangle_A \otimes |1\rangle_B\right)$$

Bob

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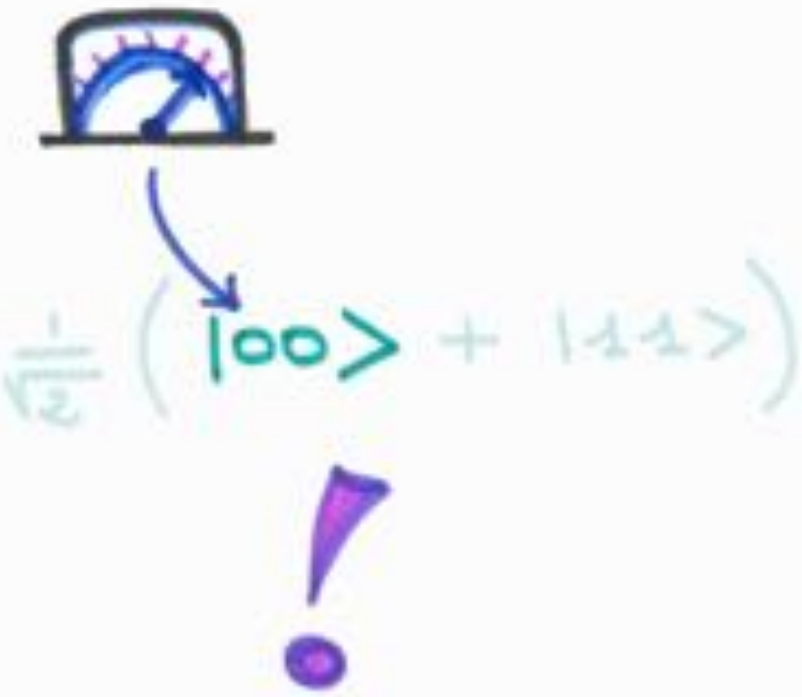

WHERE IT ALL STARTED

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

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!

if $|00\rangle$ or $|11\rangle$

if $|00\rangle$ or $|11\rangle$ ⇒ Dr. Bertlmann's socks

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$|\text{🧦🧦}\rangle$ or $|\text{🧦🧦}\rangle$

so what ?

if $|00\rangle$ or $|11\rangle$ ⇒ Dr. Bertlmann's socks

$|$ $\rangle$ or $|$ $\rangle$

so what ?

if $\frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)$ ⇒ wow!

if $|00\rangle$ or $|11\rangle$ ⇒ Dr. Bertlmann's socks

$|\text{L}\,\text{L}\rangle$ or $|\text{L}\,\text{L}\rangle$

so what ?

$$p(Z_A = Y_B) + p(Z_A = W_B) + p(Y_A = W_B) \geq 1$$

if $\frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)$ ⇒ WOW!

BELL'S INEQUALITY IS EXPERIMENTALLY VIOLATED

(WITH ALL LOOPHOLES CLOSED ~ 2015)

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

! EXISTS !

BELL'S INEQUALITY IS EXPERIMENTALLY VIOLATED

(WITH ALL LOOPHOLES CLOSED ~ 2015)

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

! EXISTS !

then

use it

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1 QUBIT

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$\dim \mathcal{H}_Q = 2$ $\qquad \{|0\rangle, |1\rangle\}$

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

1 QUBIT

1st postulate

$$\dim \mathcal{H}_Q = 2 \qquad \{|0\rangle, |1\rangle\}$$

$$\alpha|0\rangle + \beta|1\rangle \sim \begin{pmatrix} \alpha \\ \beta \end{pmatrix}, \qquad |\alpha|^2 + |\beta|^2 = 1$$

$$\alpha = \cos\frac{\theta}{2}, \quad \beta = e^{i\varphi}\sin\frac{\theta}{2}$$

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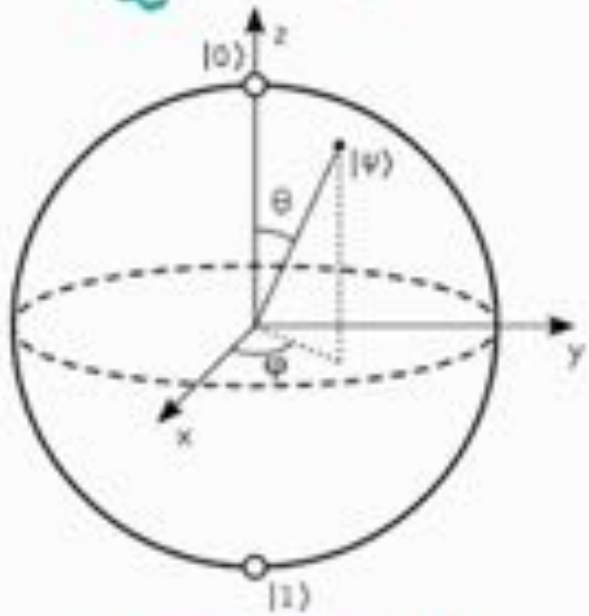

BLOCH SPHERE

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1st postulate

effectively $\dim \mathcal{H}_Q = 2$ $\{|0\rangle, |1\rangle\}$

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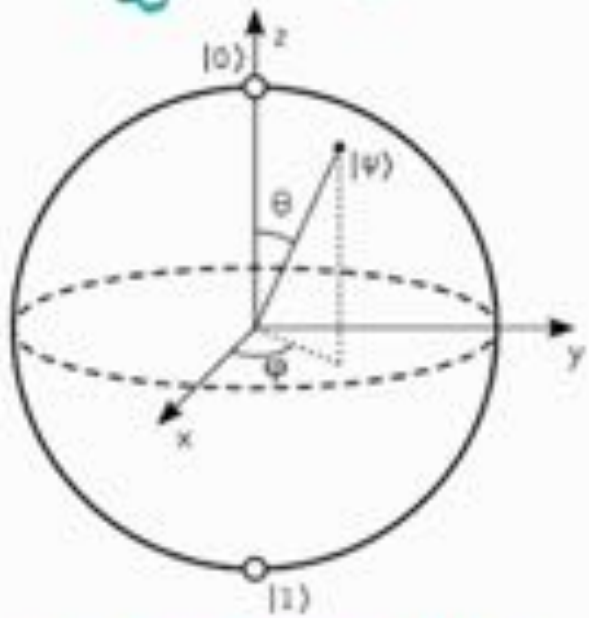
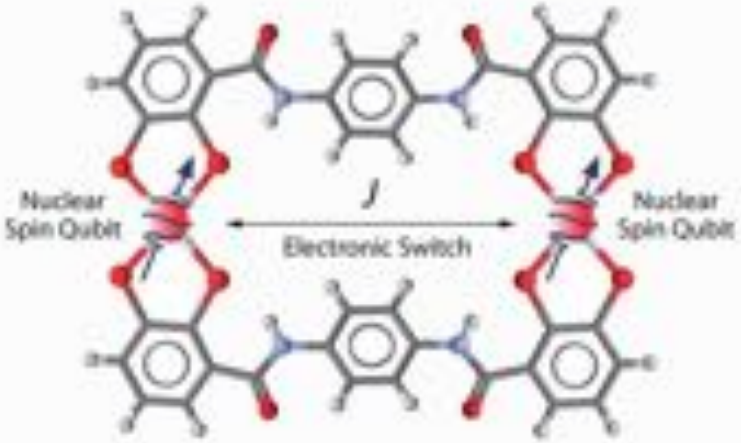
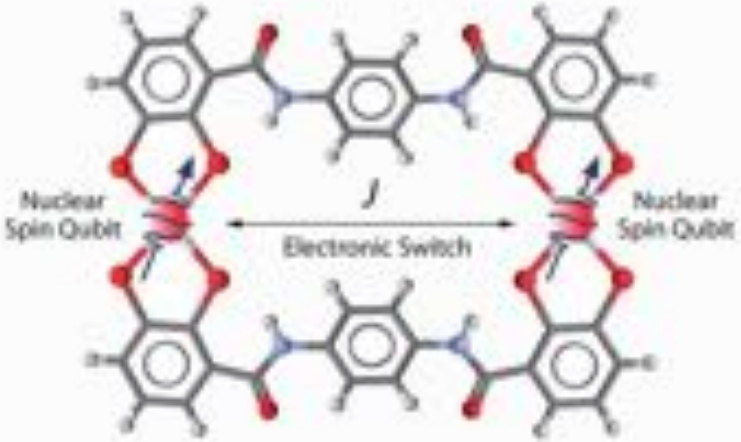


BLOCH SPHERE


Nuclear
Spin Qubit
J
Electronic Switch
Nuclear
Spin Qubit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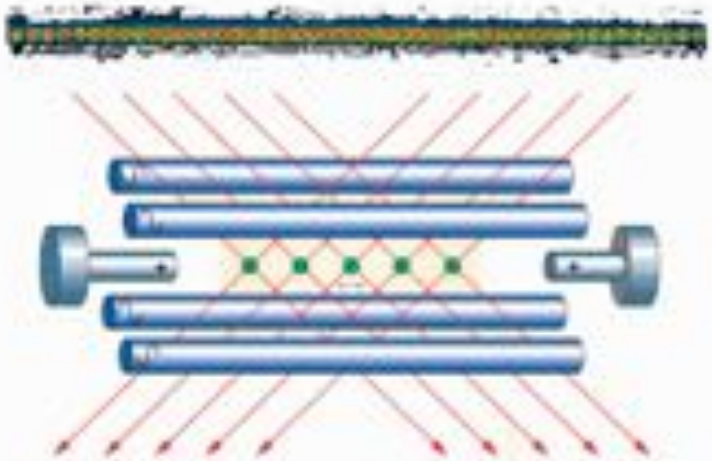

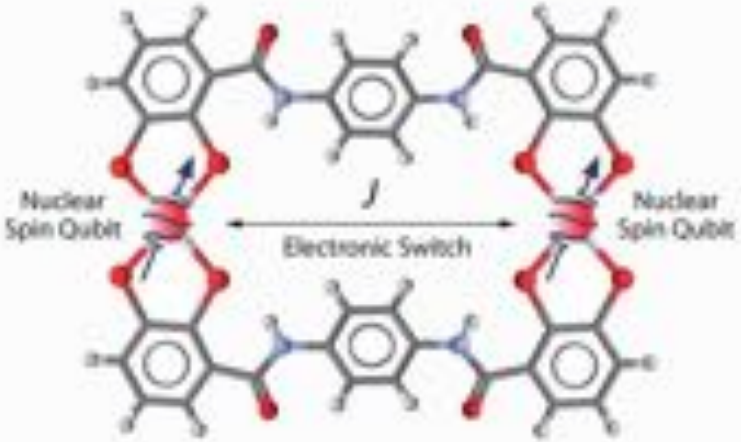
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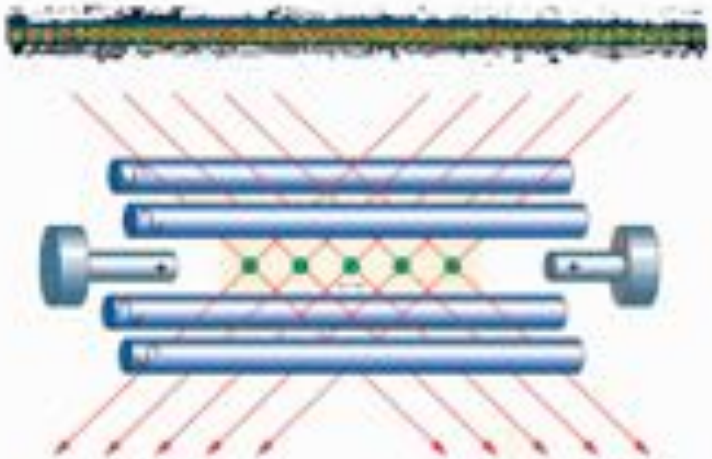
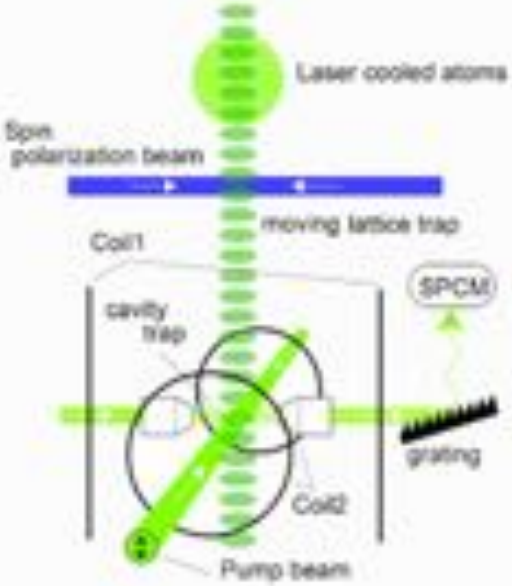
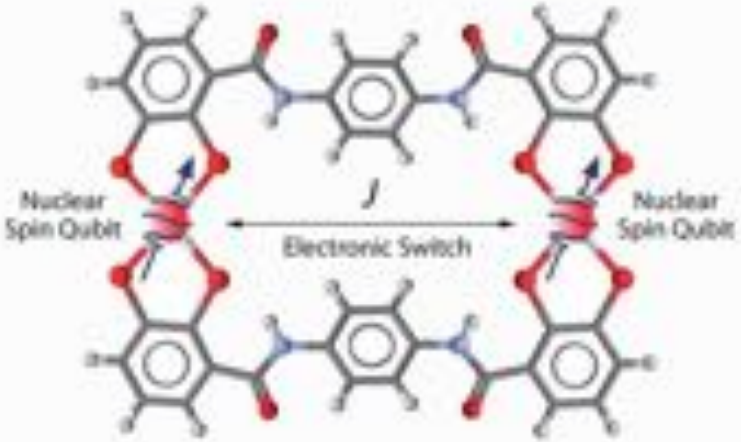



Laser cooled atoms
Spin
polarization beam
moving lattice trap
Coil1
SPCM
cavity
trap
grating
Coil2
Pump beam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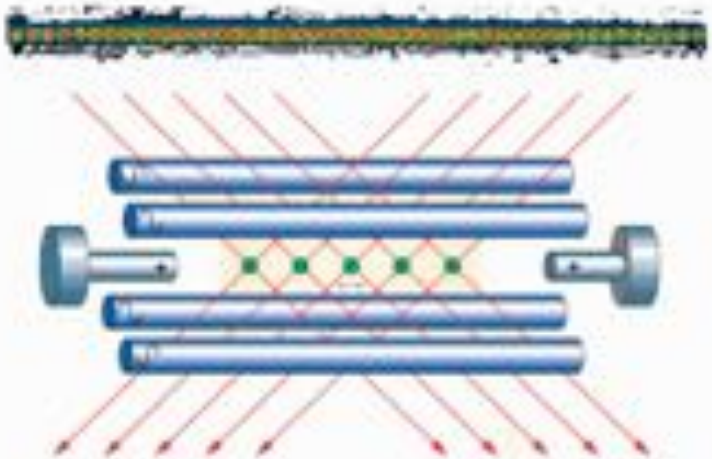

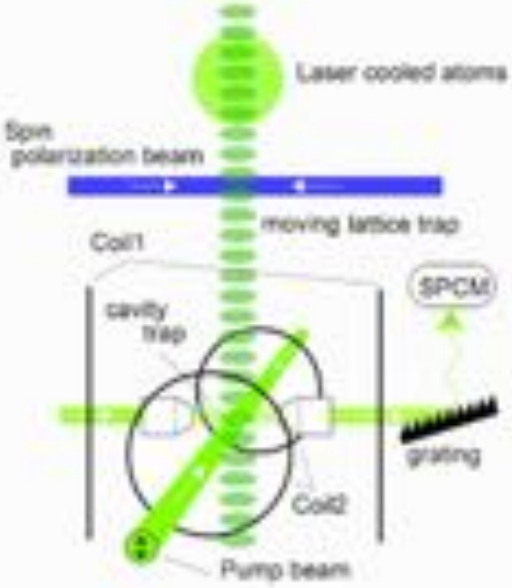
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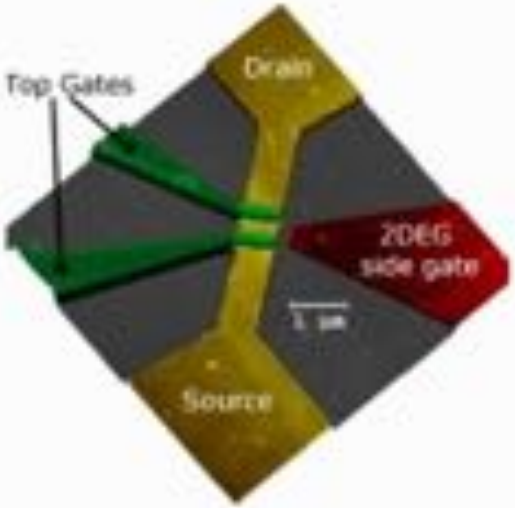
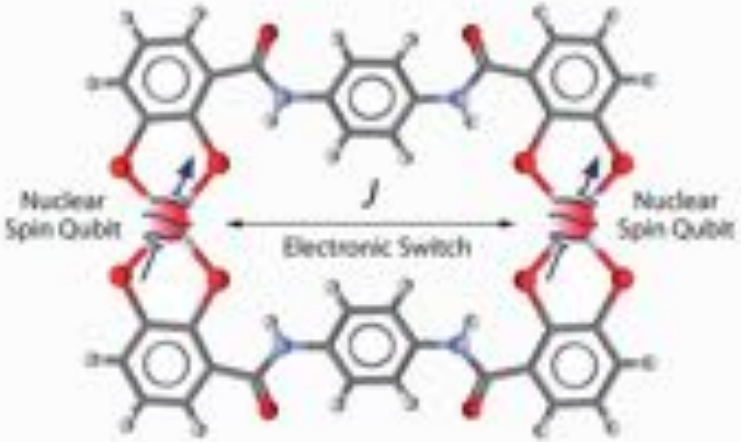

Top Gates
Drain
2DEG
side gate
1 μm
Source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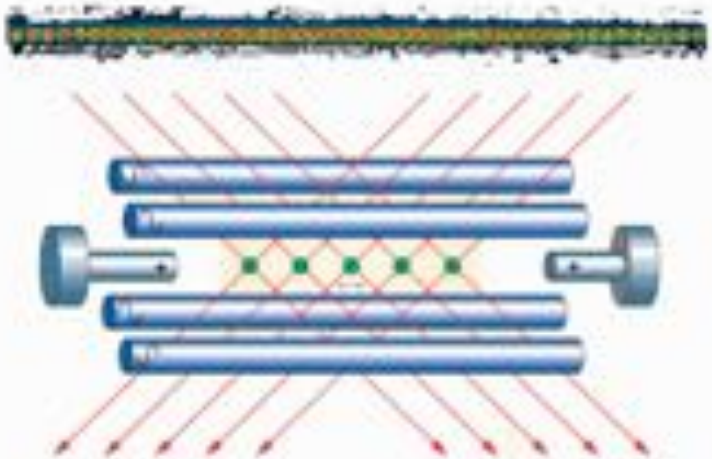

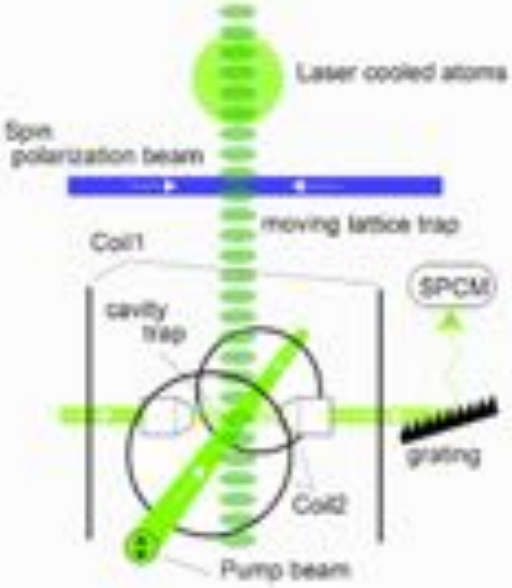
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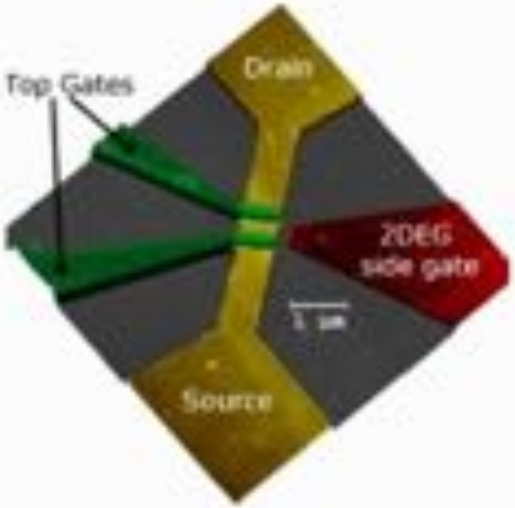
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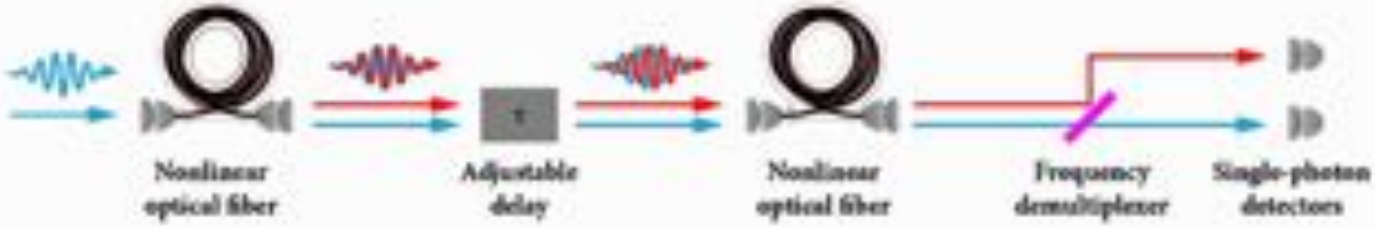
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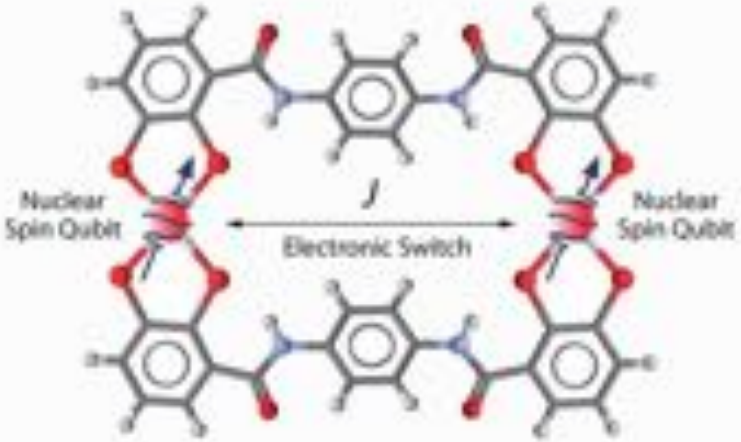
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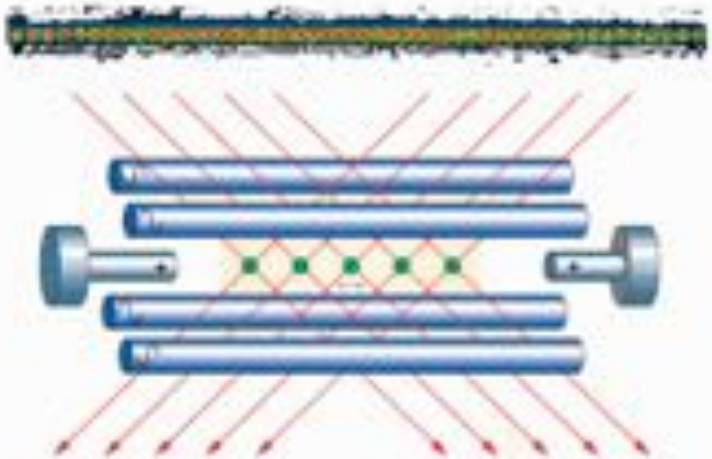

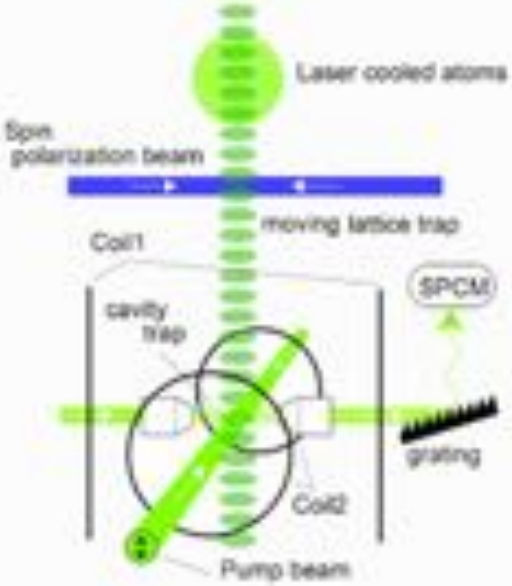
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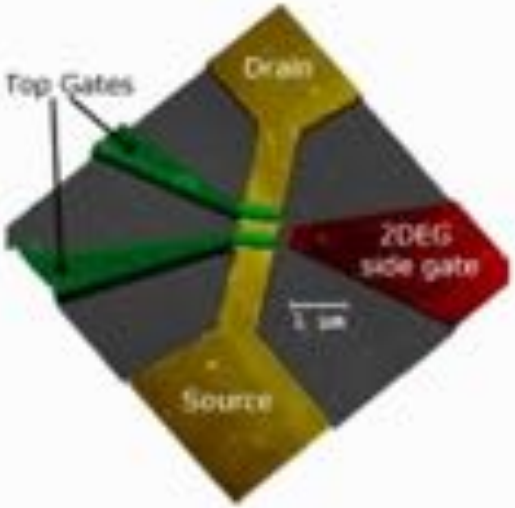
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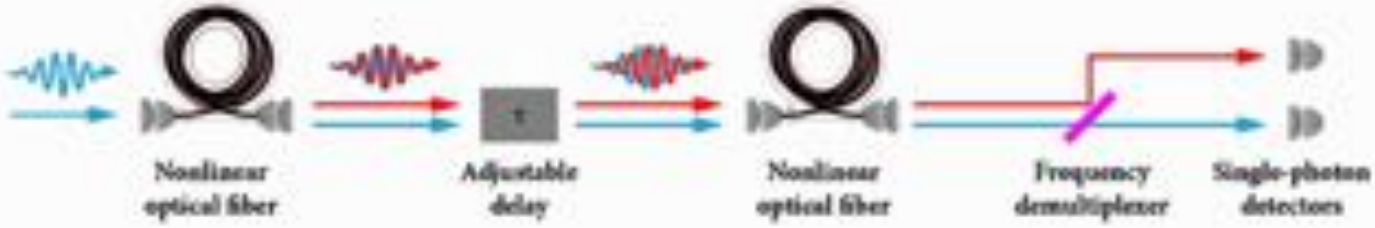
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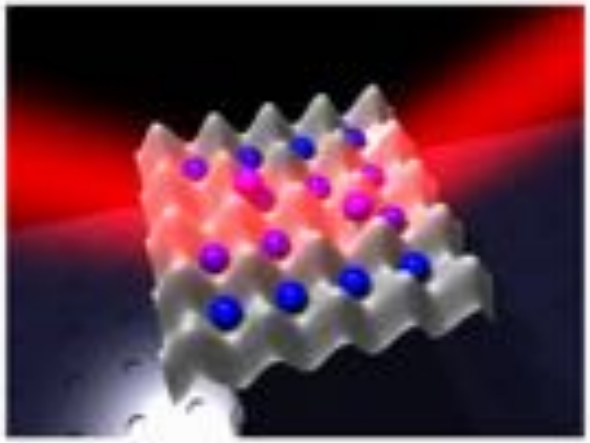

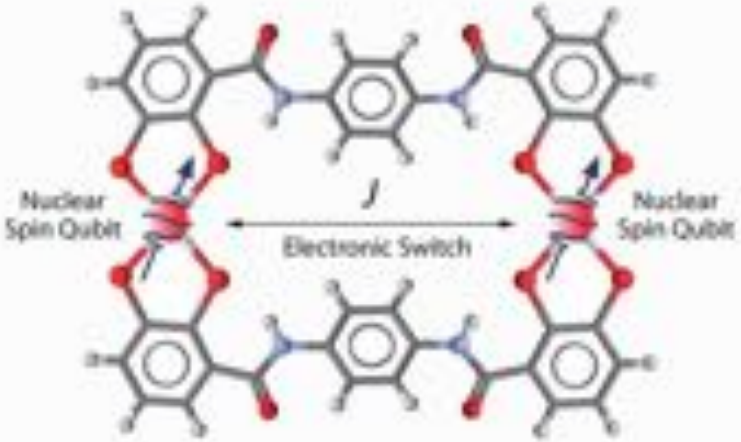
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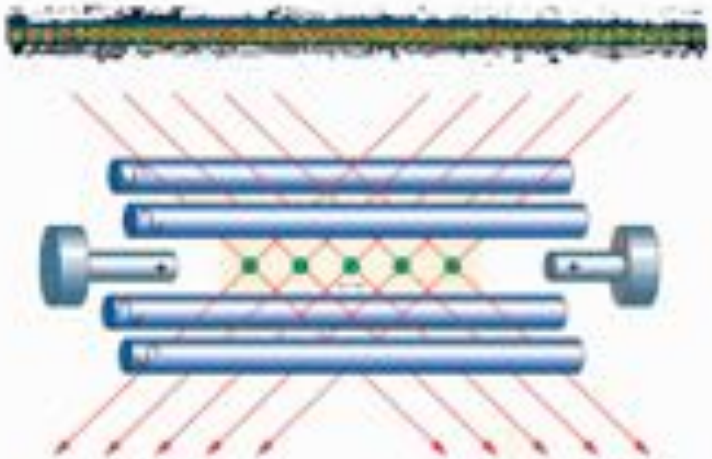

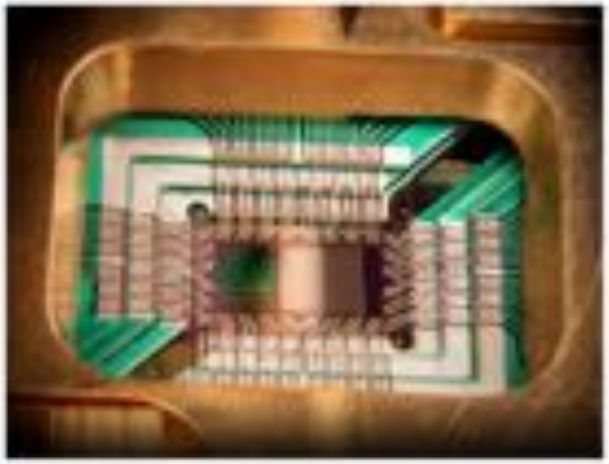

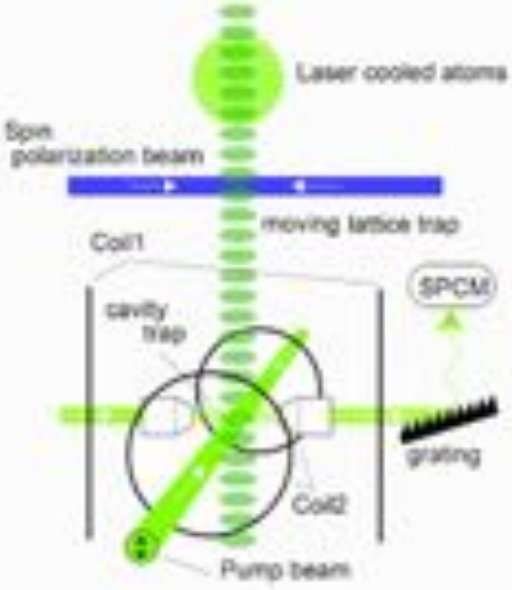
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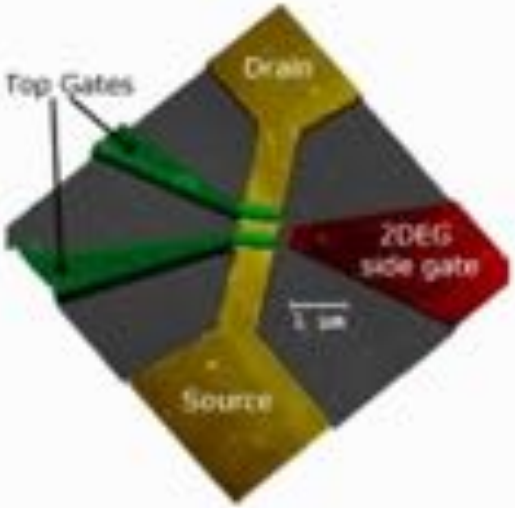
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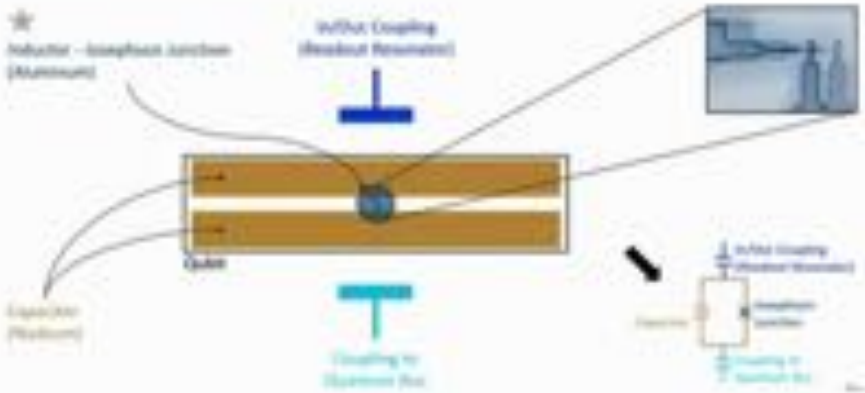

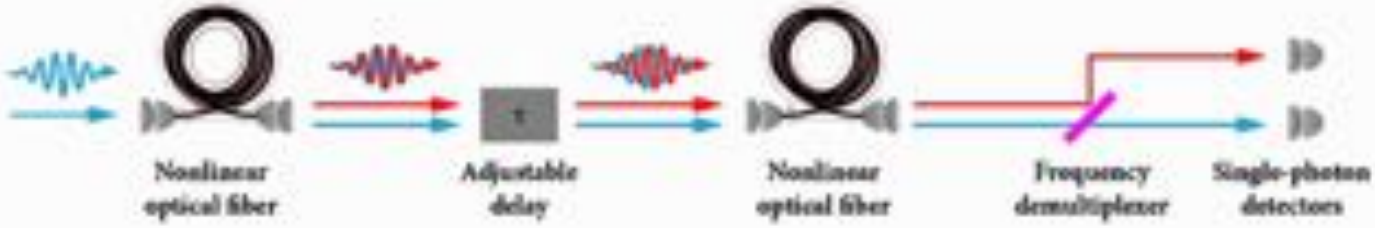
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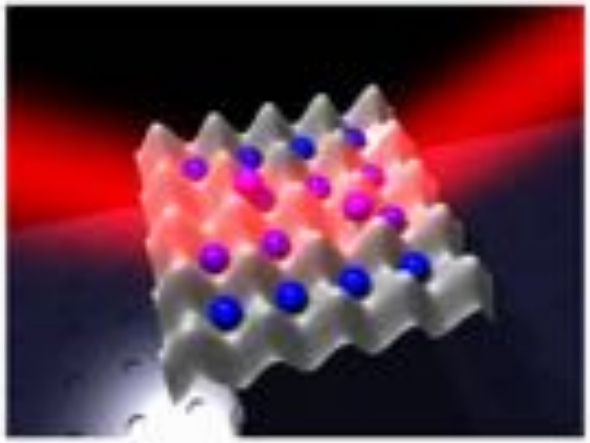

SINGLE-QUBIT GATES

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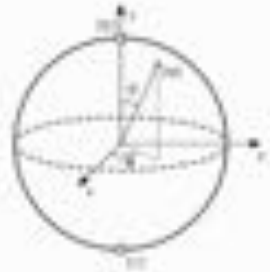

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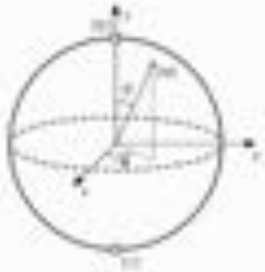
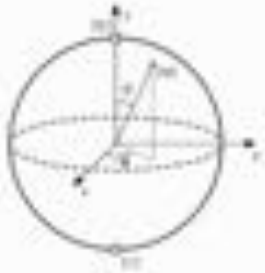


$$\rightarrow \boxed{X} \rightarrow \qquad \begin{cases} |0\rangle \leftrightarrow |1\rangle \\ |1\rangle \leftrightarrow |0\rangle \end{cases} \sim \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

spin-flip (NOT)

SINGLE-QUBIT GATES



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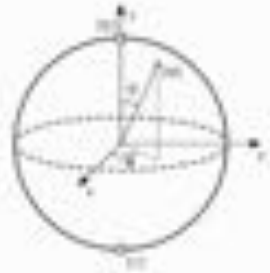
$$\rightarrow \boxed{Z} \rightarrow \quad \begin{cases} |0\rangle \leftrightarrow |0\rangle \\ |1\rangle \leftrightarrow -|1\rangle \end{cases} \sim \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

phase-shift

SINGLE-QUBIT GATES



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phase-shift

$$\rightarrow \boxed{H} \rightarrow \quad \begin{cases} |0\rangle \leftrightarrow \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \\ |1\rangle \leftrightarrow \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) \end{cases} \sim \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$$

Hadamard

QUANTUM GATES AS UNITARY EVOLUTIONS

QUANTUM GATES AS UNITARY EVOLUTIONS

suppose X is needed

QUANTUM GATES AS UNITARY EVOLUTIONS

suppose X is needed

take

$H = \vec{h} \cdot \vec{\sigma}$ $\qquad$ $\vec{h} \parallel \vec{x}$

QUANTUM GATES AS UNITARY EVOLUTIONS

suppose X is needed

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$$\sigma_x^{2n} = \mathbb{1}$$

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QUANTUM REGISTER : 2 QUBITS

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OTHERWISE

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

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maximally entangled

2-QUBIT GATES

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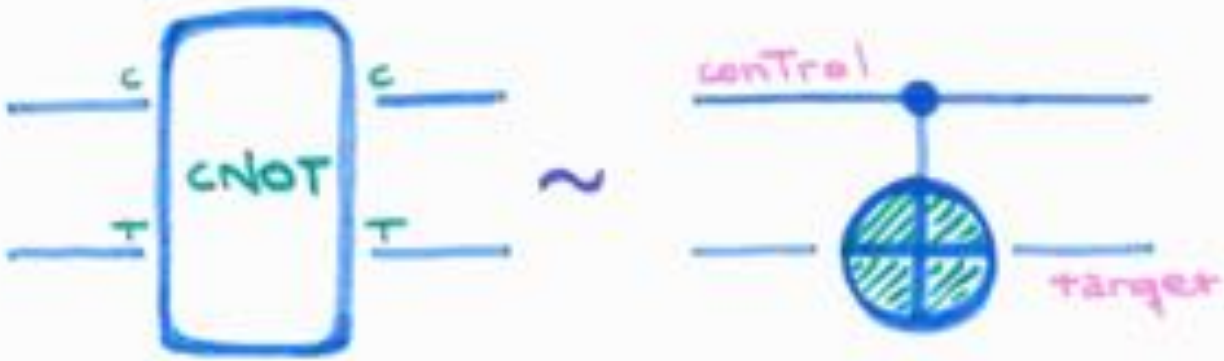

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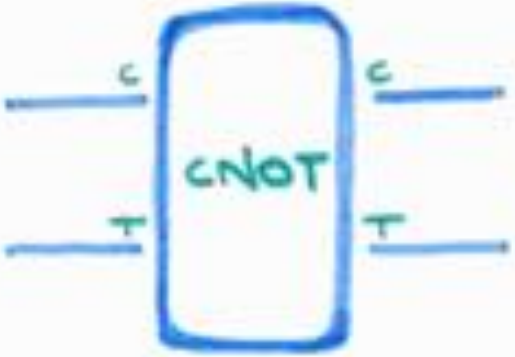

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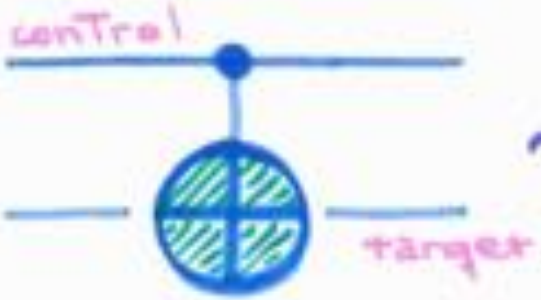

$\sim$

$$
\begin{array}{cccc}
\text{control} & \text{target} & & \\
|00\rangle & |01\rangle & |10\rangle & |11\rangle \\
\end{array}
$$

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

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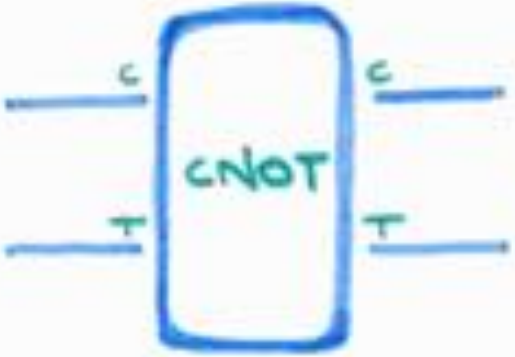
(ENTANGLING)



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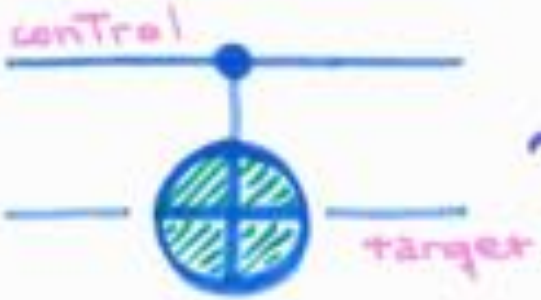

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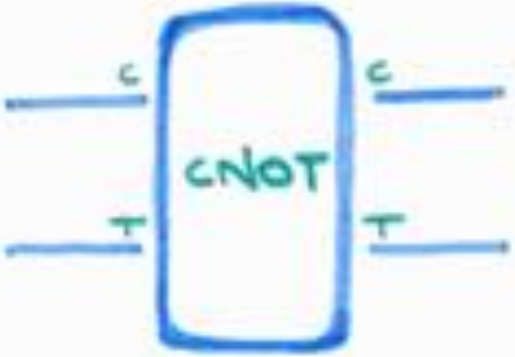

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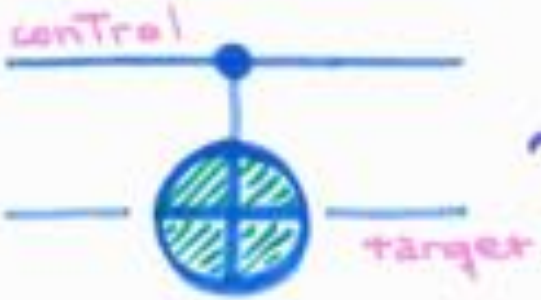

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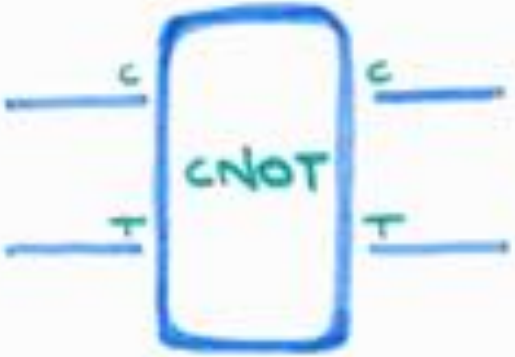

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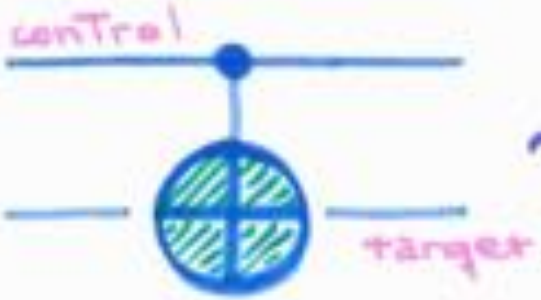

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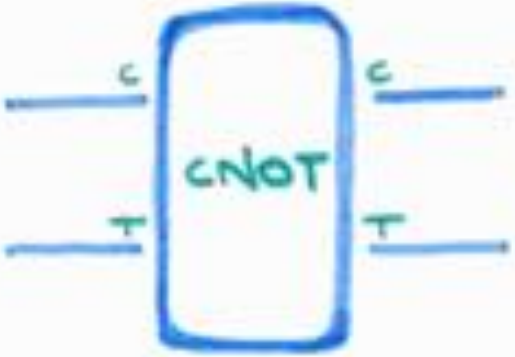

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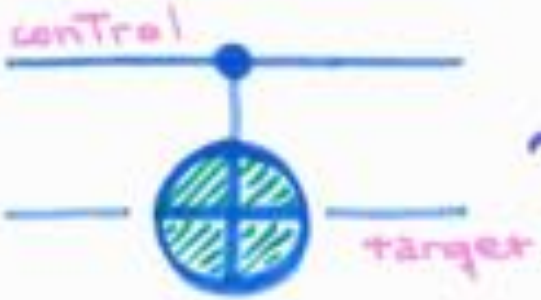

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$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & e^{i\varphi} \end{pmatrix} \qquad \varphi \neq 2n\pi$$

PREPARING THE "BELL"-STATE

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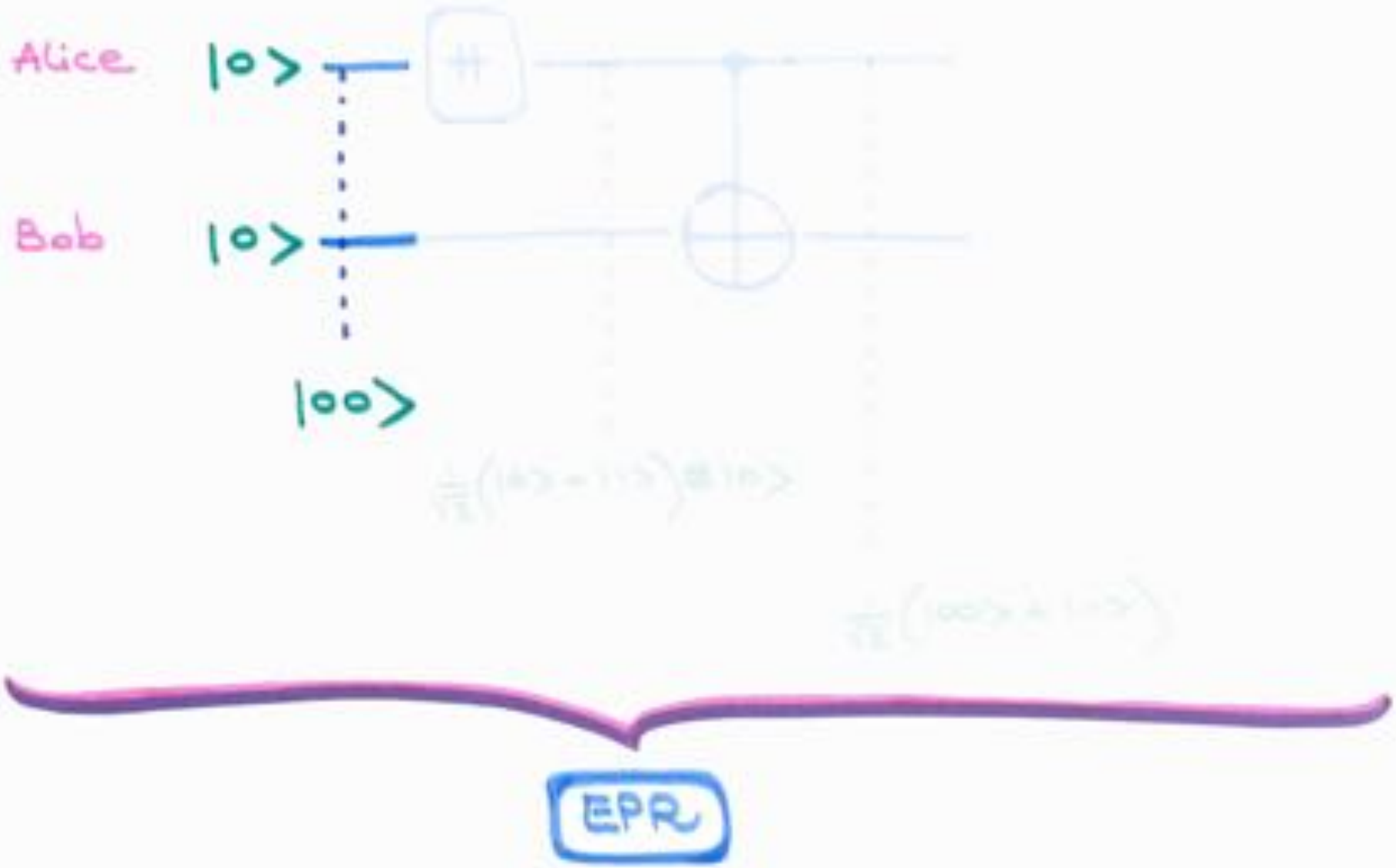

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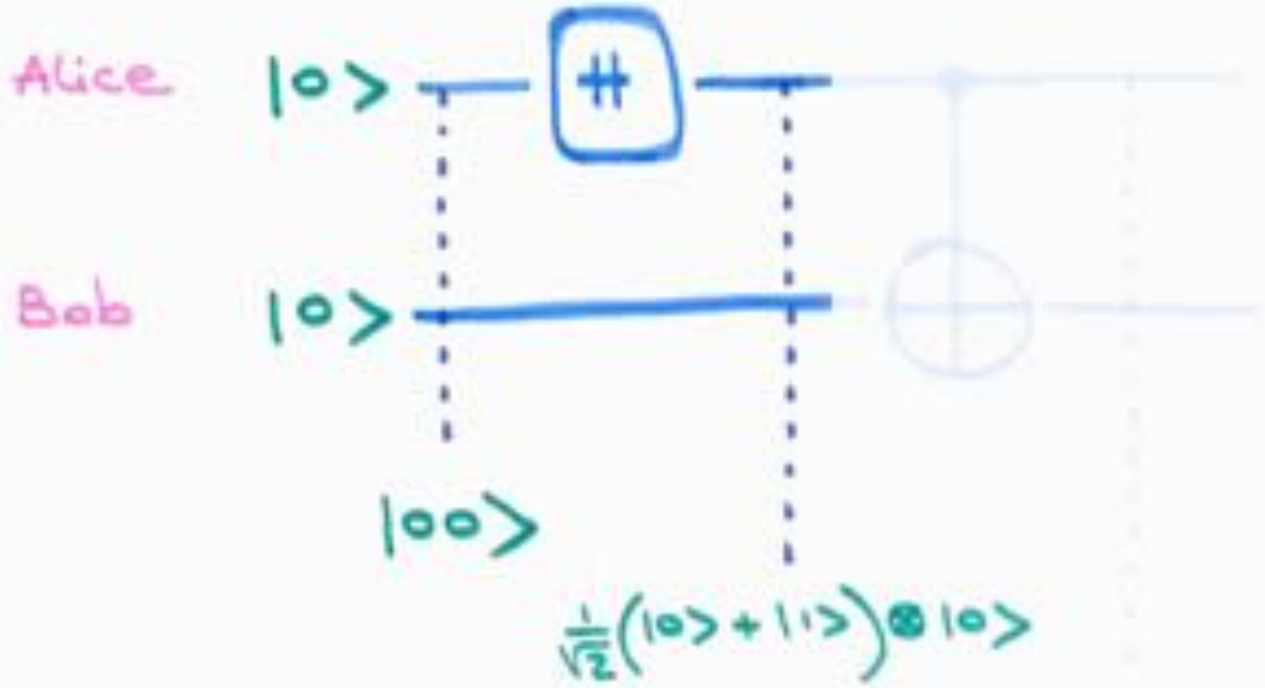

EPR

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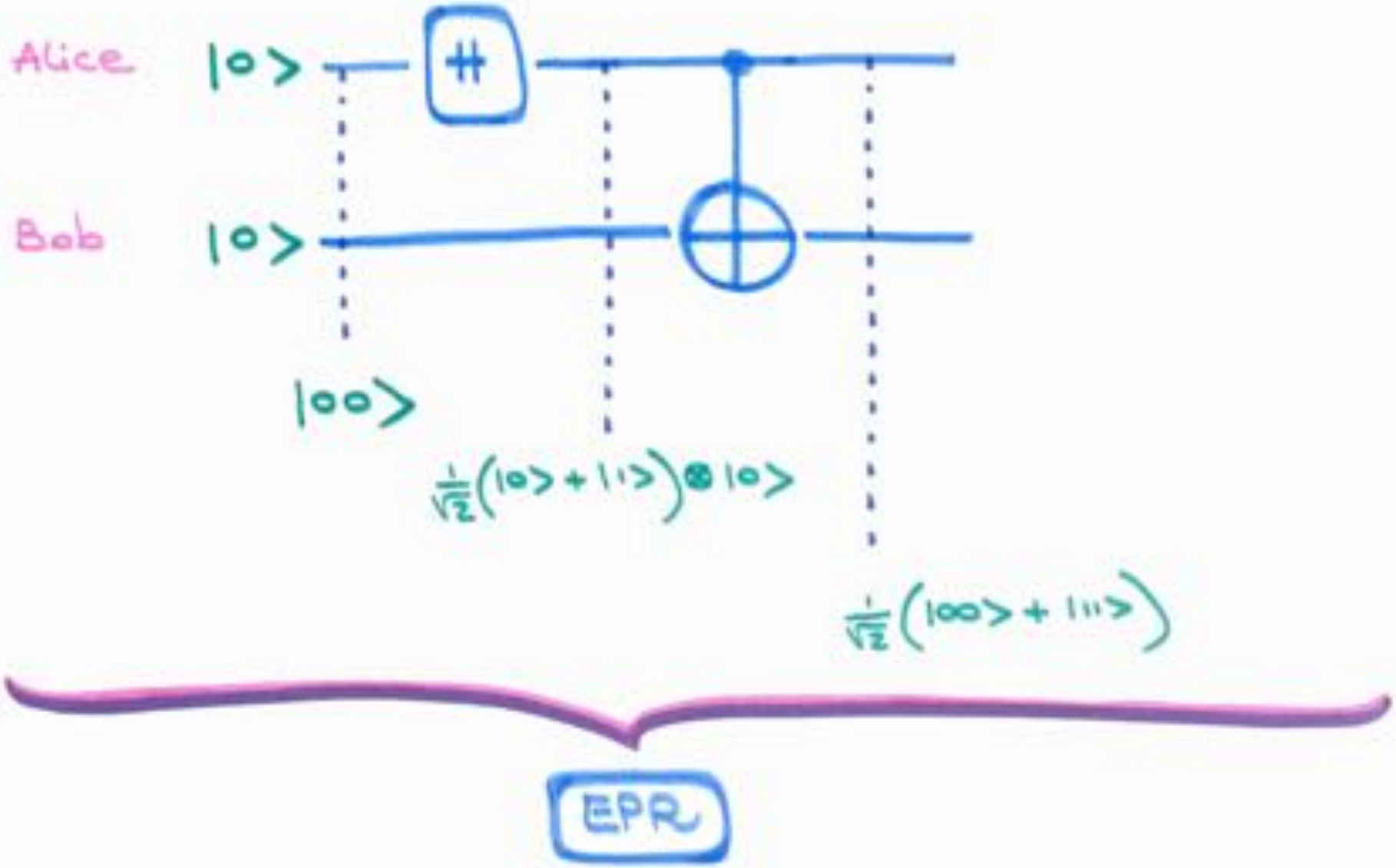
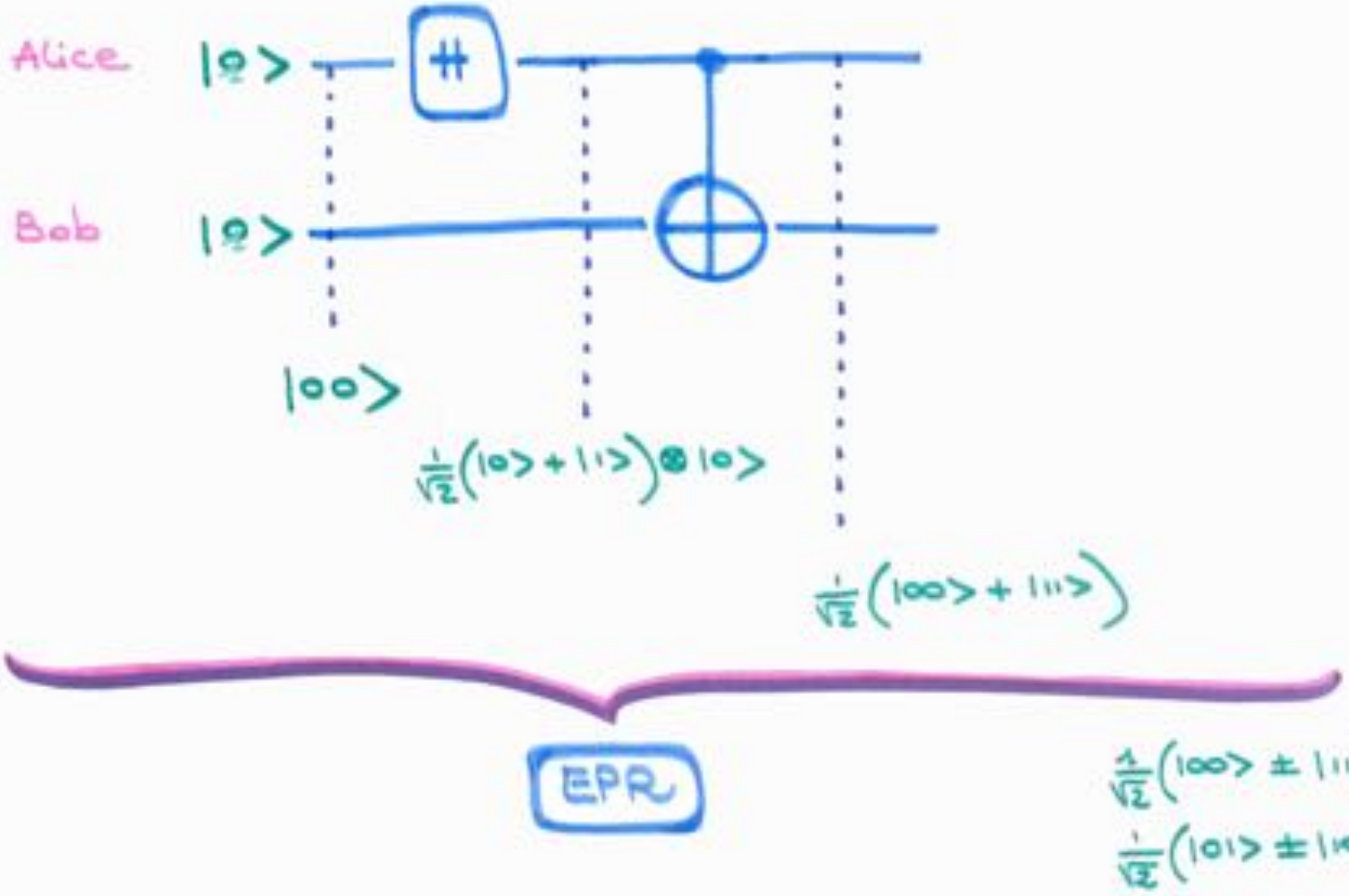


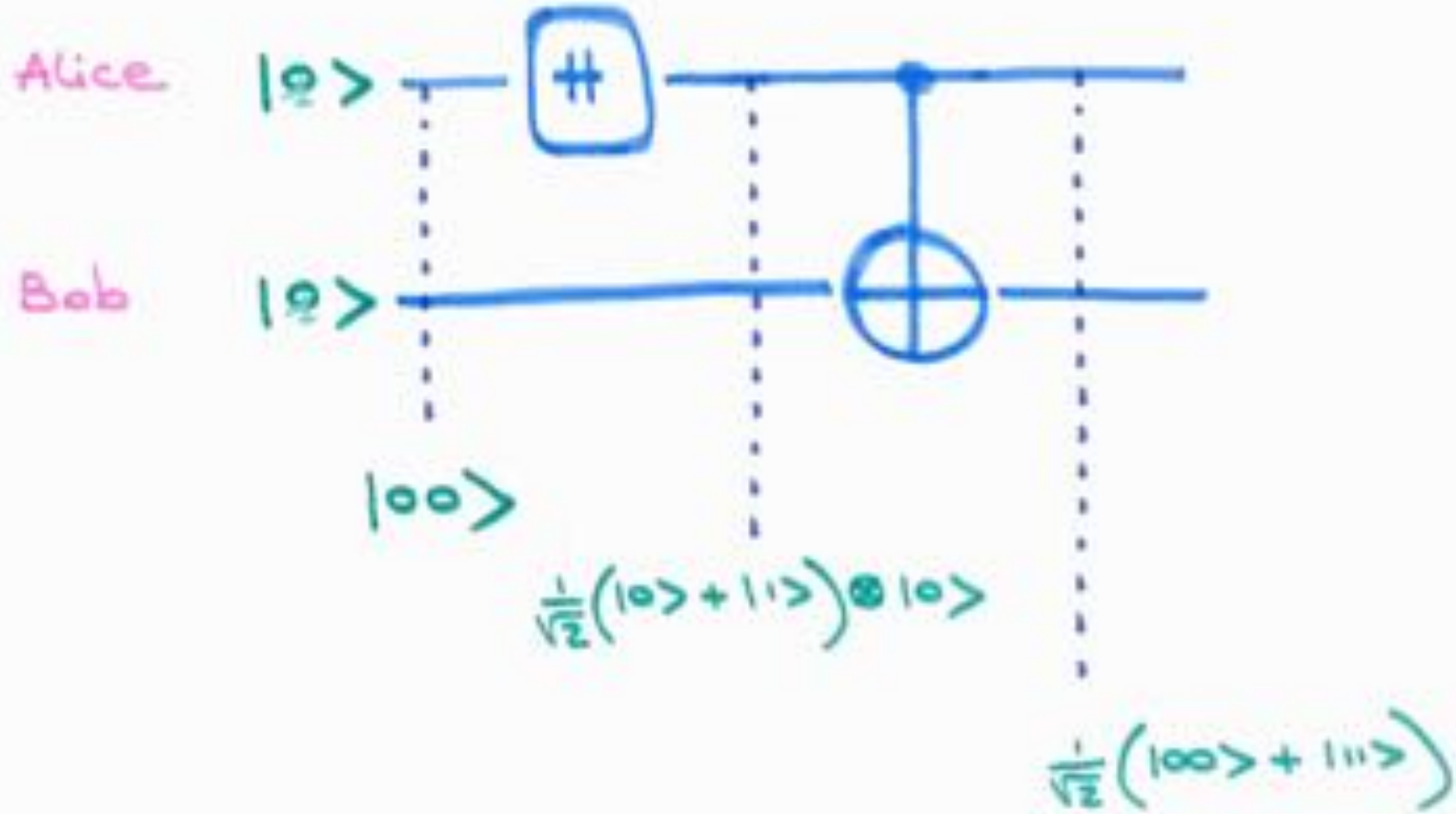
PREPARING THE "BELL"-STATES



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

$\frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$

MEASURING THE "BELL"-STATES



EPR

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JOURNEY PLAN

- WHERE IT ALL STARTED
- GETTING ORIENTED
- ★ LET'S GO ⇦
- MOVE ON
- WHERE ARE WE TODAY
- WHERE TOMORROW

TOWARDS Q-INFO : SUPERDENSE CODING ~ 1992

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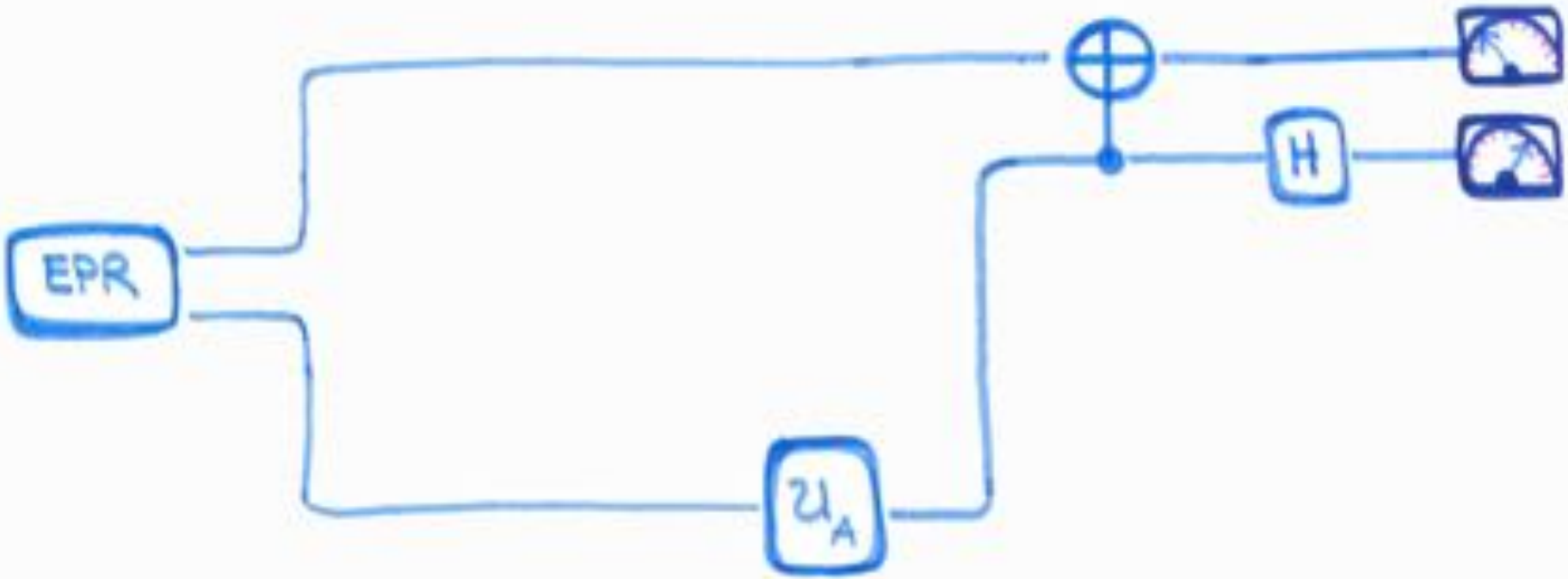

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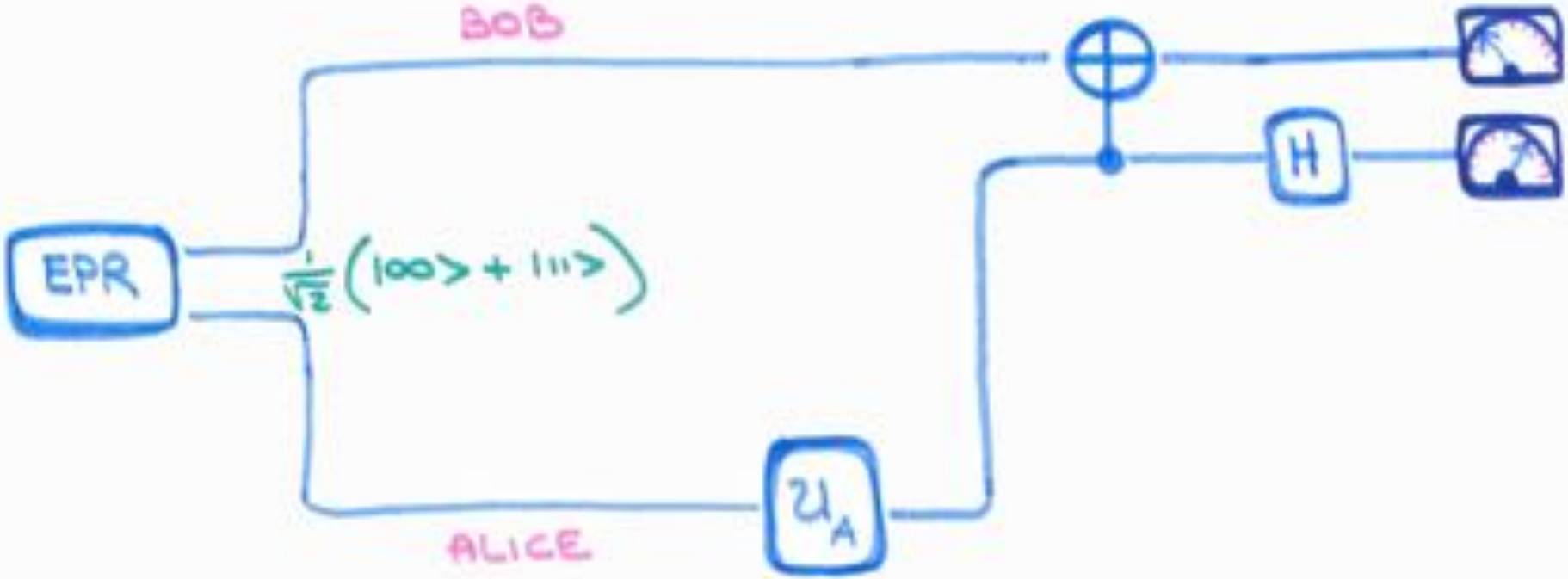

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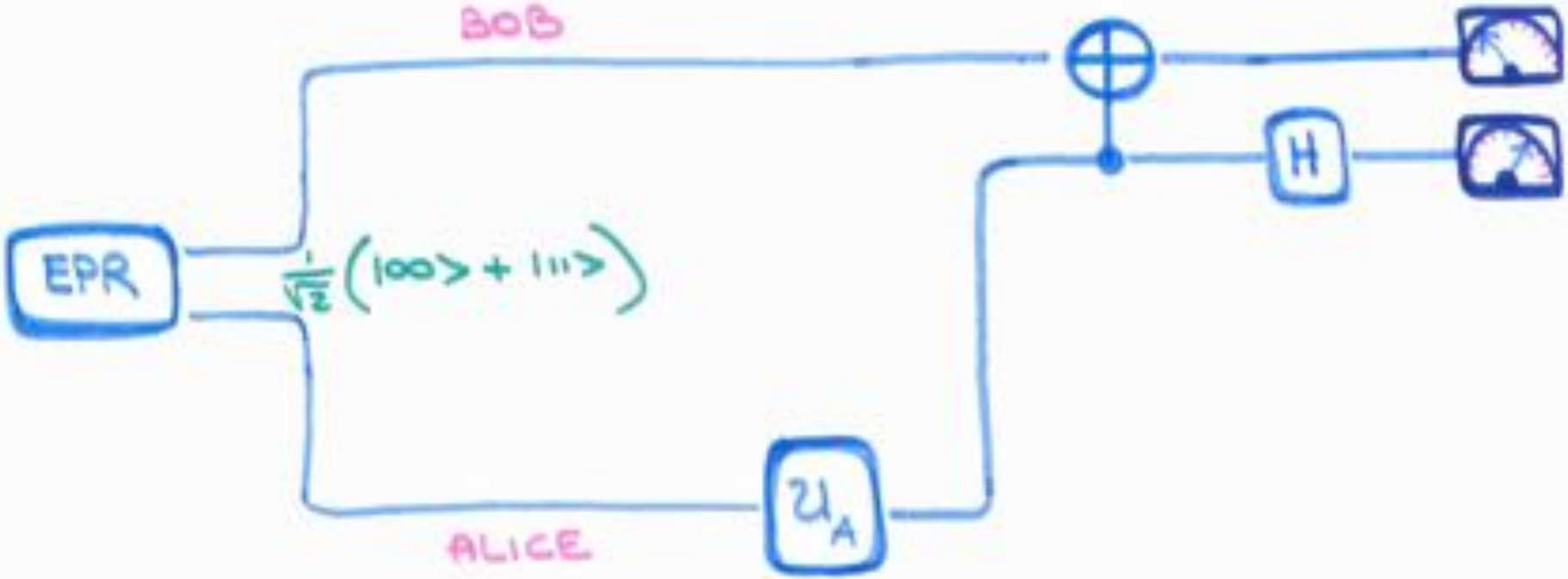

encoding

00	:	$\mathbb{1}$
01	:	X
10	:	Z
11	:	XZ

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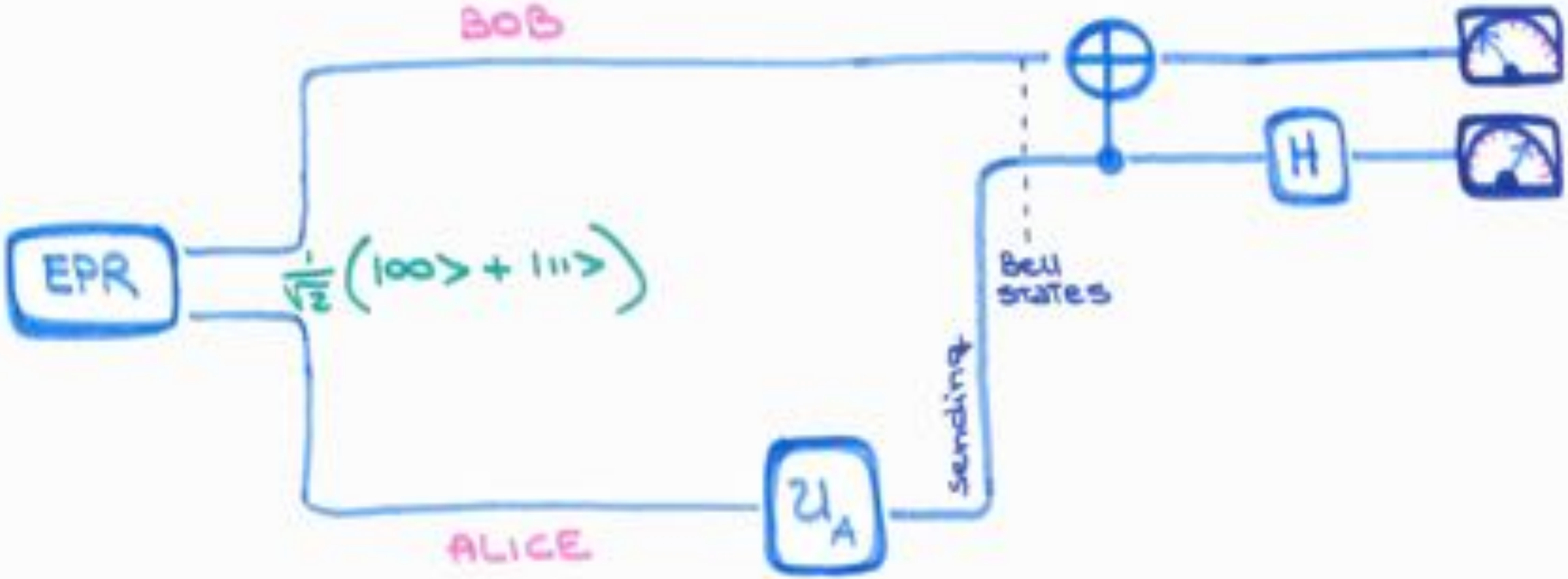

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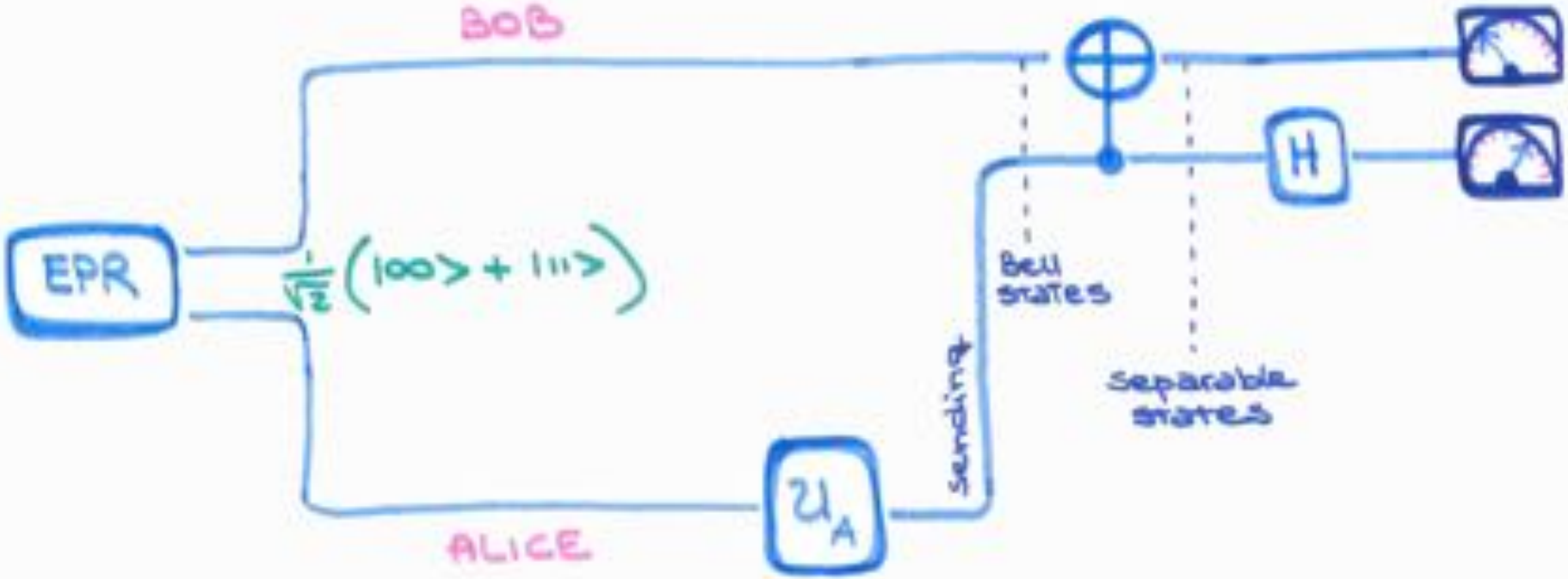

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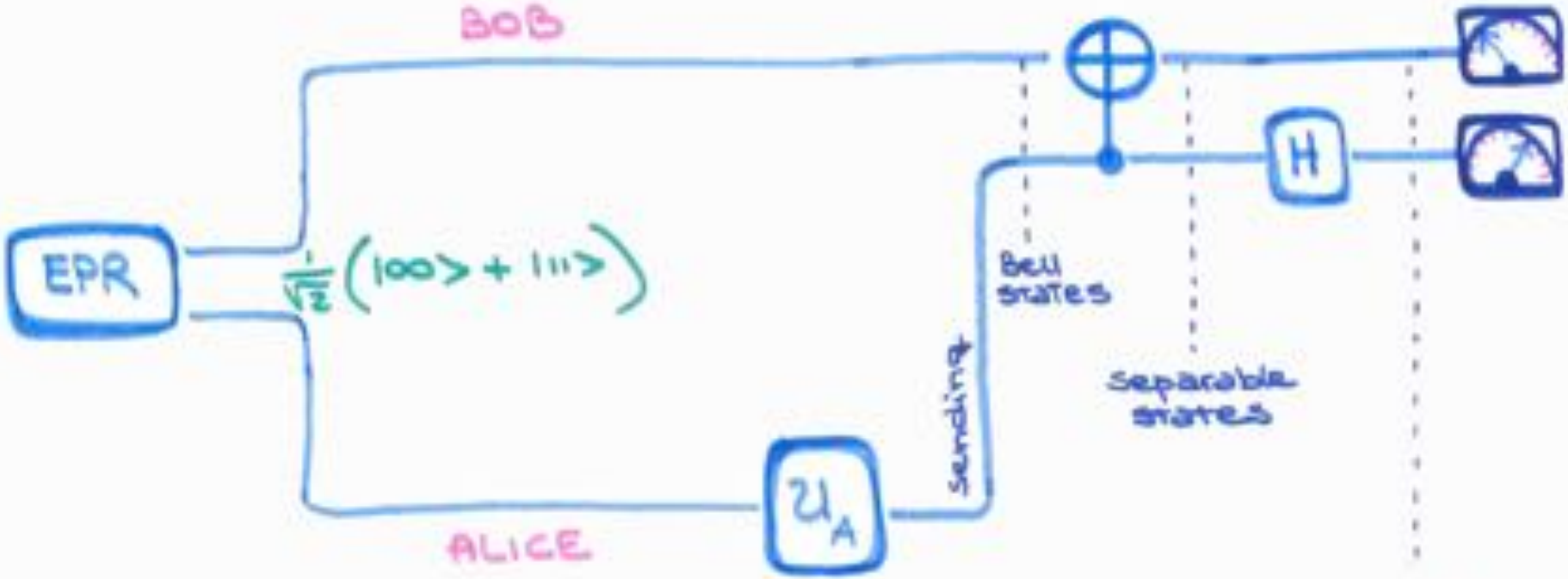

encoding	00	:	$\mathbb{1}$	$\|00\rangle$
	01	:	X	$\|01\rangle$
	10	:	Z	$\|10\rangle$
	11	:	XZ	$\|11\rangle$

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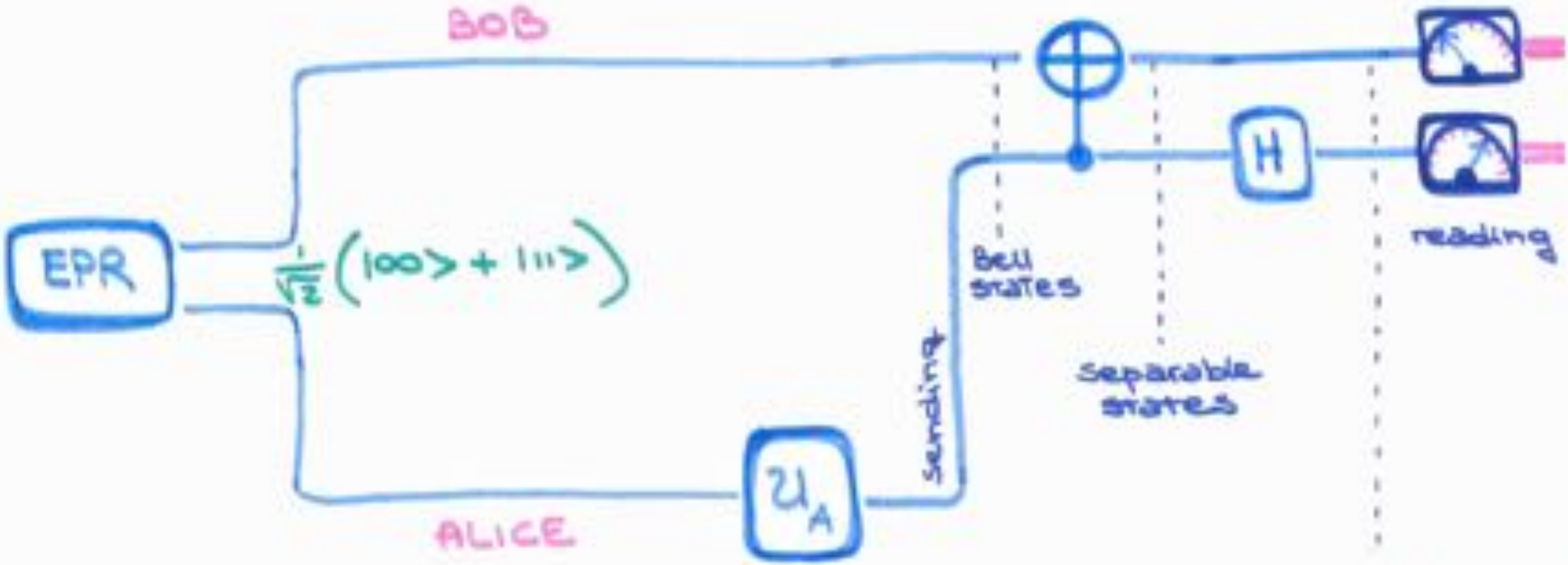

encoding

00	:	$\mathbb{1}$
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$|00\rangle \rightarrow 00$

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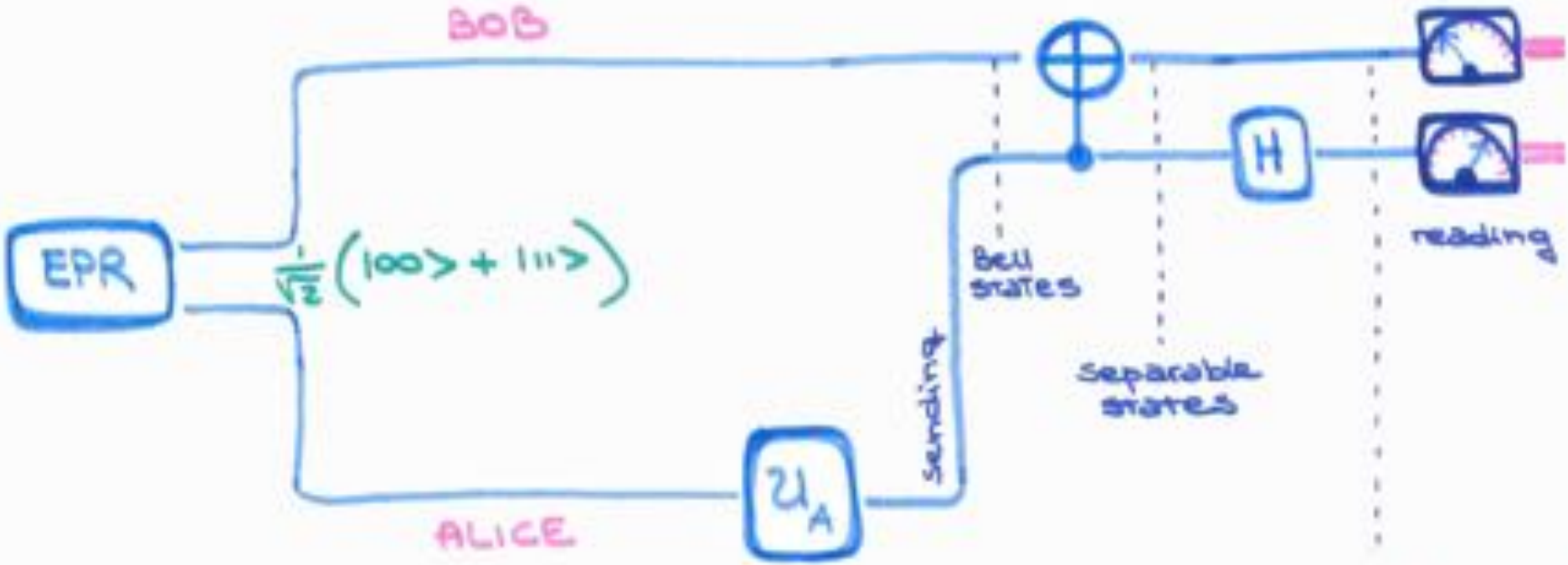

encoding

00	:	$\mathbb{1}$
01	:	X
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!! 1 QUBIT IS SENT ⇒ 2 BITS ARE TRANSMITTED

TOWARDS Q-COMP : DEUTSCH ALGORITHM ~ 1992

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CONSTANT	BALANCED

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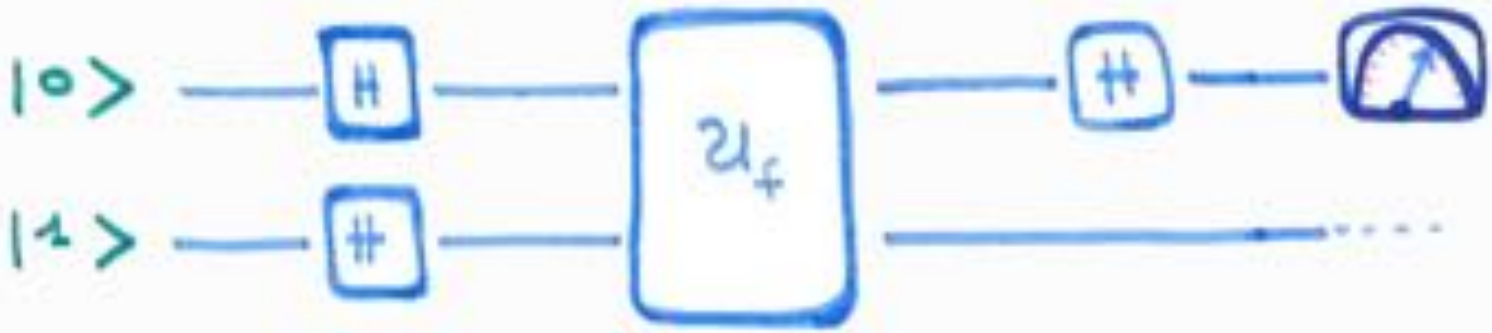

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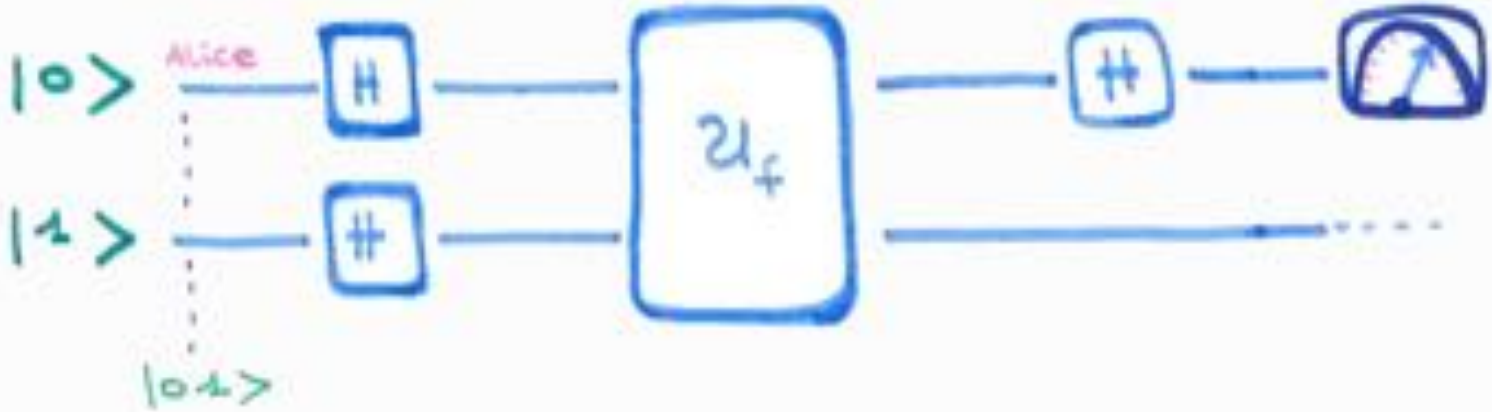

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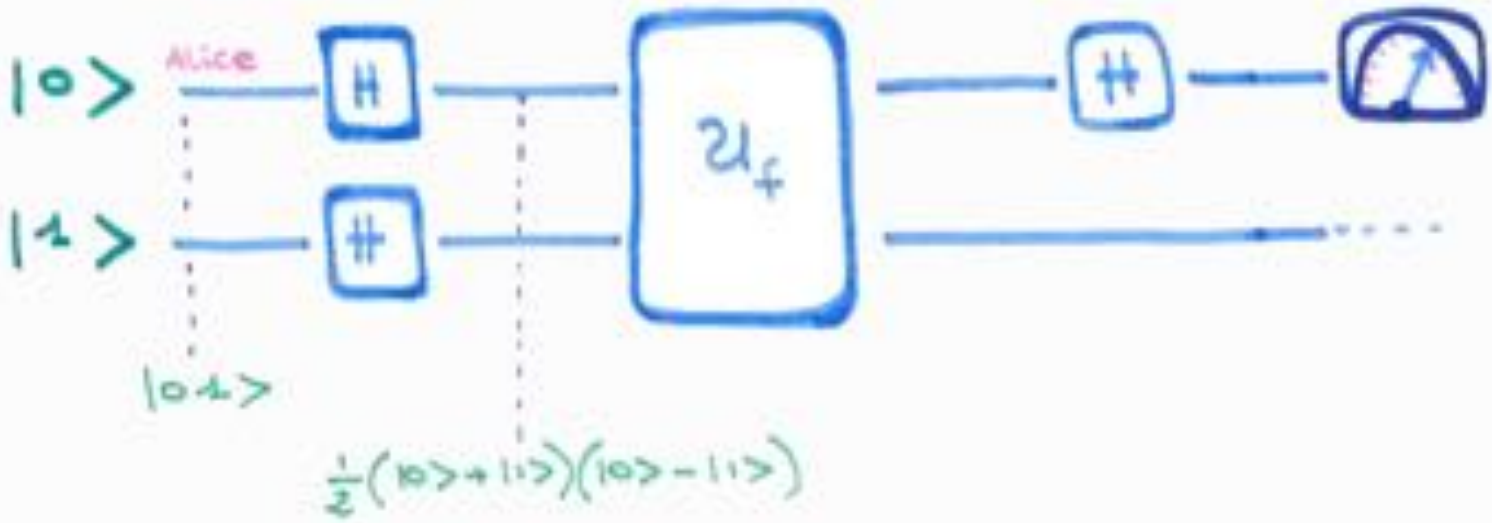

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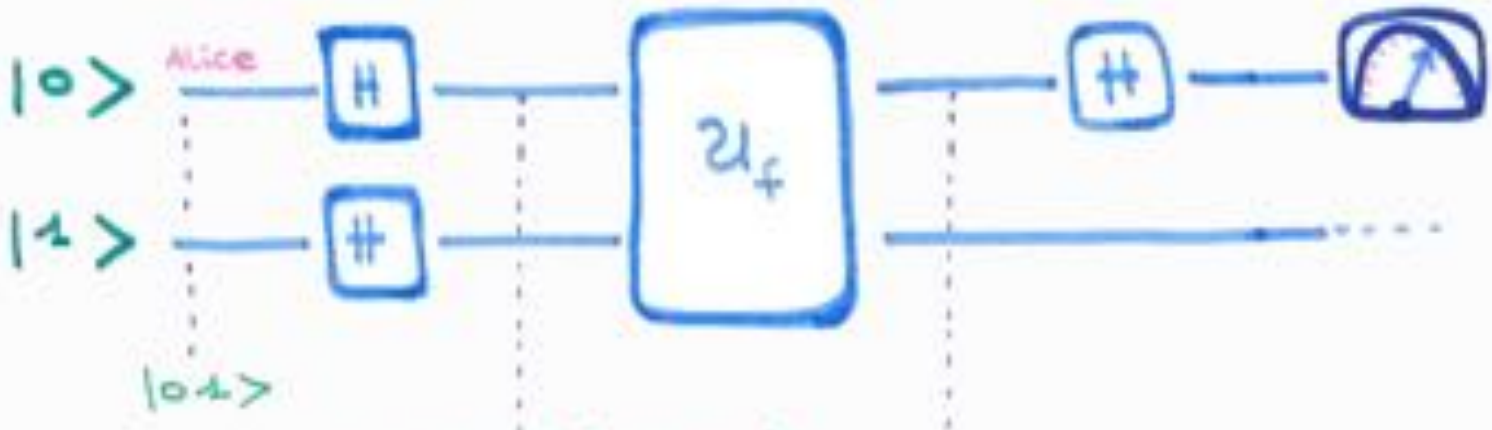

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$\alpha, \beta = 0, 1$

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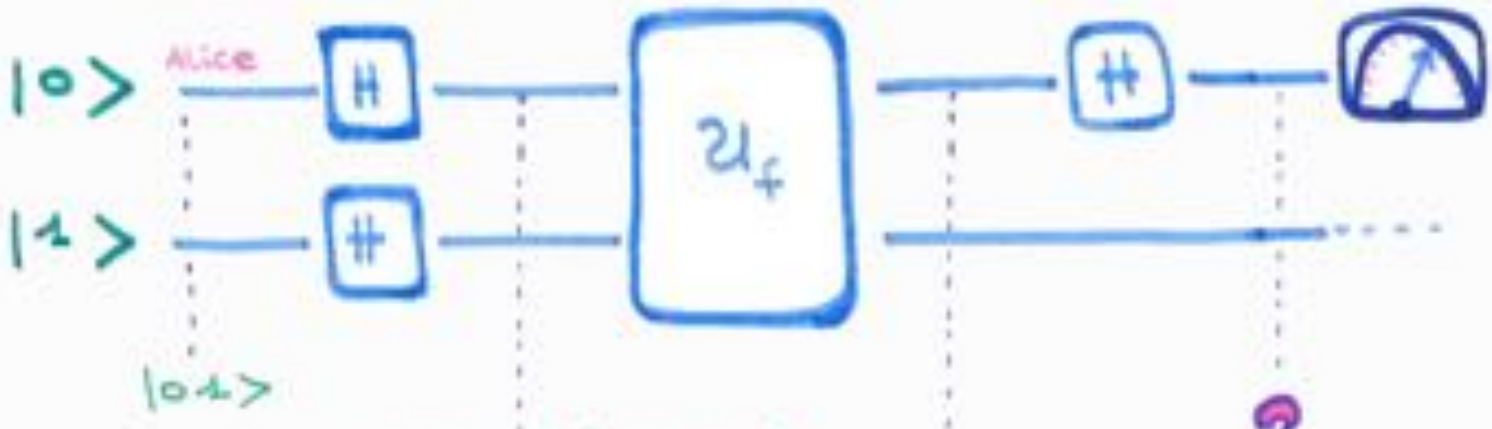

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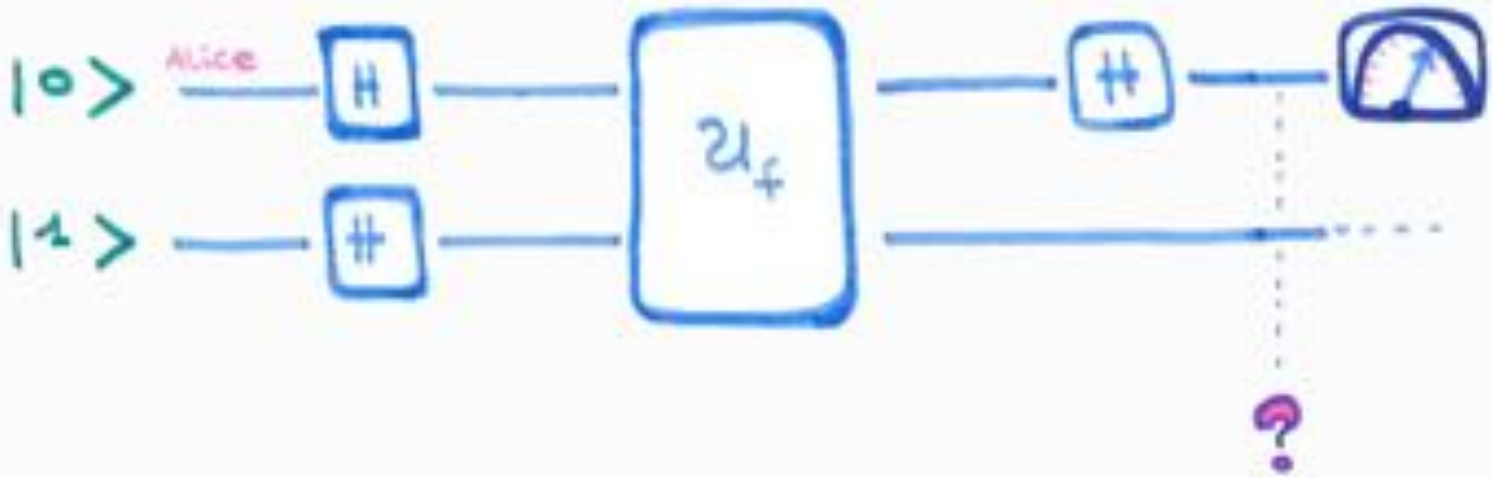


$\alpha, \beta = 0, 1$

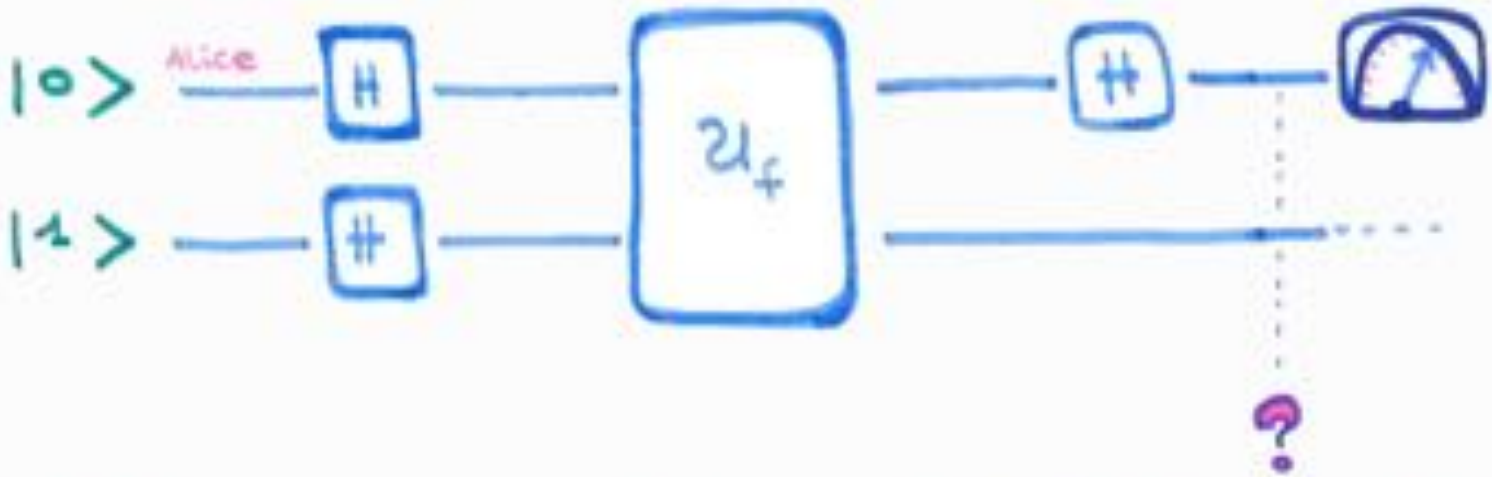
TOWARDS Q-COMP : DEUTSCH ALGORITHM

~ 1992

$$f : \{0,1\} \to \{0,1\}$$

$f(0) = f(1)$ $\qquad$ $f(0) = 1 \oplus f(1)$??

CONSTANT OR BALANCED



$$\frac{1}{2\sqrt{2}}\Big[\,|0\rangle \underbrace{\sum_x \big(|f(x)\rangle - |1\oplus f(x)\rangle\big)}_{|k\rangle} + |1\rangle \underbrace{\sum_x (-)^x \big(|f(x)\rangle - |1\oplus f(x)\rangle\big)}_{|\tau\rangle}\Big]$$

$\alpha, \beta = 0, 1$

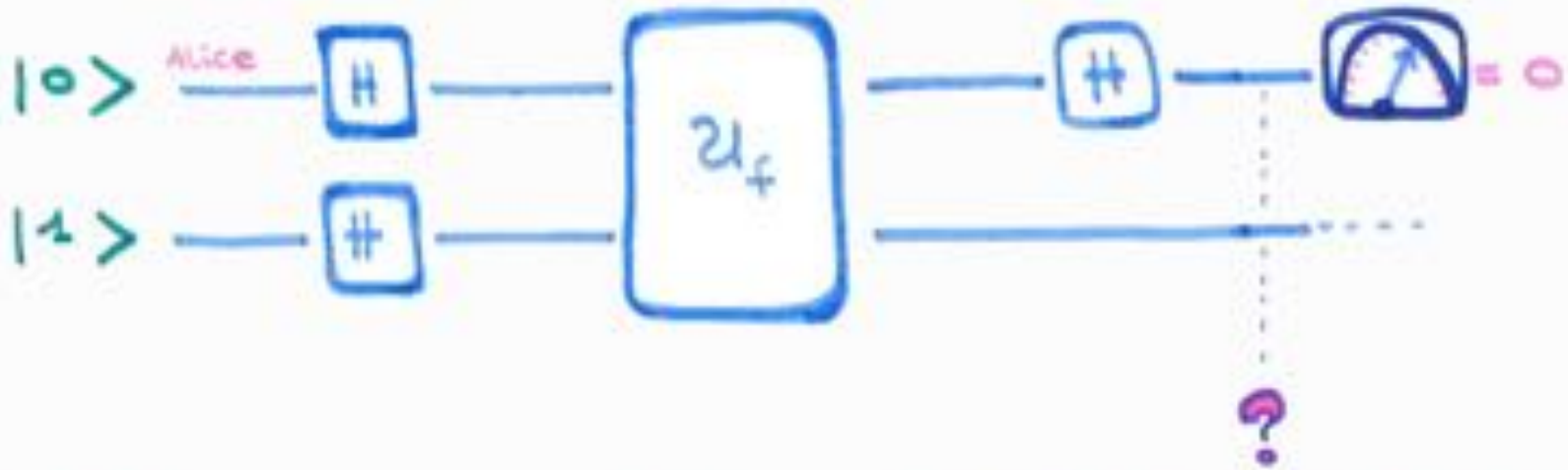
TOWARDS Q-COMP : DEUTSCH ALGORITHM

~ 1992

$$f : \{0,1\} \to \{0,1\}$$

$f(0) = f(1)$ $\qquad$ $f(0) = 1 \oplus f(1)$??

CONSTANT OR BALANCED



$$\frac{1}{2\sqrt{2}}\Big[\,|0\rangle \underbrace{\sum_x \big(|f(x)\rangle - |1\oplus f(x)\rangle\big)}_{|k\rangle} + |1\rangle \underbrace{\sum_x (-)^x \big(|f(x)\rangle - |1\oplus f(x)\rangle\big)}_{|T\rangle}\Big]$$

if f constant only $|k\rangle$ survives $\Rightarrow$ output $= 0$.

$\alpha, \beta = 0, 1$

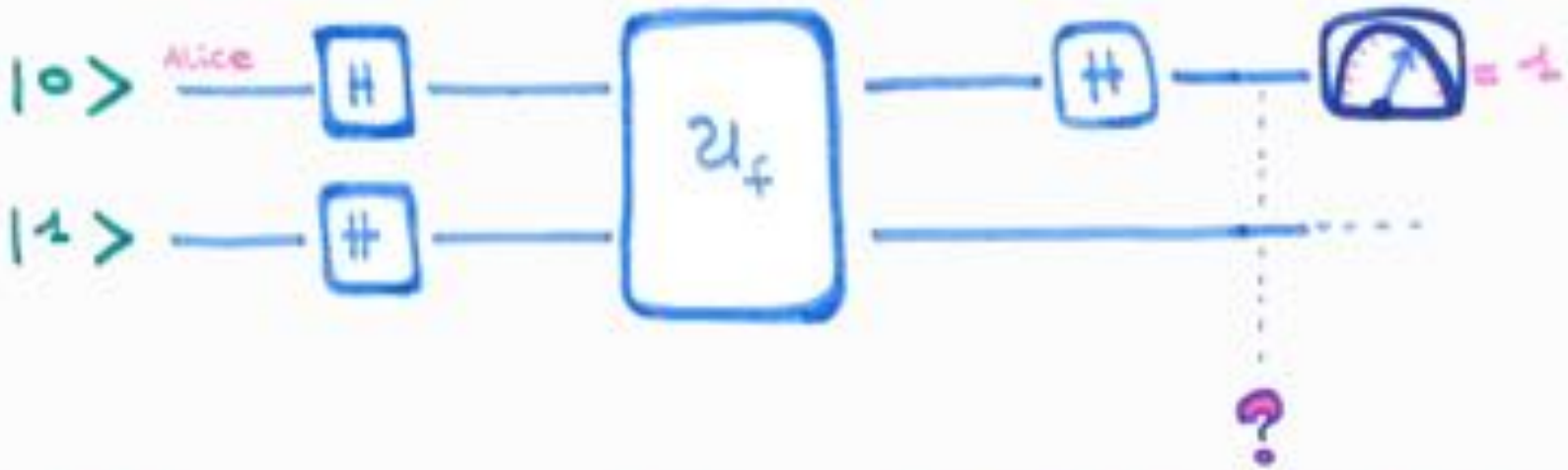
TOWARDS Q-COMP : DEUTSCH ALGORITHM

~ 1992

$$f : \{0,1\} \to \{0,1\}$$

$f(0) = f(1)$ $\qquad$ $f(0) = 1 \oplus f(1)$??

CONSTANT OR BALANCED



$$\frac{1}{2\sqrt{2}}\Big[\,|0\rangle \underbrace{\sum_x \big(|f(x)\rangle - |1\oplus f(x)\rangle\big)}_{|k\rangle} + |1\rangle \underbrace{\sum_x (-)^x \big(|f(x)\rangle - |1\oplus f(x)\rangle\big)}_{|T\rangle}\Big]$$

if f balanced only $|T\rangle$ survives $\Rightarrow$ output = 1

$\alpha, \beta = 0, 1$

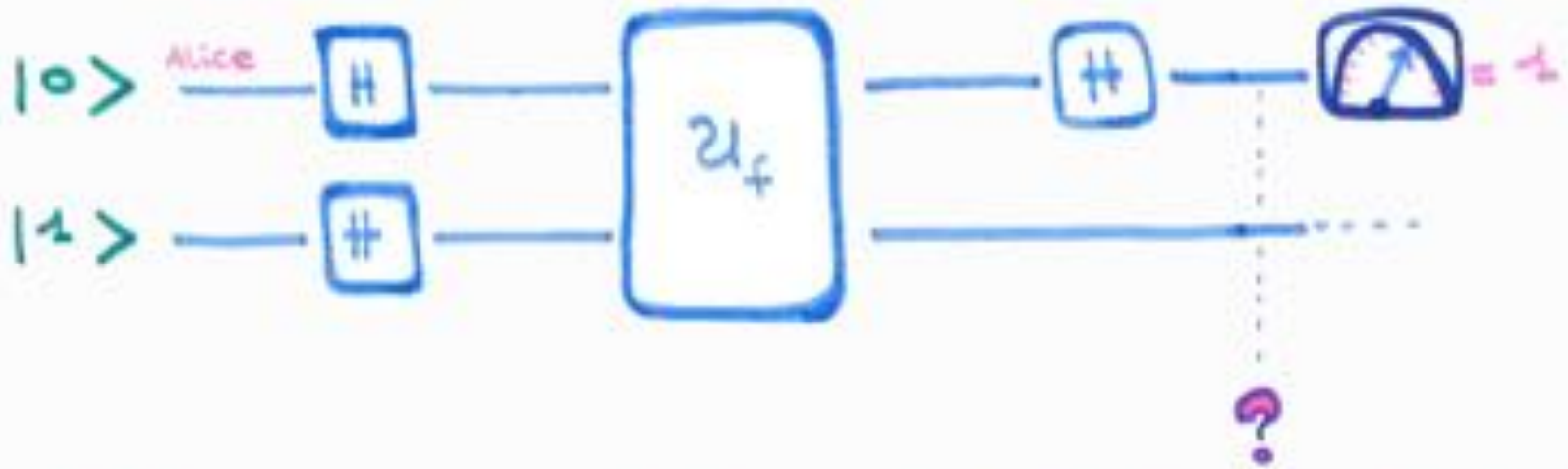
TOWARDS Q-COMP : DEUTSCH ALGORITHM

~ 1992

$$f : \{0,1\} \to \{0,1\}$$

$f(0) = f(1)$ $\qquad$ $f(0) = 1 \oplus f(1)$??

CONSTANT OR BALANCED



$$\frac{1}{2\sqrt{2}}\Big[\,|0\rangle \underbrace{\sum_x \big(|f(x)\rangle - |1\oplus f(x)\rangle\big)}_{|k\rangle} + |1\rangle \underbrace{\sum_x (-)^x \big(|f(x)\rangle - |1\oplus f(x)\rangle\big)}_{|\beta\rangle}\Big]$$

‼ 1 evaluation & 1 reading !

$\alpha, \beta = 0, 1$

JOURNEY PLAN

- WHERE IT ALL STARTED
- GETTING ORIENTED
- LET'S GO
- ★ MOVE ON ⇦
- WHERE ARE WE TODAY
- WHERE TOMORROW

QUANTUM FOURIER TRANSFORM

PHASE ESTIMATION

ORDER FINDING

QUANTUM FOURIER TRANSFORM

PHASE ESTIMATION

ORDER FINDING

SHOR ALGORITHM

~ 1994

★ QUANTUM FOURIER TRANSFORM ★

PHASE ESTIMATION

ORDER FINDING

SHOR ALGORITHM

~ 1994

! DI VINCENZO 's CRITERIA !

~ 2000

★ QUANTUM FOURIER TRANSFORM ★

PHASE ESTIMATION

ORDER FINDING

SHOR ALGORITHM

~ 1994

! DI VINCENZO 's CRITERIA !

~ 2000

- SCALABLE

★ QUANTUM FOURIER TRANSFORM ★

PHASE ESTIMATION

ORDER FINDING

SHOR ALGORITHM

~ 1994

! DI VINCENZO 's CRITERIA !

~ 2000

- SCALABLE
- SINGLE Q INIZIALIZATION

★ QUANTUM FOURIER TRANSFORM ★

PHASE ESTIMATION

ORDER FINDING

SHOR ALGORITHM

~ 1994

! DI VINCENZO 's CRITERIA !

~ 2000

- SCALABLE
- SINGLE Q INIZIALIZATION
- LONG (w.r.t. τ_G) DECOHERENCE TIME

★ QUANTUM FOURIER TRANSFORM ★

PHASE ESTIMATION

ORDER FINDING

SHOR ALGORITHM

~ 1994

! DI VINCENZO 's CRITERIA !

~ 2000

- SCALABLE
- SINGLE Q INIZIALIZATION
- LONG (w.r.t. τ_G) DECOHERENCE TIME
- UNIVERSAL SET OF Q-GATES ⇒ 2 SINGLE Q, 1 ENTANGLING 2Q

★ QUANTUM FOURIER TRANSFORM ★

PHASE ESTIMATION

ORDER FINDING

SHOR ALGORITHM

~ 1994

! DI VINCENZO 's CRITERIA !

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- SINGLE Q MEASUREMENTS

★ QUANTUM FOURIER TRANSFORM ★

PHASE ESTIMATION

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SHOR ALGORITHM

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- UNIVERSAL SET OF Q-GATES ⇒ 2 SINGLE Q, 1 ENTANGLING 2Q
- SINGLE Q MEASUREMENTS

+ NETWORKS

- STATIONARY-Q INTO FY FLYING-Q
- LET FLYING FLYING-Q FLY PROPERLY

Table 4.0-1
The Mid-Level Quantum Computation Roadmap: Promise Criteria

QC Approach	The DiVincenzo Criteria							
	Quantum Computation						QC Networkability	
	#1	#2	#3	#4	#5		#6	#7
NMR	🔴	🟡	🟡	🟢	🟡		🔴	🔴
Trapped Ion	🟡	🟢	🟡	🟢	🟢		🟡	🟡
Neutral Atom	🟡	🟢	🟡	🟡	🟡		🟡	🟡
Cavity QED	🟡	🟢	🟡	🟡	🟢		🟡	🟡
Optical	🟡	🟡	🟢	🟡	🟡		🟡	🟢
Solid State	🟡	🟡	🟡	🟡	🟡		🔴	🔴
Superconducting	🟡	🟢	🟡	🟡	🟡		🔴	🔴
Unique Qubits	This field is so diverse that it is not feasible to label the criteria with "Promise" symbols.							

Legend: 🟢 = a potentially viable approach has achieved sufficient proof of principle

🟡 = a potentially viable approach has been proposed, but there has not been sufficient proof of principle

🔴 = no viable approach is known

The column numbers correspond to the following QC criteria:

#1. A scalable physical system with well-characterized qubits.
#2. The ability to initialize the state of the qubits to a simple fiducial state.
#3. Long (relative) decoherence times, much longer than the gate-operation time.
#4. A universal set of quantum gates.
#5. A qubit-specific measurement capability.
#6. The ability to interconvert stationary and flying qubits.
#7. The ability to faithfully transmit flying qubits between specified locations.

TOWARDS Q-COMM : TELEPORTATION

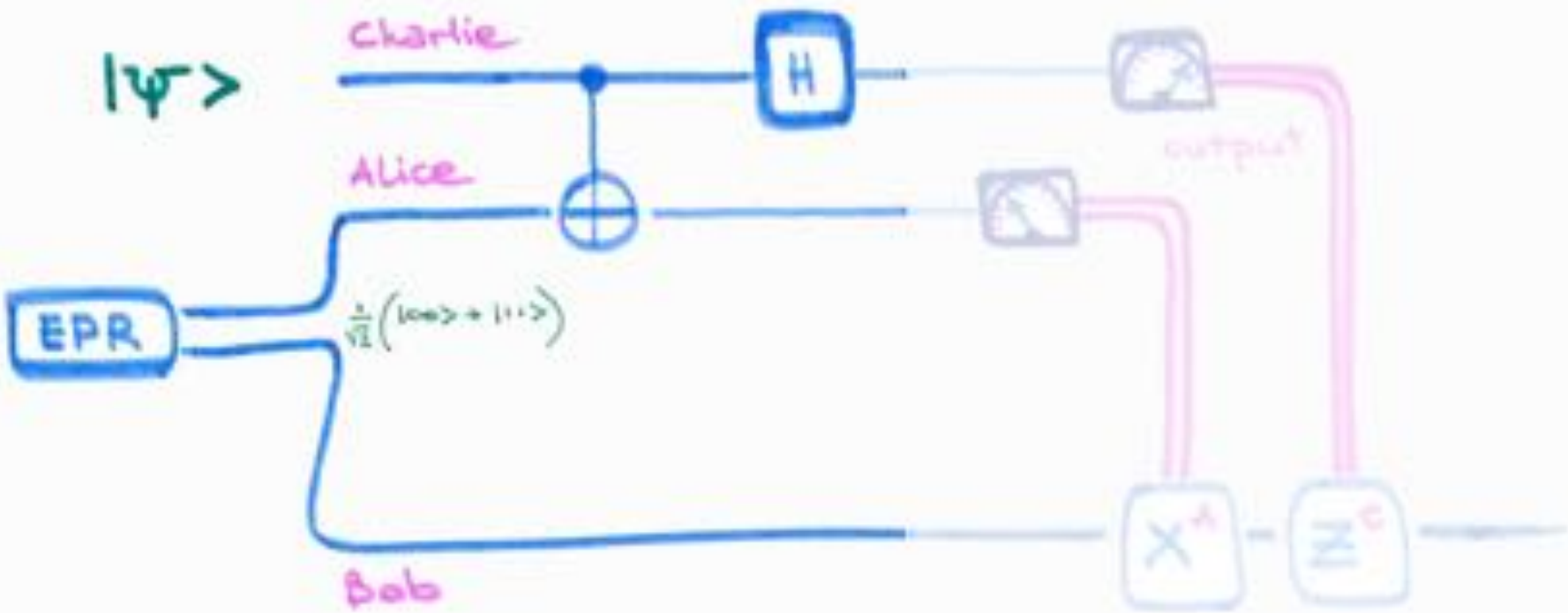
TOWARDS Q-COMM : TELEPORTATION

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

$|\psi\rangle \longrightarrow$

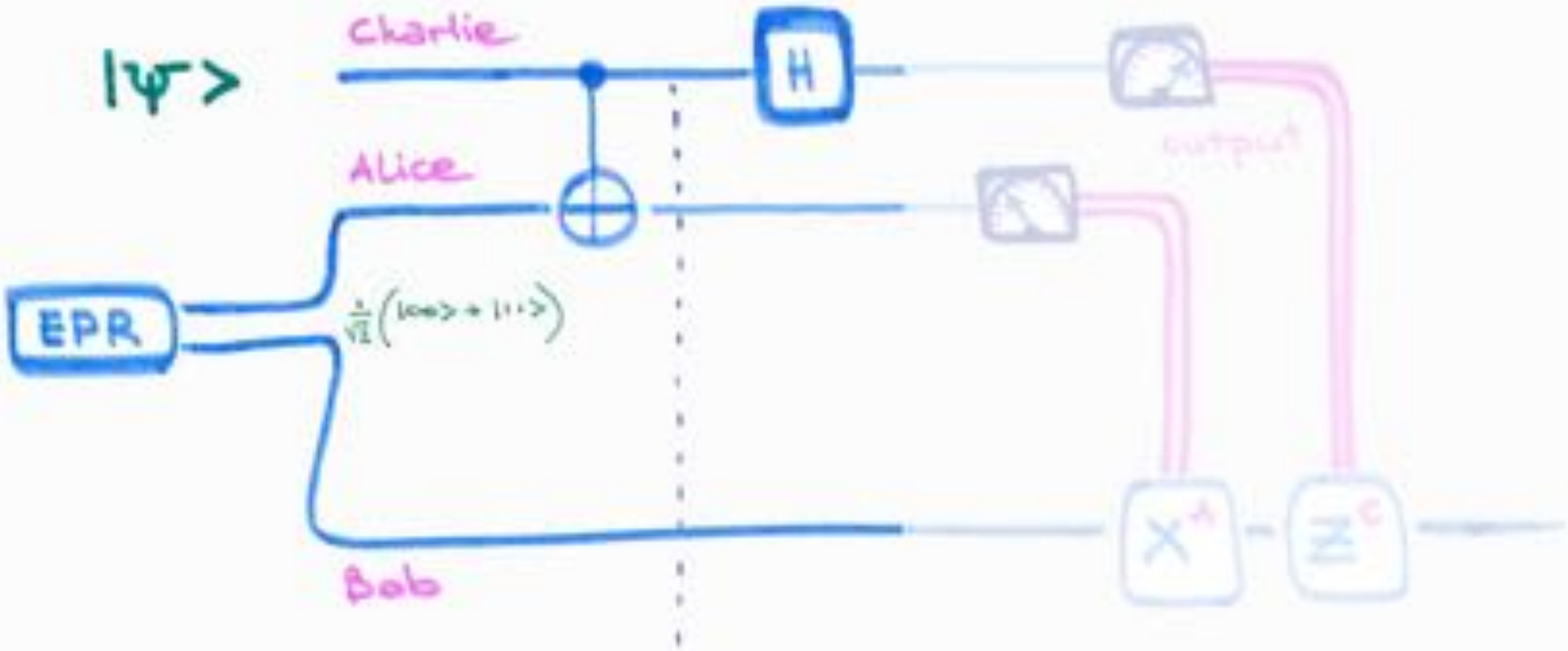
TOWARDS Q-COMM : TELEPORTATION

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



TOWARDS Q-COMM : TELEPORTATION

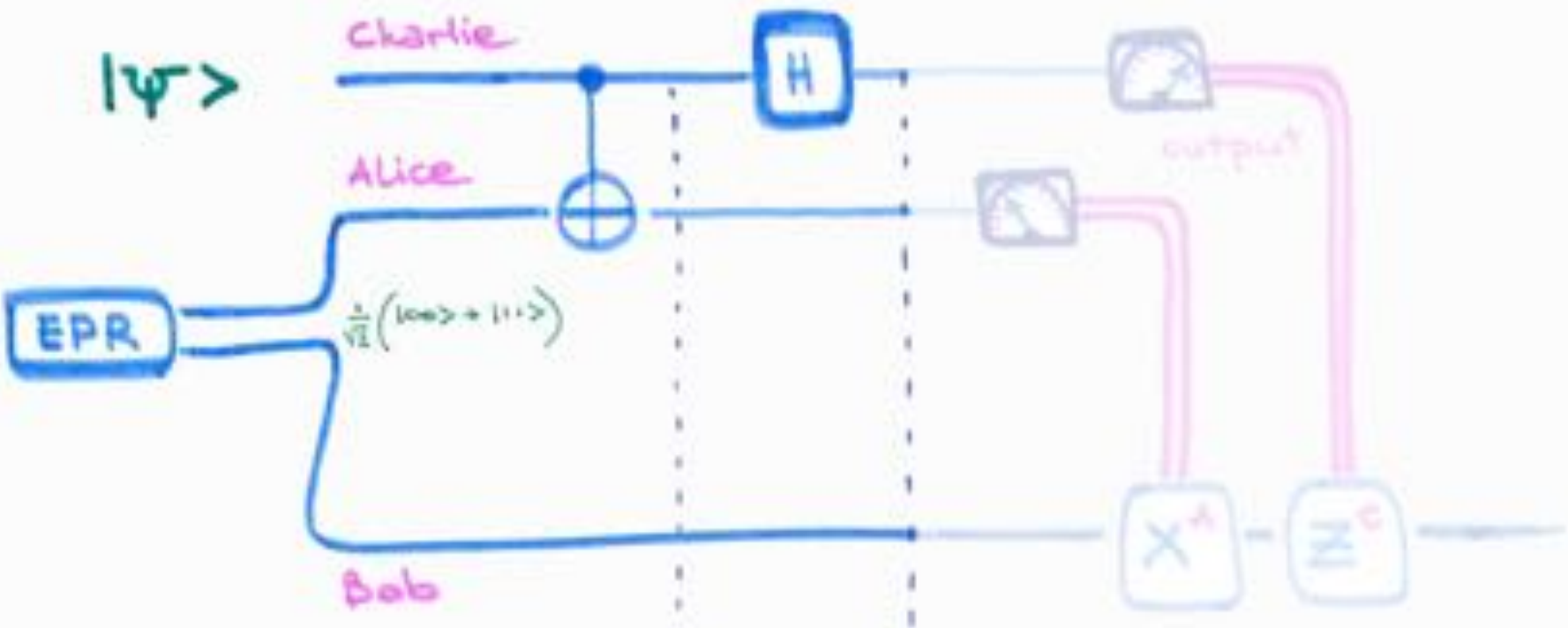
$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$



$\frac{1}{\sqrt{2}}\left(\alpha|000\rangle + \alpha|011\rangle + \beta|110\rangle + \beta|101\rangle\right)$ (CAB)

TOWARDS Q-COMM : TELEPORTATION

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

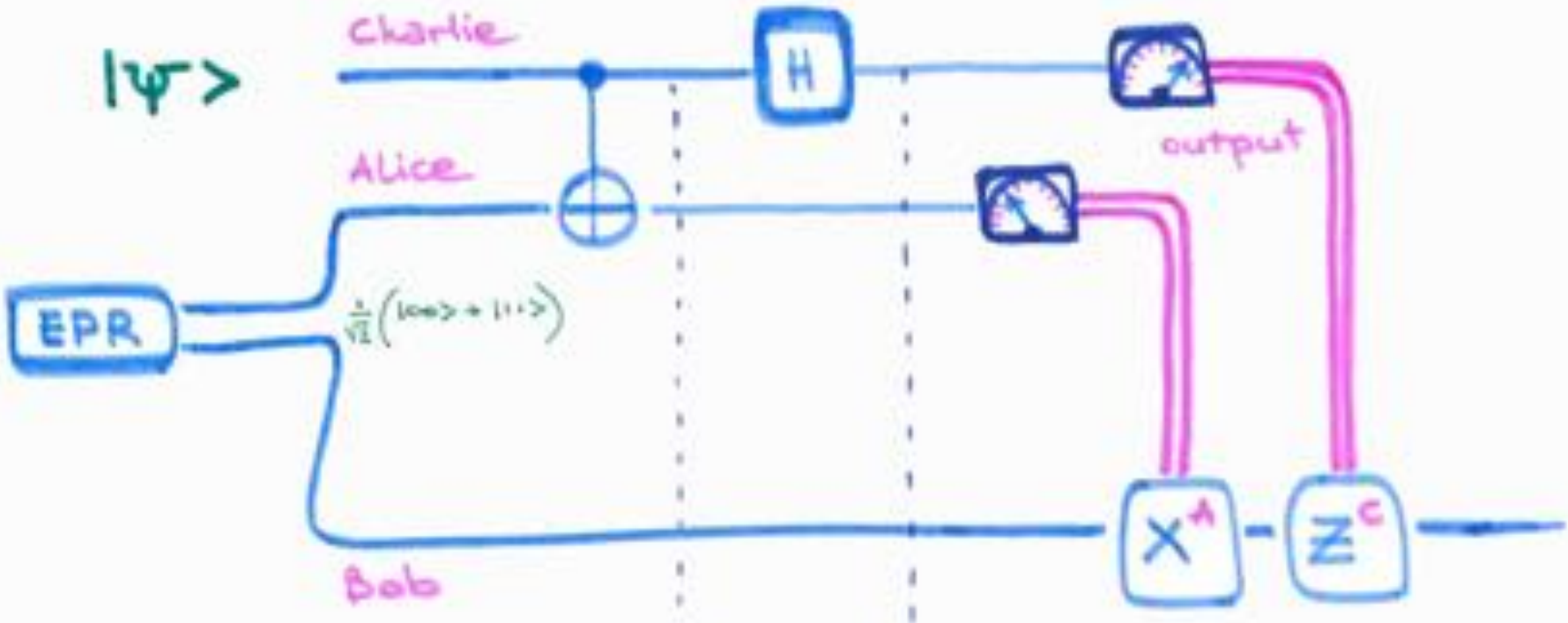


$$\frac{1}{\sqrt{2}}\left(\alpha|\overset{CAB}{000}\rangle + \alpha|011\rangle + \beta|110\rangle + \beta|101\rangle\right)$$

$$\frac{1}{\sqrt{2}}\Big[\Big(|\overset{CA}{00}\rangle(\alpha|\overset{B}{0}\rangle + \beta|1\rangle) + |\overset{CA}{01}\rangle(\alpha|\overset{B}{1}\rangle + \beta|0\rangle)$$
$$+ |\overset{CA}{10}\rangle(\alpha|\overset{B}{0}\rangle - \beta|1\rangle) + |\overset{CA}{11}\rangle(\alpha|\overset{B}{1}\rangle - \beta|0\rangle)\Big]$$

TOWARDS Q-COMM : TELEPORTATION

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



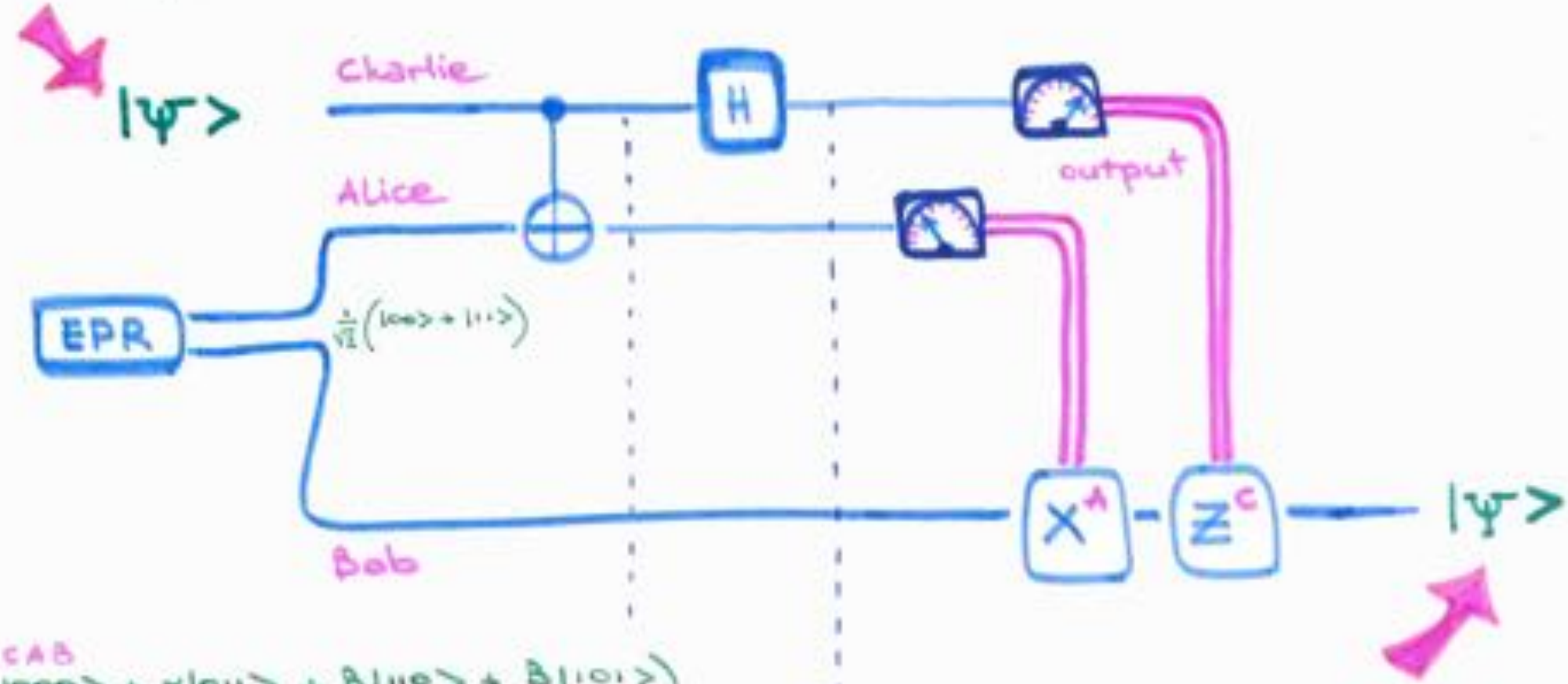
$\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$

$$\frac{1}{\sqrt{2}}\left(\alpha|\overset{CAB}{000}\rangle + \alpha|011\rangle + \beta|110\rangle + \beta|101\rangle\right)$$

$$\frac{1}{\sqrt{2}}\Big[\Big(|\overset{CA}{00}\rangle(\alpha|\overset{B}{0}\rangle + \beta|1\rangle) + |\overset{CA}{01}\rangle(\alpha|\overset{B}{1}\rangle + \beta|0\rangle)$$
$$+ |\overset{CA}{10}\rangle(\alpha|\overset{B}{0}\rangle - \beta|1\rangle) + |\overset{CA}{11}\rangle(\alpha|\overset{B}{1}\rangle - \beta|0\rangle)\Big]$$

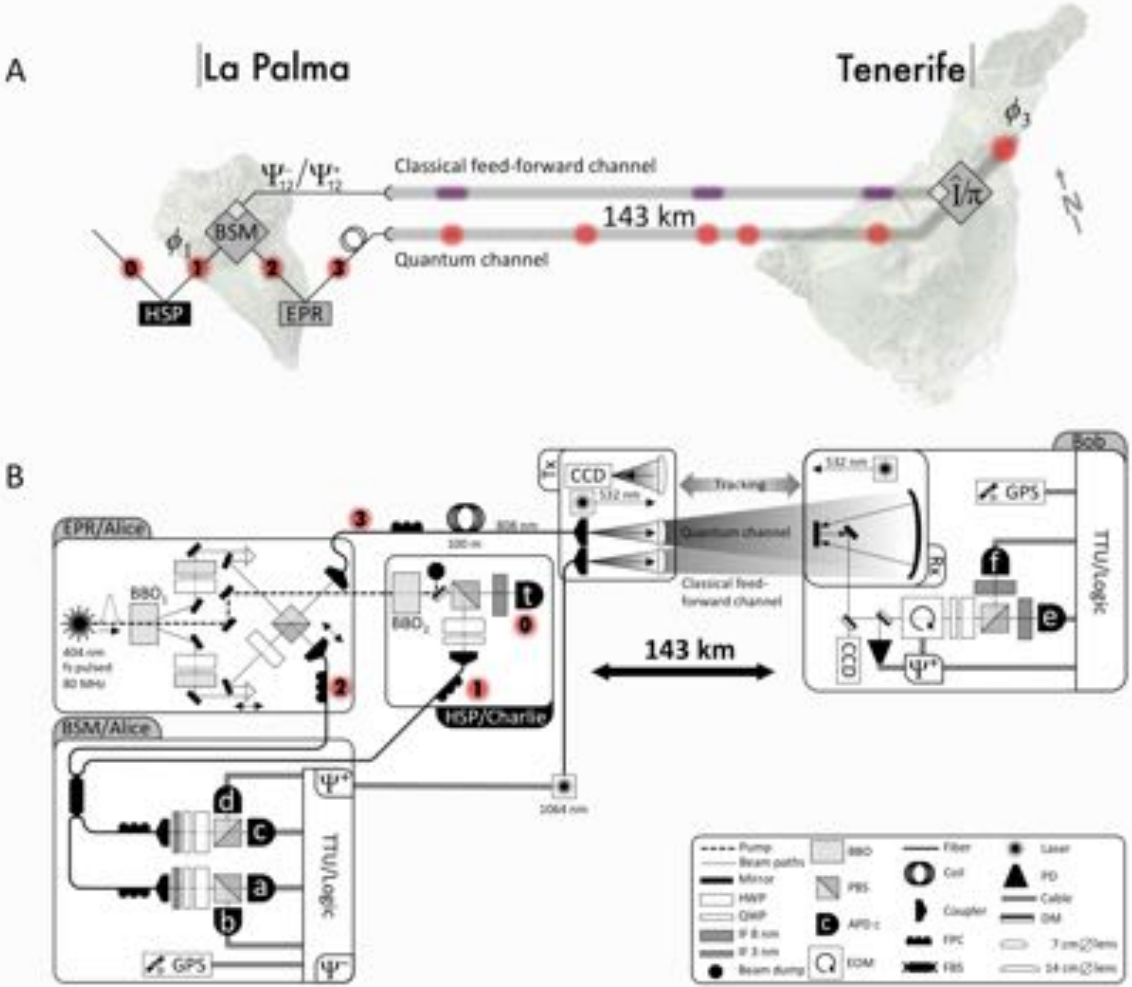
TOWARDS Q-COMM : TELEPORTATION

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



$$\frac{1}{\sqrt{2}}\left(\alpha|\overset{CAB}{000}\rangle + \alpha|011\rangle + \beta|110\rangle + \beta|101\rangle\right)$$

$$\frac{1}{\sqrt{2}}\Big[\Big(|\overset{CA}{00}\rangle(\alpha|\overset{B}{0}\rangle + \beta|1\rangle) + |\overset{CA}{01}\rangle(\alpha|\overset{B}{1}\rangle + \beta|0\rangle)$$
$$+ |\overset{CA}{10}\rangle(\alpha|\overset{B}{0}\rangle - \beta|1\rangle) + |\overset{CA}{11}\rangle(\alpha|\overset{B}{1}\rangle - \beta|0\rangle)\Big]$$


A
La Palma
Tenerife
Classical feed-forward channel
143 km
Quantum channel
BSM
HSP
EPR
B
EPR/Alice
BSM/Alice
HSP/Charlie
Bob
CCD
Tracking
Quantum channel
Classical feed-forward channel
143 km
GPS
TTU/Logic
Pump
Beam paths
Mirror
HWP
QWP
Beam dump
BBO
PBS
APD
EOM
Fiber
Coil
Coupler
FPC
FBS
Laser
PD
Cable
DM

TOWARDS Q-COMM QUANTUM CRYPTO

private key vs public key

TOWARDS Q-COMM QUANTUM CRYPTO

private key vs public key

secure key distribution

TOWARDS Q-COMM QUANTUM CRYPTO

private key vs public key

secure key distribution

BB84 B92 EPR ...

different protocols

TOWARDS Q-COMM QUANTUM CRYPTO

private key vs public key

secure key distribution

BB84 B92 EPR ...

different protocols : same ingredients

TOWARDS Q-COMM QUANTUM CRYPTO

private key vs public key

secure key distribution

BB84 B92 EPR ...

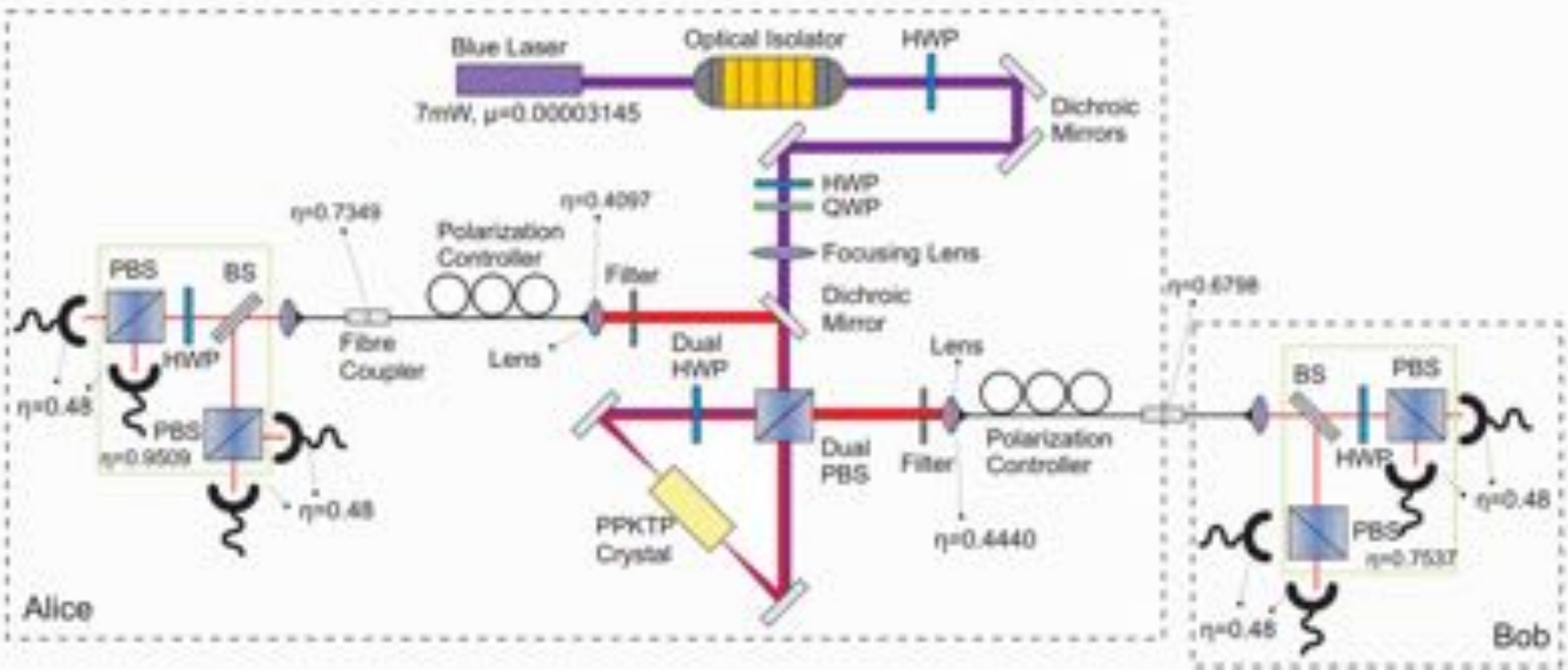
different protocols : same ingredients

- ★ QBITS
- ★ QUANTUM CHANNELS
- ★ MEASURING APPARATUSES

TOWARDS Q-COMM : QUANTUM CRYPTO

private key vs public key

secure key distribution



JOURNEY PLAN

- WHERE IT ALL STARTED
- GETTING ORIENTED
- LET'S GO
- MOVE ON
- ★ WHERE ARE WE TODAY ⟸
- WHERE TOMORROW

QUANTUM SUPREMACY ??

QUANTUM SUPREMACY ??

- DEVICES

  D-WAVE (GOVERNMENT)

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D-Wave is the leader in the development and delivery of quantum computing systems and software, and the world's only commercial supplier of quantum computers. D-Wave Government Inc., a U.S. subsidiary, was formed in 2013 to provide D-Wave's quantum computing systems to the U.S. government. Its independent board includes prominent executives with deep experience at U.S. government agencies including the Department of Energy, the Department of Defense, the National Science Board, the Defense Science Board, and the Intelligence Community.

D-Wave's quantum computers are being used by some of the world's most advanced organizations, including Lockheed Martin, Google, NASA Ames, Los Alamos National Laboratory, and Oak Ridge National Laboratory. D-Wave has been granted over 140 US patents and has published over 90 scientific papers, many of which have appeared in leading science journals.

D-Wave Government offices are located in Hanover, MD.

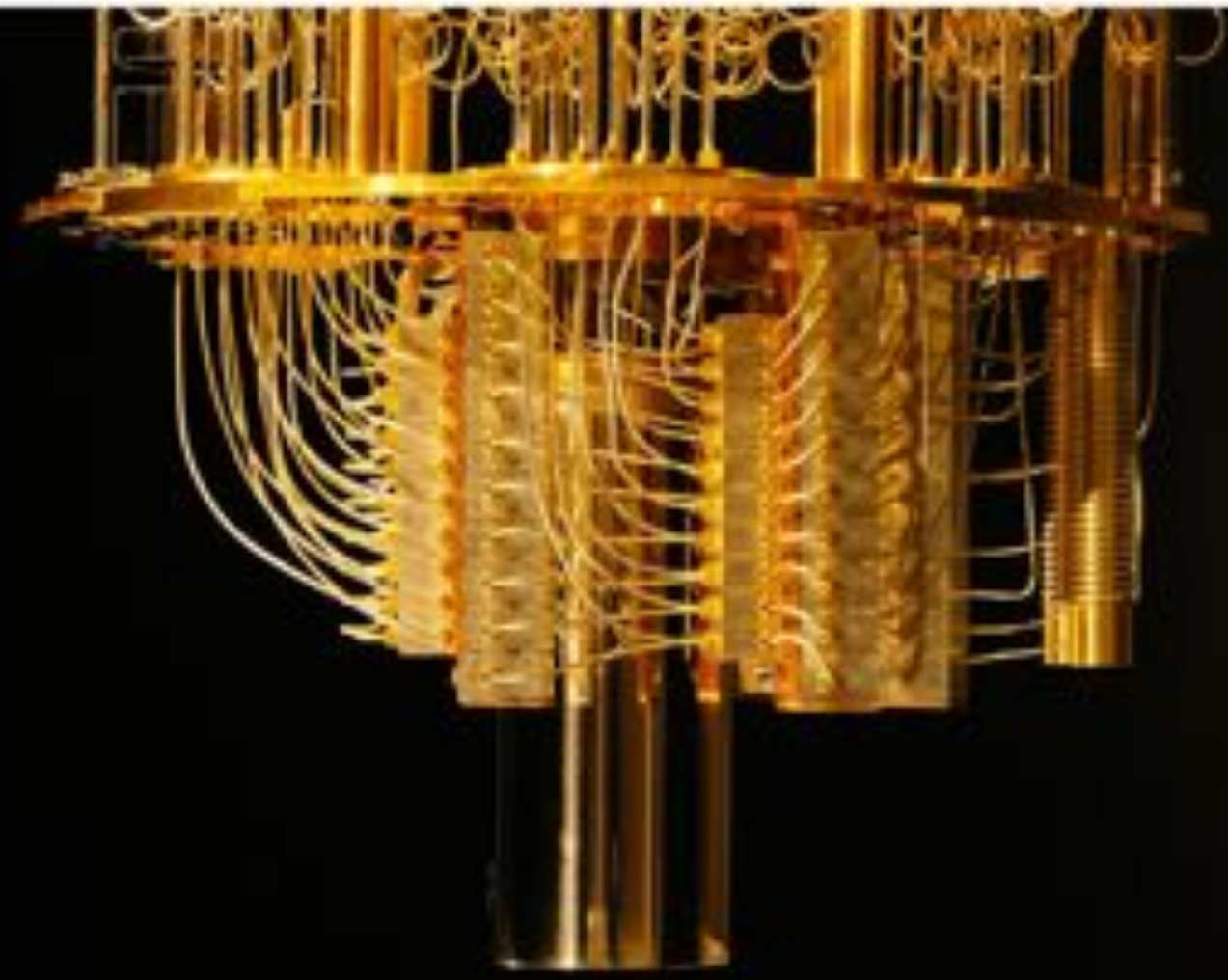
QUANTUM SUPREMACY ??

- DEVICES — D-WAVE (GOVERNMENT)
- COMPUTERS — IBM (QISKIT)

The future is quantum

IBM Q is an industry-first initiative to build commercially available universal quantum computers for business and science.

Watch video (04:46)



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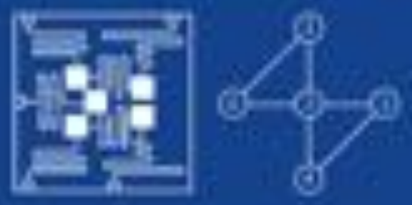


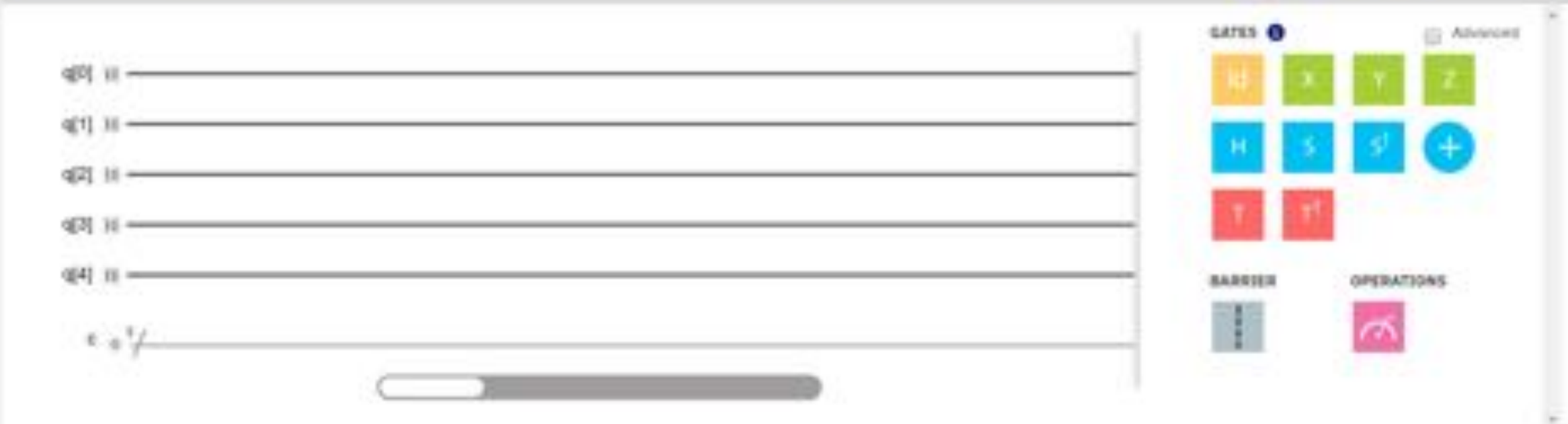
Last Calibration: 2018-04-13 17:53:48

	Q0	Q1	Q2	Q3	Q4
Frequency (GHz)	5.28	5.21	5.02	5.28	5.07
T1 (μs)	62.40	55.10	48.40	59.00	53.30
T2 (μs)	77.50	64.00	54.70	57.50	36.40
Gate error (10^{-3})	1.37	1.37	2.23	1.72	0.94
Readout error (10^{-2})	2.40	2.60	3.00	2.20	4.50
MultiQubit gate error (10^{-2})	CX0_1 2.72	CX1_2 3.77		CX3_2 3.97	CX4_2 3.51
	CX0_2 4.18			CX3_4 3.62	

New experiment

New | Save | Save as

Switch to Qasm Editor | Backend: ibmqx4 | Experiment Units: 3 | Run | Simulate



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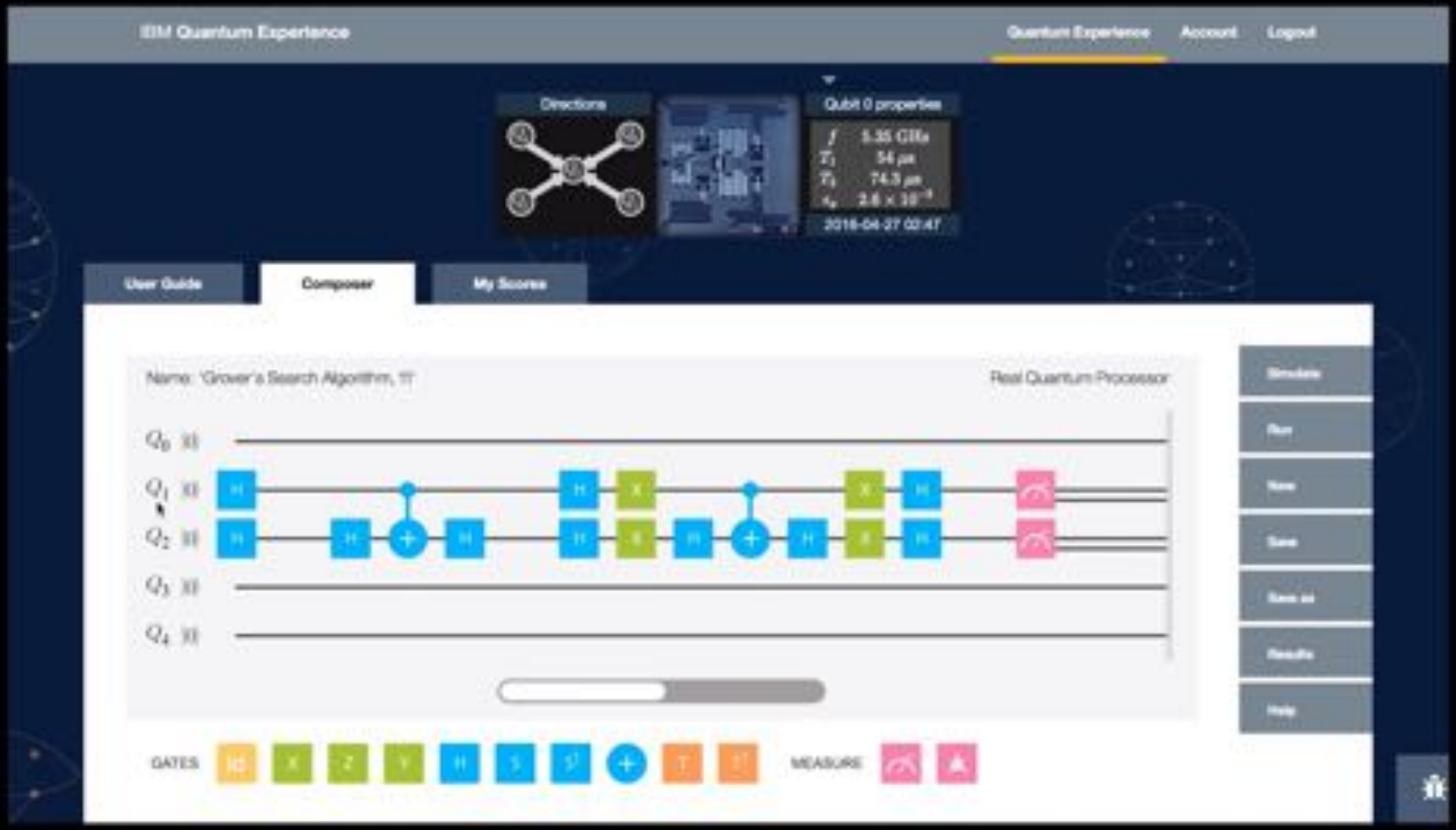
Cookie Preferences

Running an experiment in the IBM Quantum Experience



1:03 / 3:52

Scorri per i dettagli

JOURNEY PLAN

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- ★ WHERE TOMORROW ⇦

QUANTUM SUPREMACY ??

- DEVICES — D-WAVE (GOVERNMENT)
- COMPUTERS — IBM (QISKIT)
- SIMULATORS — GOOGLE
- MACHINE LEARNING — GOOGLE AI (NASA)
- 2nd-LEVEL Q PROGRAMMING — RIGETTI, MICROSOFT
- CHIPS — INTEL

...

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THANKS !!