Classical information

$S_i \in \{0, 1)$ state i has value of either 0 or 1

Quantum Information is differentated by allowing a superposition of classical states allowing for a mixture. classical states are represented as vector using BRA-KET notation, also known as dirac notation

$|0\rangle = \begin{pmatrix}1\\0\end{pmatrix} \quad |1\rangle = \begin{pmatrix}0\\1\end{pmatrix}$ for the classical states

Definition of BRA-KET vectors

* indicates a conjugate

$$\langle A| = (A_1^* \; A_2^* \ldots A_n^*) \qquad |B\rangle = \begin{pmatrix}B_1\\B_2\\ \vdots \\ B_n\end{pmatrix}$$

Inner product:

$$\langle A|B\rangle = A_1^* B_1 + A_2^* B_2 + \ldots + A_n^* B_n$$

Examples

$$\langle 0|0\rangle = [1\,0]\cdot\begin{bmatrix}1\\0\end{bmatrix} = 1+0 = 1$$

$$\langle 0|1\rangle = [1\,0]\cdot\begin{bmatrix}0\\1\end{bmatrix} = 0+0 = 0$$

$$\langle A|A\rangle = \langle B|B\rangle = 1$$

$$\langle A|B\rangle = \langle B|A\rangle = 0$$

Outer products of the form $|\phi\rangle\langle\rho|$ are operators on state $|\psi\rangle$

Example $|\phi\rangle = |\rho\rangle = |0\rangle$

$$|0\rangle\langle 0| = \underset{(2,1)}{\begin{bmatrix}1\\0\end{bmatrix}} \underset{(1,2)}{[1\,0]} = \underset{(2,2)}{\begin{bmatrix}1&0\\0&0\end{bmatrix}}$$

Example $|\phi\rangle = |\rho\rangle = |1\rangle$

$$|1\rangle\langle 1| = \underset{(2,1)}{\begin{bmatrix}0\\1\end{bmatrix}} \underset{(1,2)}{[0\,1]} = \underset{(2,2)}{\begin{bmatrix}0&0\\0&1\end{bmatrix}}$$

Example $|\phi\rangle = |0\rangle, |\rho\rangle = |1\rangle$

$$|0\rangle\langle 1| = \begin{bmatrix}1\\0\end{bmatrix}[0\,1] = \begin{bmatrix}0&1\\0&0\end{bmatrix}$$

Example $|\phi\rangle = |1\rangle, |\rho\rangle = |0\rangle$

$$|1\rangle\langle 0| = \begin{bmatrix}0\\1\end{bmatrix}[1\,0] = \begin{bmatrix}0&0\\1&0\end{bmatrix}$$

$$\alpha\,|\overset{\text{row}}{0}\rangle\langle\overset{\text{col}}{0}| + \beta\,|\overset{\text{row}}{0}\rangle\langle\overset{\text{col}}{1}| + \gamma\,|\overset{\text{row}}{1}\rangle\langle\overset{\text{col}}{0}| + \varepsilon\,|\overset{\text{row}}{1}\rangle\langle\overset{\text{col}}{1}| = A$$

$$A = \begin{bmatrix}\alpha&\beta\\\gamma&\varepsilon\end{bmatrix}$$

Simple gates

$I_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ Identity does nothing to state $|\psi\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$

$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$ Not gate given (pauli-X)

$|0\rangle = \binom{1}{0}$ $X|0\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} = |1\rangle$

$|1\rangle = \binom{0}{1}$ $X|1\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} = |0\rangle$

Or more generally

$X\psi = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \alpha|0\rangle + \beta|1\rangle$

$Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$ $Z\psi = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \alpha|0\rangle - \beta|1\rangle$

$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$ $H\psi = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \frac{1}{\sqrt{2}}\left(\alpha + \beta|0\rangle + \alpha - \beta|1\rangle\right)$

$S = \begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$ $S\psi = \begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \alpha \\ i\beta \end{bmatrix} = \alpha|0\rangle + i\beta|1\rangle$

BRA-KET equivalent notation:

$|0\rangle\langle 0| = \underset{(2,1)}{\begin{bmatrix} 1 \\ 0 \end{bmatrix}} \underset{(1,2)}{[1\ 0]} = \underset{(2,2)}{\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}}$

$|1\rangle\langle 1| = \begin{bmatrix} 0 \\ 1 \end{bmatrix}[0\ 1] = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$

$S = |0\rangle\langle 0| + i|1\rangle\langle 1|$

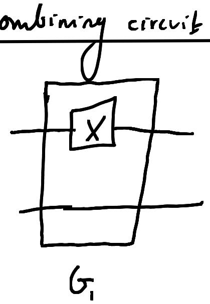
$S\psi = (|0\rangle\langle 0| + i|1\rangle\langle 1|)(\alpha|0\rangle + \beta|1\rangle)$

$= \alpha|0\rangle\underbrace{\langle 0|0\rangle}_{1} + \beta|0\rangle\underbrace{\langle 0|1\rangle}_{0} + i\alpha|1\rangle\underbrace{\langle 1|0\rangle}_{0} + i\beta|1\rangle\underbrace{\langle 1|1\rangle}_{1}$

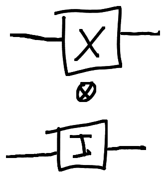
$= \alpha|0\rangle + i\beta|1\rangle$

$T_{\pi/8} = \begin{bmatrix} 1 & 0 \\ 0 & e^{\frac{i\pi}{4}} \end{bmatrix}$

Combining circuit elements in parallel:



$=$



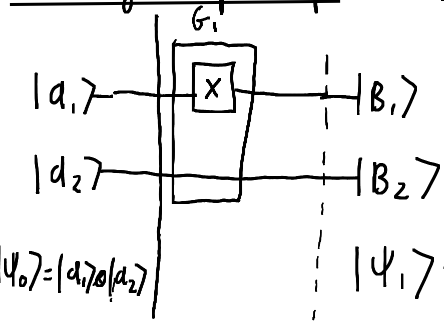
$=$ Kronecker Product

$$X \otimes I = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

2,2   2,2

$$G_1 = X \otimes I = \begin{bmatrix} 0\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} & 1\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\ 1\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} & 0\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

Processing a simple example $|\psi_0\rangle \to |\psi_1\rangle$



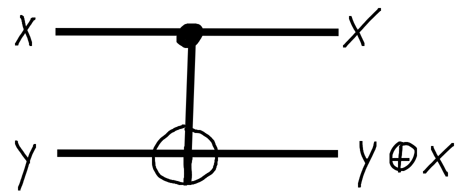
$|\psi_0\rangle = |a_1\rangle \otimes |a_2\rangle$

$$|\psi_1\rangle = G_1|\psi_0\rangle = G_1(|a_1\rangle \otimes |a_2\rangle)$$
$$= |B_1\rangle \otimes |B_2\rangle$$

$$|\psi_1\rangle = |B_1\rangle \otimes |B_2\rangle$$

Input			Output		
$\lvert a_1\rangle$	$\lvert a_2\rangle$	$\lvert\psi_0\rangle$	$\lvert B_1\rangle$	$\lvert B_2\rangle$	$\lvert\psi_1\rangle = G\lvert\psi_0\rangle$
$\lvert 0\rangle$	$\lvert 0\rangle$	$[1000]^T$	$\lvert 1\rangle$	$\lvert 0\rangle$	$[0010]^T$
$\lvert 0\rangle$	$\lvert 1\rangle$	$[0100]^T$	$\lvert 1\rangle$	$\lvert 1\rangle$	$[0001]^T$
$\lvert 1\rangle$	$\lvert 0\rangle$	$[0010]^T$	$\lvert 0\rangle$	$\lvert 0\rangle$	$[1000]^T$
$\lvert 1\rangle$	$\lvert 1\rangle$	$[0001]^T$	$\lvert 0\rangle$	$\lvert 1\rangle$	$[0100]^T$

Control gates (dual qubits) CNOT



Input		Output	
X	Y	X	X ⊕ Y
$\lvert 0\rangle$	$\lvert 0\rangle$	$\lvert 0\rangle$	$\lvert 0\rangle$
$\lvert 0\rangle$	$\lvert 1\rangle$	$\lvert 0\rangle$	$\lvert 1\rangle$
$\lvert 1\rangle$	$\lvert 0\rangle$	$\lvert 1\rangle$	$\lvert 1\rangle$
$\lvert 1\rangle$	$\lvert 1\rangle$	$\lvert 1\rangle$	$\lvert 0\rangle$

Convolve states $X \otimes Y$

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

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

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

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

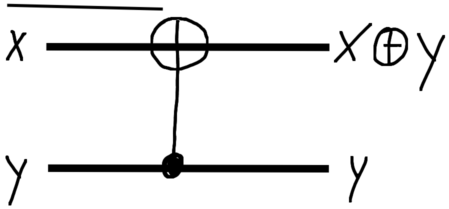
Input	Output
$\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$
$\begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}$
$\begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$
$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$

Input	Output
$\begin{bmatrix}1\\0\\0\\0\end{bmatrix}$	$\begin{bmatrix}1\\0\\0\\0\end{bmatrix}$
$\begin{bmatrix}0\\1\\0\\0\end{bmatrix}$	$\begin{bmatrix}0\\1\\0\\0\end{bmatrix}$
$\begin{bmatrix}0\\0\\1\\0\end{bmatrix}$	$\begin{bmatrix}0\\0\\0\\1\end{bmatrix}$
$\begin{bmatrix}0\\0\\0\\1\end{bmatrix}$	$\begin{bmatrix}0\\0\\1\\0\end{bmatrix}$

what is the matrix that describes such a transformation

$$\begin{array}{c} \text{row 1} \\ \text{row 2} \\ \text{row 3} \\ \text{row 4} \end{array} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Upside down:

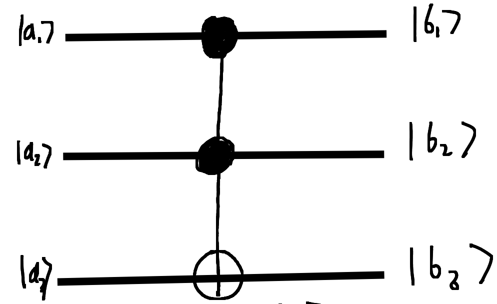


input		output	
X	Y	$x \oplus y$	Y
$\|0\rangle$	$\|0\rangle$	$\|0\rangle$	$\|0\rangle$
$\|0\rangle$	$\|1\rangle$	$\|1\rangle$	$\|1\rangle$
$\|1\rangle$	$\|0\rangle$	$\|1\rangle$	$\|0\rangle$
$\|1\rangle$	$\|1\rangle$	$\|0\rangle$	$\|1\rangle$

Input	Output
$\begin{bmatrix}1\\0\\0\\0\end{bmatrix}$	$\begin{bmatrix}1\\0\\0\\0\end{bmatrix}$
$\begin{bmatrix}0\\1\\0\\0\end{bmatrix}$	$\begin{bmatrix}0\\0\\0\\1\end{bmatrix}$
$\begin{bmatrix}0\\0\\1\\0\end{bmatrix}$	$\begin{bmatrix}0\\0\\1\\0\end{bmatrix}$
$\begin{bmatrix}0\\0\\0\\1\end{bmatrix}$	$\begin{bmatrix}0\\1\\0\\0\end{bmatrix}$

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

Toffoli gate (CCNOT) 3 qubits



$|b_3\rangle = |a_3 \oplus a_1 a_2\rangle$

	Inputs a_1	a_2	a_3	Outputs b_1	b_2	b_3
1)	$\|0\rangle$	$\|0\rangle$	$\|0\rangle$	$\|0\rangle$	$\|0\rangle$	$\|0\rangle$
2)	$\|0\rangle$	$\|0\rangle$	$\|1\rangle$	$\|0\rangle$	$\|0\rangle$	$\|1\rangle$
3)	$\|0\rangle$	$\|1\rangle$	$\|0\rangle$	$\|0\rangle$	$\|1\rangle$	$\|0\rangle$
4)	$\|0\rangle$	$\|1\rangle$	$\|1\rangle$	$\|0\rangle$	$\|1\rangle$	$\|1\rangle$
5)	$\|1\rangle$	$\|0\rangle$	$\|0\rangle$	$\|1\rangle$	$\|0\rangle$	$\|0\rangle$
6)	$\|1\rangle$	$\|0\rangle$	$\|1\rangle$	$\|1\rangle$	$\|0\rangle$	$\|1\rangle$
7)	$\|1\rangle$	$\|1\rangle$	$\|0\rangle$	$\|1\rangle$	$\|1\rangle$	$\|1\rangle$
8)	$\|1\rangle$	$\|1\rangle$	$\|1\rangle$	$\|1\rangle$	$\|1\rangle$	$\|0\rangle$
	$\|a_1\rangle \otimes \|a_2\rangle \otimes \|a_3\rangle$			$\|b_1\rangle \otimes \|b_2\rangle \otimes \|b_3\rangle$		

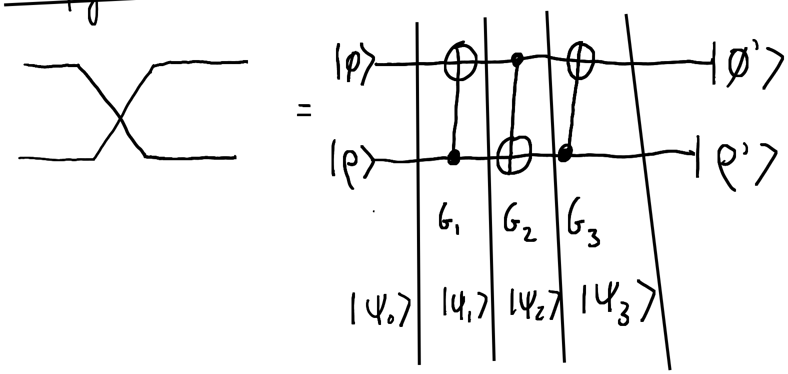
$\lvert a_1\rangle$ $\lvert a_2\rangle$ $\lvert a_3\rangle$	$\lvert a_1\rangle \otimes \lvert a_2\rangle \otimes \lvert a_3\rangle$
$\lvert 0\rangle \lvert 0\rangle \lvert 0\rangle$	$\begin{pmatrix}1\\0\end{pmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}1\\0\\0\\0\end{bmatrix} = \begin{bmatrix}1\\0\\0\\0\\0\\0\\0\\0\end{bmatrix}$
$\lvert 0\rangle \lvert 0\rangle \lvert 1\rangle$	$\begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\1\\0\\0\end{bmatrix} = \begin{bmatrix}0\\1\\0\\0\\0\\0\\0\\0\end{bmatrix}$
$\lvert 0\rangle \lvert 1\rangle \lvert 0\rangle$	$\begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\0\\1\\0\end{bmatrix} = \begin{bmatrix}0\\0\\1\\0\\0\\0\\0\\0\end{bmatrix}$
$\lvert 0\rangle \lvert 1\rangle \lvert 1\rangle$	$\begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\0\\0\\1\end{bmatrix} = \begin{bmatrix}0\\0\\0\\1\\0\\0\\0\\0\end{bmatrix}$
$\lvert 1\rangle \lvert 0\rangle \lvert 0\rangle$	$\begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}1\\0\\0\\0\end{bmatrix} = \begin{bmatrix}0\\0\\0\\0\\1\\0\\0\\0\end{bmatrix}$
$\lvert 1\rangle \lvert 0\rangle \lvert 1\rangle$	$\begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}0\\1\\0\\0\end{bmatrix} = \begin{bmatrix}0\\0\\0\\0\\0\\1\\0\\0\end{bmatrix}$
$\lvert 1\rangle \lvert 1\rangle \lvert 0\rangle$	$\begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}0\\0\\1\\0\end{bmatrix} = \begin{bmatrix}0\\0\\0\\0\\0\\0\\1\\0\end{bmatrix}$
$\lvert 1\rangle \lvert 1\rangle \lvert 1\rangle$	$\begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}0\\0\\0\\1\end{bmatrix} = \begin{bmatrix}0\\0\\0\\0\\0\\0\\0\\1\end{bmatrix}$

Inputs = outputs except from state 7 & 8 which are swapped so the matrix is:

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

Combining circuit elements in series

Swap gate



$$\lvert\psi_3\rangle = G_3\, G_2\, G_1\, \lvert\psi_0\rangle$$

$$G_1 = G_3 = \begin{bmatrix}1&0&0&0\\0&0&0&1\\0&0&1&0\\0&1&0&0\end{bmatrix} \qquad G_2 = \begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{bmatrix}$$

$$G_2\, G_1 = \begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&0&0&1\\0&0&1&0\\0&1&0&0\end{bmatrix} = \begin{bmatrix}1&0&0&0\\0&0&0&1\\0&1&0&0\\0&0&1&0\end{bmatrix}$$

$$G_3\, G_2\, G_1 = \begin{bmatrix}1&0&0&0\\0&0&0&1\\0&0&1&0\\0&1&0&0\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&0&0&1\\0&1&0&0\\0&0&1&0\end{bmatrix} = \begin{bmatrix}1&0&0&0\\0&0&1&0\\0&1&0&0\\0&0&0&1\end{bmatrix}$$

Input		Output	
$\lvert 0\rangle \lvert 0\rangle$	$[1000]^T$	$\lvert 0\rangle \lvert 0\rangle$	$[1000]^T$
$\lvert 0\rangle \lvert 1\rangle$	$[0100]^T$	$\lvert 1\rangle \lvert 0\rangle$	$[0010]^T$
$\lvert 1\rangle \lvert 0\rangle$	$[0010]^T$	$\lvert 0\rangle \lvert 1\rangle$	$[0100]^T$
$\lvert 1\rangle \lvert 1\rangle$	$[0001]^T$	$\lvert 1\rangle \lvert 1\rangle$	$[0001]^T$