

Kvanttilaskenta, kevät 2015 – Viikko 5

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edx Problem 1

We have

$$\begin{aligned} QFT_M &= \frac{1}{\sqrt{6}} \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & \omega & \omega^2 & \omega^3 & \omega^4 & \omega^5 \\ 1 & \omega^2 & \omega^4 & \omega^6 & \omega^8 & \omega^{10} \\ 1 & \omega^3 & \omega^6 & \omega^9 & \omega^{12} & \omega^{15} \\ 1 & \omega^4 & \omega^8 & \omega^{12} & \omega^{16} & \omega^{20} \\ 1 & \omega^5 & \omega^{10} & \omega^{15} & \omega^{20} & \omega^{25} \end{pmatrix} \\ &= \frac{1}{\sqrt{6}} \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & \omega & \omega^2 & \omega^3 & \omega^4 & \omega^5 \\ 1 & \omega^2 & \omega^4 & 1 & \omega^2 & \omega^4 \\ 1 & \omega^3 & 1 & \omega^3 & 1 & \omega^3 \\ 1 & \omega^4 & \omega^2 & 1 & \omega^4 & \omega^2 \\ 1 & \omega^5 & \omega^4 & \omega^3 & \omega^2 & \omega^1 \end{pmatrix} \end{aligned}$$

Now $\omega = e^{2\pi i j/M}$, for $j = 0, 1, \dots, M-1$.

edx Problem 2

What is QFT_6 of $\frac{1}{\sqrt{2}}(|0\rangle + |3\rangle)$?

Now the matrix representation of the input state is

$$|\psi\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{pmatrix},$$

so the QFT of $|\psi\rangle$ is

$$\frac{1}{\sqrt{12}} \begin{pmatrix} 2 \\ 1 + \omega^3 \\ 2 \\ 1 + \omega^3 \\ 2 \\ 1 + \omega^3 \end{pmatrix},$$

where $\omega^3 = e^{2\pi i \times 3/6} = e^{\pi i} = \cos \pi + i \sin \pi = -1$, so

$$|\psi\rangle = \frac{1}{2\sqrt{3}} \begin{pmatrix} 2 \\ 0 \\ 2 \\ 0 \\ 2 \\ 0 \end{pmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}.$$

The probability of measuring $|0\rangle, |2\rangle, |4\rangle$ is $\frac{1}{3}$ each and other probabilities are 0.

edx Problem 3

What is QFT_6 of $\frac{1}{\sqrt{2}}(|1\rangle + |4\rangle)$? Now we have a state

$$|\psi\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 1 \\ 0 \end{pmatrix},$$

so the result is

$$\frac{1}{\sqrt{12}} \begin{pmatrix} 2 \\ \omega + \omega^4 \\ 2\omega^2 \\ 1 + \omega^3 \\ 2\omega^4 \\ \omega^5 + \omega^2 \end{pmatrix} = \frac{1}{2\sqrt{3}} \begin{pmatrix} 2 \\ 0 \\ 2\omega^2 \\ 0 \\ 2\omega^4 \\ 0 \end{pmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 \\ 0 \\ \omega^2 \\ 0 \\ -\omega \\ 0 \end{pmatrix}.$$

Now it is easy to see that the probability of measuring $|0\rangle, |2\rangle, |4\rangle$ is $\frac{1}{3}$ each and zero probability of seeing other.

edx Problem 4

What is QFT_6 of $\frac{1}{\sqrt{3}}(|0\rangle + |2\rangle + |4\rangle)$? Now the input state is

$$|\psi\rangle = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \\ 1 \\ 0 \end{pmatrix},$$

so that the result state is

$$\frac{1}{\sqrt{18}} \begin{pmatrix} 3 \\ 1 + \omega^2 + \omega^4 \\ 1 + \omega^4 + \omega^2 \\ 3 \\ 1 + \omega^2 + \omega^4 \\ 1 + \omega^4 + \omega^2 \end{pmatrix} = \frac{1}{\sqrt{18}} \begin{pmatrix} 3 \\ 0 \\ 0 \\ 3 \\ 0 \\ 0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{pmatrix},$$

so the probability of measuring $|0\rangle$ or $|3\rangle$ is $\frac{1}{2}$ each and the other states has probability 0.

edx Problem 5

What is QFT_6 of $\frac{1}{\sqrt{3}}(|1\rangle + |3\rangle + |5\rangle)$? The input state is

$$\frac{1}{\sqrt{3}} \begin{pmatrix} 0 \\ 1 \\ 0 \\ 1 \\ 0 \\ 1 \end{pmatrix},$$

so the result state is

$$\frac{1}{\sqrt{18}} \begin{pmatrix} 3 \\ \omega + \omega^3 + \omega^5 \\ \omega^2 + 1 + \omega^4 \\ 3\omega^3 \\ \omega^4 + 1 + \omega^2 \\ \omega^5 + \omega^3 + \omega \end{pmatrix} = \frac{1}{\sqrt{18}} \begin{pmatrix} 3 \\ 0 \\ 0 \\ -3 \\ 0 \\ 0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ -1 \\ 0 \\ 0 \end{pmatrix}.$$

The probability of measuring $|0\rangle$ or $|3\rangle$ is $\frac{1}{2}$ each, and other probabilities are zero.

edx Problem 6

$$\beta'_j = \omega^j \beta_j.$$

edx Problem 7

Consider the periodic superposition $|a\rangle = \sqrt{\frac{k}{M}} \sum_{j=0}^{M/k-1} |jk\rangle$. Let $\beta = \sum_j \beta_j |j\rangle$ be its QFT_M .

(a) Derive an expression for β_j . The desired expression is

$$\frac{\sqrt{k}}{M} \sum_{l=0}^{M/k-1} e^{2\pi j l k i / M}.$$

(b) If j is a multiple of M/k , what is the value of β_j ? So we have that $j = aM/k$ for some nonnegative integer a . Now

$$\begin{aligned} \frac{\sqrt{k}}{M} \sum_{l=0}^{M/k-1} e^{2\pi j l k i / M} &= \frac{\sqrt{k}}{M} \sum_{l=0}^{M/k-1} e^{2\pi a l i} \\ &= \frac{\sqrt{k}}{M} \sum_{l=0}^{M/k-1} 1 \\ &= \frac{\sqrt{k}}{M} M/k \\ &= \frac{1}{\sqrt{k}}. \end{aligned}$$

(c) If j is not a multiple of M/k , what is the value of β_j ? Now suppose $j = aM/k + r$ for some nonnegative integer a and an integer $r \in [1, a)$. We have

$$\begin{aligned} \frac{\sqrt{k}}{M} \sum_{l=0}^{M/k-1} e^{2\pi j l k i / M} &= \frac{\sqrt{k}}{M} \sum_{l=0}^{M/k-1} e^{2\pi l k i (aM/k + r) / M} \\ &= \frac{\sqrt{k}}{M} \sum_{l=0}^{M/k-1} e^{2\pi l k i (aM/k) / M + 2\pi l k i r / M} \\ &= \frac{\sqrt{k}}{M} \sum_{l=0}^{M/k-1} e^{2\pi l i a} e^{2i\pi l k r / M} \\ &= \frac{\sqrt{k}}{M} \sum_{l=0}^{M/k-1} e^{2i\pi l k r / M} \\ &= \end{aligned}$$

edx Problem 8

$$|\beta\rangle = \sqrt{\frac{k}{M}} \sum_{l=0}^{M/k-1} e^{2\pi li/M} |lk+1\rangle$$

edx Problem 9

(a) $f(j) = 2^j \bmod 21$, so

- $f(0) = 1$,
- $f(1) = 2$,
- $f(2) = 4$,
- $f(3) = 8$,
- $f(4) = 16$,
- $f(5) = 11$,
- $f(6) = 1$,

and the period is $k = 6$.

(b) $a = 2^{k/2} = 2^3 = 8$. $a^2 = 64 = 1 \bmod 21$. On the other hand $a \pm 1$ are not $1 \bmod 21$.

(c) $\gcd(21, 9) = 3$.

edx Problem 10

The answer: If Alice now applies QFT_{2^n} and measure, she will still get k with probability 99%.

QCE 7.1

$$\vec{\sigma} = \sigma_x \hat{x} + \sigma_y \hat{y} + \sigma_z \hat{z}, \quad \vec{n} = \sin \theta \cos \phi \hat{x} + \sin \theta \sin \phi \hat{y} + \cos \theta \hat{z}.$$

Now

$$\begin{aligned} \vec{\sigma} \cdot \vec{n} &= (\sigma_x \hat{x} + \sigma_y \hat{y} + \sigma_z \hat{z})(\sin \theta \cos \phi \hat{x} + \sin \theta \sin \phi \hat{y} + \cos \theta \hat{z}) \\ &= \end{aligned}$$

QCE 7.2

Let

$$|\psi\rangle = \frac{|0\rangle|1\rangle - |1\rangle|0\rangle}{\sqrt{2}}.$$

Now we have

$$|0\rangle = \frac{|+\rangle + i|-\rangle}{\sqrt{2}}, \quad |1\rangle = \frac{|+\rangle - i|-\rangle}{\sqrt{2}},$$

so

$$\begin{aligned} |\psi\rangle &= \frac{|0\rangle|1\rangle - |1\rangle|0\rangle}{\sqrt{2}} \\ &= \frac{1}{2\sqrt{2}} \left((|+\rangle + i|-\rangle)(|+\rangle - i|-\rangle) - (|+\rangle - i|-\rangle)(|+\rangle + i|-\rangle) \right) \\ &= \frac{1}{2\sqrt{2}} \left(|++\rangle - i|+-\rangle + i|-+\rangle + |--\rangle + |++\rangle + i|+-\rangle - i|-+\rangle + |--\rangle \right) \\ &= \frac{1}{2\sqrt{2}} (2|++\rangle + 2|--\rangle) \\ &= \frac{1}{\sqrt{2}} (|++\rangle + |--\rangle). \end{aligned}$$

QCE 7.3

Let

$$|\beta_{00}\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix}, \quad |\beta_{01}\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ 1 \\ 0 \end{pmatrix}.$$

Also we know that

$$Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix},$$

so

$$\begin{aligned} Z \otimes Z &= \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \otimes \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \end{aligned}$$

Now

$$\begin{aligned}
Z \otimes Z |\beta_{00}\rangle &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix} \\
&= \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix} \\
&= \beta_{00} \\
&= (-1)^y |\beta_{xy}\rangle,
\end{aligned}$$

where $y = 0$ and $x = 0$. Also

$$\begin{aligned}
Z \otimes Z |\beta_{01}\rangle &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ 1 \\ 0 \end{pmatrix} \\
&= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ -1 \\ -1 \\ 0 \end{pmatrix} \\
&= -\beta_{01} \\
&= (-1)^y |\beta_{xy}\rangle,
\end{aligned}$$

where $y = 1$ and $x = 0$.

QCE 7.4

Show that $X \otimes X |\beta_{xy}\rangle = (-1)^x |\beta_{xy}\rangle$. From the book we know that

$$|\beta_{xy}\rangle = \frac{|0y\rangle + (-1)^x |1\bar{y}\rangle}{\sqrt{2}} = \frac{1}{\sqrt{2}} \begin{pmatrix} \bar{y} \\ y \\ (-1)^x y \\ (-1)^x \bar{y} \end{pmatrix}.$$

Also

$$\begin{aligned}
X \otimes X &= \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \otimes \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \\
&= \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix},
\end{aligned}$$

so

$$\begin{aligned}
X \otimes X |\beta_{xy}\rangle &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \bar{y} \\ y \\ (-1)^x y \\ (-1)^x \bar{y} \end{pmatrix} \\
&= \frac{1}{\sqrt{2}} \begin{pmatrix} (-1)^x \bar{y} \\ (-1)^x y \\ y \\ \bar{y} \end{pmatrix} \\
&= \frac{(-1)^x |0y\rangle + |1\bar{y}\rangle}{\sqrt{2}} \\
&= (-1)^x \beta_{xy}.
\end{aligned}$$

QCE 7.5

Show that $Y \otimes Y |\beta_{xy}\rangle = (-1)^{x+y} |\beta_{xy}\rangle$. From the book we know that

$$|\beta_{xy}\rangle = \frac{|0y\rangle + (-1)^x |1\bar{y}\rangle}{\sqrt{2}} = \frac{1}{\sqrt{2}} \begin{pmatrix} \bar{y} \\ y \\ (-1)^x y \\ (-1)^x \bar{y} \end{pmatrix}.$$

Also

$$\begin{aligned}
Y \otimes Y &= \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \otimes \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \\
&= \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix},
\end{aligned}$$

so

$$\begin{aligned}
Y \otimes Y |\beta_{xy}\rangle &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \bar{y} \\ y \\ (-1)^x y \\ (-1)^x \bar{y} \end{pmatrix} \\
&= \frac{1}{\sqrt{2}} \begin{pmatrix} -(-1)^x \bar{y} \\ (-1)^x y \\ y \\ -\bar{y} \end{pmatrix} \\
&= (-1)^{x+\bar{y}} |\beta_{xy}\rangle.
\end{aligned}$$

The book has a typo as in the above formula in the term $x + y$ y should be \bar{y} .

QCE 7.6

Show that $X \otimes X$ commutes with $Z \otimes Z$. They commute if and only if $X \otimes XZ \otimes Z = X \otimes XZ \otimes Z$:

$$\begin{aligned} X \otimes X &= \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}^{\otimes 2} \\ &= \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}. \end{aligned}$$

$$\begin{aligned} Z \otimes Z &= \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}^{\otimes 2} \\ &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \end{aligned}$$

Now

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

Also

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

which proves that the two matrices commute.

QCE 7.7

Consider the eigenvectors in Example 7.4. Show that $[H_I, \vec{\sigma}_A \cdot \vec{\sigma}_B] = 0$, and hence show that the eigenvectors of the Hamiltonian are eigenvectors of the $\vec{\sigma}_A \cdot \vec{\sigma}_B$ operator. In particular, show that $\vec{\sigma}_A \cdot \vec{\sigma}_B |\phi_i\rangle = |\phi_i\rangle$ for $i = 1, 2, 3$ and $\vec{\sigma}_A \cdot \vec{\sigma}_B |\phi_4\rangle = -3|\phi_4\rangle$.

From the Example 7.4 we have that

$$H_I = \frac{\mu^2}{r^3} \begin{pmatrix} -2 & 0 & 0 & 0 \\ 0 & 2 & 2 & 0 \\ 0 & 2 & 2 & 0 \\ 0 & 0 & 0 & -2 \end{pmatrix}, \quad \vec{\sigma}_A \cdot \vec{\sigma}_B = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 2 & 0 \\ 0 & 2 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$

Condition $[H_I, \vec{\sigma}_A \cdot \vec{\sigma}_B] = 0$ means that the two matrices commute and that is the case as a routine calculation may show. Wolframalpha tells me that the eigenvectors of H_I are

$$\begin{pmatrix} 0 \\ -1 \\ -1 \\ 0 \end{pmatrix}, \quad \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}, \quad \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \quad \begin{pmatrix} 0 \\ -1 \\ 1 \\ 0 \end{pmatrix},$$

and that is not in accord with the eigenvectors of $\vec{\sigma}_A \cdot \vec{\sigma}_B$, thank you, book. :(
Now

$$\begin{aligned} \vec{\sigma}_A \cdot \vec{\sigma}_B |\phi_1\rangle &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 2 & 0 \\ 0 & 2 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ 1 \\ 0 \end{pmatrix} \\ &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ 1 \\ 0 \end{pmatrix} \\ &= |\phi_1\rangle, \end{aligned}$$

$$\begin{aligned} \vec{\sigma}_A \cdot \vec{\sigma}_B |\phi_2\rangle &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 2 & 0 \\ 0 & 2 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} \\ &= \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} \\ &= |\phi_2\rangle, \end{aligned}$$

$$\begin{aligned} \vec{\sigma}_A \cdot \vec{\sigma}_B |\phi_3\rangle &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 2 & 0 \\ 0 & 2 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \\ &= \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \\ &= |\phi_3\rangle, \end{aligned}$$

$$\begin{aligned}
\vec{\sigma}_A \cdot \vec{\sigma}_B |\phi_4\rangle &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 2 & 0 \\ 0 & 2 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ -1 \\ 0 \end{pmatrix} \\
&= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ -3 \\ 3 \\ 0 \end{pmatrix} \\
&= -3 |\phi_4\rangle.
\end{aligned}$$

QCE 7,8

Is the state $X \otimes Z |\beta_{00}\rangle$ entangled?

$$\begin{aligned}
X \otimes Z |00\rangle &= \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \otimes \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix} \\
&= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix} \\
&= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ -1 \\ 1 \\ 0 \end{pmatrix} \\
&= \frac{-|01\rangle + |10\rangle}{\sqrt{2}} \\
&= -|\beta_{11}\rangle,
\end{aligned}$$

so the state is entangled but is not a Bell state.

QCE 7.9

Find the Pauli representation of

$$\rho = \begin{pmatrix} \sin^2 \theta & e^{-i\phi} \sin \theta \cos \theta \\ e^{i\phi} \sin \theta \cos \theta & \cos^2 \theta \end{pmatrix}.$$

First we need to compute

$$\begin{aligned}
c_0 &= \text{Tr}(\rho\sigma_0) \\
&= \text{Tr}(\rho) \\
&= \sin^2 \theta + \cos^2 \theta \\
&= 1,
\end{aligned}$$

$$\begin{aligned}
c_1 &= \text{Tr}(\rho\sigma_1) \\
&= \text{Tr}(\rho\sigma_x) \\
&= \text{Tr} \begin{pmatrix} \sin^2 \theta & e^{-i\phi} \sin \theta \cos \theta \\ e^{i\phi} \sin \theta \cos \theta & \cos^2 \theta \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \\
&= \text{Tr} \begin{pmatrix} e^{-i\phi} \sin \theta \cos \theta & \sin^2 \theta \\ \cos^2 \theta & e^{i\phi} \sin \theta \cos \theta \end{pmatrix} \\
&= e^{-i\phi} \sin \theta \cos \theta + e^{i\phi} \sin \theta \cos \theta \\
&= (\sin \theta \cos \theta)(\cos \phi - i \sin \phi + \cos \phi + i \sin \phi) \\
&= 2 \sin \theta \cos \theta \cos \phi,
\end{aligned}$$

$$\begin{aligned}
c_2 &= \text{Tr}(\rho\sigma_2) \\
&= \text{Tr}(\rho\sigma_y) \\
&= \text{Tr} \begin{pmatrix} \sin^2 \theta & e^{-i\phi} \sin \theta \cos \theta \\ e^{i\phi} \sin \theta \cos \theta & \cos^2 \theta \end{pmatrix} \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \\
&= \text{Tr} \begin{pmatrix} ie^{-i\phi} \sin \theta \cos \theta & -i \sin^2 \theta \\ i \cos^2 \theta & -ie^{i\phi} \sin \theta \cos \theta \end{pmatrix} \\
&= ie^{-i\phi} \sin \theta \cos \theta - ie^{i\phi} \sin \theta \cos \theta \\
&= \sin \theta \cos \theta (ie^{-i\phi} - ie^{i\phi}) \\
&= \sin \theta \cos \theta (i(\cos \phi - i \sin \phi) - i(\cos \phi + i \sin \phi)) \\
&= \sin \theta \cos \theta (i \cos \phi - i^2 \sin \phi - i \cos \phi - i^2 \sin \phi) \\
&= 2 \sin \theta \cos \theta \sin \phi.
\end{aligned}$$

$$\begin{aligned}
c_3 &= \text{Tr}(\rho\sigma_3) \\
&= \text{Tr}(\rho\sigma_z) \\
&= \text{Tr} \begin{pmatrix} \sin^2 \theta & e^{-i\phi} \sin \theta \cos \theta \\ e^{i\phi} \sin \theta \cos \theta & \cos^2 \theta \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \\
&= \text{Tr} \begin{pmatrix} \sin^2 \theta & -e^{-i\phi} \sin \theta \cos \theta \\ e^{i\phi} \sin \theta \cos \theta & -\cos^2 \theta \end{pmatrix} \\
&= \sin^2 \theta - \cos^2 \theta.
\end{aligned}$$

The Pauli representation for the system is

$$\rho = \sum_{i=0}^3 \text{Tr}(\sigma_i) \sigma_i.$$

QCE 7.10

Use (7.36) to show that $|\beta_{10}\rangle$ is entangled. Apply the same criterion to test $X \otimes Z |\beta_{00}\rangle$.

Here we have

$$|\beta_{00}\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}, \quad |\beta_{10}\rangle = \frac{|00\rangle - |11\rangle}{\sqrt{2}}.$$

The density operator for $|\beta_{10}\rangle$ is

$$\rho = \frac{1}{2}(|00\rangle - |11\rangle)(\langle 00| - \langle 11|) = \frac{1}{2}(|00\rangle\langle 00| - |00\rangle\langle 11| - |11\rangle\langle 00| + |11\rangle\langle 11|),$$

and its density matrix is

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

Next we find

$$\begin{aligned} c_{11} &= \text{Tr}(\rho X \otimes X) = \text{Tr} \frac{1}{2} \begin{pmatrix} 1 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \\ &= \frac{1}{2} \text{Tr} \begin{pmatrix} -1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & -1 \end{pmatrix} \\ &= -1 \end{aligned}$$

$$\begin{aligned} c_{22} &= \text{Tr}(\rho Y \otimes Y) = \text{Tr} \frac{1}{2} \begin{pmatrix} 1 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix} \\ &= \frac{1}{2} \text{Tr} \begin{pmatrix} 1 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 \end{pmatrix} \\ &= 1 \end{aligned}$$

$$\begin{aligned}
c_{33} &= \text{Tr}(\rho Z \otimes Z) = \text{Tr} \frac{1}{2} \begin{pmatrix} 1 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \\
&= \frac{1}{2} \text{Tr} \begin{pmatrix} 1 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 \end{pmatrix} \\
&= 1.
\end{aligned}$$

Now we see that $|c_{11}| + |c_{22}| + |c_{33}| = 3$, so the state is entangled.

$$\begin{aligned}
X \otimes Z |\beta_{00}\rangle &= \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \otimes \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix} \\
&= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix} \\
&= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ -1 \\ 1 \\ 0 \end{pmatrix} \\
&= \frac{-|01\rangle + |10\rangle}{\sqrt{2}}.
\end{aligned}$$

Now the density operator/matrix for the above state is

$$\begin{aligned}
\rho &= \frac{1}{2} (-|01\rangle + |10\rangle)(-\langle 01| + \langle 10|) \\
&= \frac{1}{2} (|01\rangle \langle 01| - |01\rangle \langle 10| - |10\rangle \langle 01| + |10\rangle \langle 10|) \\
&= \frac{1}{2} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}.
\end{aligned}$$

Next we find

$$\begin{aligned}
c_{11} &= \text{Tr}(\rho X \otimes X) = \frac{1}{2} \text{Tr} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \\
&= \frac{1}{2} \text{Tr} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} = -1,
\end{aligned}$$

$$\begin{aligned}
c_{22} &= \text{Tr}(\rho Y \otimes Y) = \frac{1}{2} \text{Tr} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix} \\
&= \frac{1}{2} \text{Tr} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} = -1,
\end{aligned}$$

$$\begin{aligned}
c_{33} &= \text{Tr}(\rho Z \otimes Z) = \frac{1}{2} \text{Tr} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \\
&= \frac{1}{2} \text{Tr} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} = -1.
\end{aligned}$$

Once again we have $|c_{11}| + |c_{22}| + |c_{33}| = 3$ so this state is entangled as well.

QCE 7.11

Derive

$$|\beta_{00}\rangle \langle \beta_{00}| = \frac{1}{4}(I \otimes I + X \otimes X - Y \otimes Y + Z \otimes Z).$$

We have that

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

so

$$\begin{aligned}
|\beta_{00}\rangle \langle \beta_{00}| &= \frac{1}{2}(|00\rangle + |11\rangle)(\langle 00| + \langle 11|) \\
&= \frac{1}{2}(|00\rangle \langle 00| + |00\rangle \langle 11| + |11\rangle \langle 00| + |11\rangle \langle 11|) \\
&= \frac{1}{2} \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{pmatrix}.
\end{aligned}$$

Now

$$\begin{aligned}
I \otimes I + X \otimes X - Y \otimes Y + Z \otimes Z &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \\
&- \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \end{pmatrix} + \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & -1 & -1 & 0 \\ 0 & -1 & -1 & 0 \\ 1 & 0 & 0 & 1 \end{pmatrix} \\
&= \begin{pmatrix} 2 & 0 & 0 & 2 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 2 \end{pmatrix} \\
&= 4 |\beta_{00}\rangle \langle \beta_{00}|,
\end{aligned}$$

which yields the desired result.

QCE 7.12

Can the following state be written in diagonal form in terms of the Bell basis?

$$\rho = \begin{pmatrix} \frac{1}{2} & 0 & 0 & -\frac{1}{8} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -\frac{1}{8} & 0 & 0 & \frac{1}{2} \end{pmatrix}$$

Using (7.43), determine if this state is a separable state.

Now

$$\begin{aligned}
\rho &= \frac{1}{2} \left(|00\rangle \langle 00| + |11\rangle \langle 11| \right) - \frac{1}{8} \left(|00\rangle \langle 11| + |11\rangle \langle 00| \right) \\
&= \frac{1}{2} \left(|\beta_{00}\rangle \langle \beta_{00}| + |\beta_{10}\rangle \langle \beta_{10}| \right) - \frac{1}{8} \left(|\beta_{00}\rangle \langle \beta_{00}| - |\beta_{10}\rangle \langle \beta_{10}| \right) \\
&= \frac{3}{8} \left(|\beta_{00}\rangle \langle \beta_{00}| \right) + \frac{5}{8} \left(|\beta_{10}\rangle \langle \beta_{10}| \right).
\end{aligned}$$

Since $c_{00} = \frac{3}{8} \leq \frac{1}{2}$, this state is separable.

QCE 7.13

Verify that

$$|\psi\rangle = \left(\frac{|0\rangle - |1\rangle}{\sqrt{2}} \right) \otimes \left(\frac{|0\rangle - |1\rangle}{\sqrt{2}} \right)$$

is a product state using (7.36).

A product state is also called separable. Now

$$\begin{aligned}
|\psi\rangle &= \left(\frac{|0\rangle - |1\rangle}{\sqrt{2}} \right) \otimes \left(\frac{|0\rangle - |1\rangle}{\sqrt{2}} \right) \\
&= \frac{1}{2} (|00\rangle - |01\rangle - |10\rangle + |11\rangle).
\end{aligned}$$

Now

$$\begin{aligned}
\rho &= |\psi\rangle \langle \psi| \\
&= \frac{1}{4} (|00\rangle - |01\rangle - |10\rangle + |11\rangle)(\langle 00| - \langle 01| - \langle 10| + \langle 11|) \\
&= \frac{1}{4} \left(|00\rangle \langle 00| - |00\rangle \langle 01| - |00\rangle \langle 10| + |00\rangle \langle 11| \right. \\
&\quad - |01\rangle \langle 00| + |01\rangle \langle 01| + |01\rangle \langle 10| - |01\rangle \langle 11| \\
&\quad - |10\rangle \langle 00| + |10\rangle \langle 01| + |10\rangle \langle 10| - |10\rangle \langle 11| \\
&\quad \left. + |11\rangle \langle 00| - |11\rangle \langle 01| - |11\rangle \langle 10| + |11\rangle \langle 11| \right) \\
&= \frac{1}{4} \begin{pmatrix} 1 & -1 & -1 & 1 \\ -1 & 1 & 1 & -1 \\ -1 & 1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix}.
\end{aligned}$$

The first term is

$$\begin{aligned}
c_{11} &= \text{Tr}(\rho X \otimes X) \\
&= \frac{1}{4} \text{Tr} \begin{pmatrix} 1 & -1 & -1 & 1 \\ -1 & 1 & 1 & -1 \\ -1 & 1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \\
&= \frac{1}{4} \text{Tr} \begin{pmatrix} 1 & -1 & -1 & 1 \\ -1 & 1 & 1 & -1 \\ -1 & 1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix} \\
&= 1.
\end{aligned}$$

$$\begin{aligned}
c_{22} &= \text{Tr}(\rho Y \otimes Y) \\
&= \frac{1}{4} \text{Tr} \begin{pmatrix} 1 & -1 & -1 & 1 \\ -1 & 1 & 1 & -1 \\ -1 & 1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix} \\
&= \frac{1}{4} \text{Tr} \begin{pmatrix} -1 & -1 & -1 & -1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ -1 & -1 & -1 & -1 \end{pmatrix} \\
&= 0,
\end{aligned}$$

$$\begin{aligned}
c_{33} &= \text{Tr}(\rho Z \otimes Z) \\
&= \frac{1}{4} \text{Tr} \begin{pmatrix} 1 & -1 & -1 & 1 \\ -1 & 1 & 1 & -1 \\ -1 & 1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \\
&= \frac{1}{4} \text{Tr} \begin{pmatrix} 1 & 1 & 1 & 1 \\ -1 & -1 & -1 & -1 \\ -1 & -1 & -1 & -1 \\ 1 & 1 & 1 & 1 \end{pmatrix} \\
&= 0.
\end{aligned}$$

As $|c_{11}| + |c_{22}| + |c_{33}| = 1 \leq 1$, it is a product state in question.

QCE 7.14

Verify that the state

$$|\psi\rangle = \frac{1}{\sqrt{2}} |\beta_{00}\rangle - \frac{1}{\sqrt{2}} |\beta_{01}\rangle$$

is entangled by calculating the Schmidt number.

First, let us rewrite the state:

$$\begin{aligned} |\psi\rangle &= \frac{1}{\sqrt{2}} |\beta_{00}\rangle - \frac{1}{\sqrt{2}} |\beta_{01}\rangle \\ &= \frac{1}{2}(|00\rangle + |11\rangle) - \frac{1}{2}(|01\rangle + |10\rangle) \\ &= \frac{1}{2}(|00\rangle - |01\rangle - |10\rangle + |11\rangle). \end{aligned}$$

Now

$$\begin{aligned} \rho &= |\psi\rangle \langle\psi| \\ &= \frac{1}{4} \begin{pmatrix} |00\rangle - |01\rangle - |10\rangle + |11\rangle \end{pmatrix} \begin{pmatrix} \langle 00| - \langle 01| - \langle 10| + \langle 11| \end{pmatrix} \\ &= \frac{1}{4} \begin{pmatrix} |00\rangle \langle 00| - |00\rangle \langle 01| - |00\rangle \langle 10| + |00\rangle \langle 11| \\ - |01\rangle \langle 00| + |01\rangle \langle 01| + |01\rangle \langle 10| - |01\rangle \langle 11| \\ - |10\rangle \langle 00| + |10\rangle \langle 01| + |10\rangle \langle 10| - |10\rangle \langle 11| \\ + |11\rangle \langle 00| - |11\rangle \langle 01| - |11\rangle \langle 10| + |11\rangle \langle 11| \end{pmatrix} \\ &= \frac{1}{4} \begin{pmatrix} 1 & -1 & -1 & 1 \\ -1 & 1 & 1 & -1 \\ -1 & 1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix}. \end{aligned}$$

Now

$$\begin{aligned} \rho' &= Tr(|\psi\rangle \langle\psi|) \\ &= \langle 0|\psi\rangle \langle\psi|0\rangle + \langle 1|\psi\rangle \langle\psi|1\rangle \\ &= \frac{1}{4}(|0\rangle \langle 0| - |0\rangle \langle 1| - |1\rangle \langle 0| + |1\rangle \langle 1|) \\ &\quad + \frac{1}{4}(|0\rangle \langle 0| - |0\rangle \langle 1| - |1\rangle \langle 0| + |1\rangle \langle 1|) \\ &= \frac{1}{2}(|0\rangle \langle 0| - |0\rangle \langle 1| - |1\rangle \langle 0| + |1\rangle \langle 1|) \\ &= \frac{1}{2} \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix}. \end{aligned}$$

On page 169 of the book, it is told that the above matrix has eigenvalues $\lambda_1 = 1, \lambda_2 = 0$, so the Schmidt number is one and this is a separable state.

QCE 8.1

Describe the action of the Y gate in terms of the Bloch sphere picture.

We have

$$|\psi\rangle = \cos\theta |0\rangle + e^{i\phi} \sin\theta |1\rangle = \begin{pmatrix} \cos\theta \\ e^{i\phi} \sin\theta \end{pmatrix}, \quad Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}.$$

Now

$$\begin{aligned} Y|\psi\rangle &= \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \begin{pmatrix} \cos\theta \\ e^{i\phi} \sin\theta \end{pmatrix} \\ &= \begin{pmatrix} -ie^{i\phi} \sin\theta \\ i \cos\theta \end{pmatrix} \\ &= \begin{pmatrix} -i(\cos\phi + i \sin\phi) \sin\theta \\ i \cos\theta \end{pmatrix} \\ &= \begin{pmatrix} -i \cos\phi \sin\theta + \sin\phi \sin\theta \\ i \cos\theta \end{pmatrix} \end{aligned}$$

QCE 8.2

$$X^{11} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \quad X^{12} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \quad X^{21} = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}, \quad X^{22} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}.$$

The Hadamard basis is

$$|+\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix}, \quad |-\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \end{pmatrix},$$

so

$$X^{11}|+\rangle = \frac{1}{\sqrt{2}}|0\rangle, \quad X^{12}|+\rangle = \frac{1}{\sqrt{2}}|0\rangle, \quad X^{21}|+\rangle = \frac{1}{\sqrt{2}}|1\rangle, \quad X^{22}|+\rangle = \frac{1}{\sqrt{2}}|1\rangle,$$

and

$$X^{11}|-\rangle = \frac{1}{\sqrt{2}}|0\rangle, \quad X^{12}|-\rangle = -\frac{1}{\sqrt{2}}|0\rangle, \quad X^{21}|-\rangle = \frac{1}{\sqrt{2}}|1\rangle, \quad X^{22}|-\rangle = -\frac{1}{\sqrt{2}}|1\rangle.$$

QCE 8.3

Find a way to write the Pauli operators X, Y and Z in terms of the Hubbard operators.

This is a basic matrix shit:

$$\begin{aligned} X &= \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} = X^{12} + X^{21}, \\ Y &= \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} = -iX^{12} + iX^{21} = i(X^{21} - X^{12}), \\ Z &= \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} = X^{11} - X^{22}. \end{aligned}$$

QCE 8.4

Show that the controlled NOT gate is Hermitian and unitary.

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}^{\dagger},$$

so the matrix is Hermitian. Also

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

so the matrix is unitary.

QCE 8.5

Let $|a\rangle = |1\rangle$, and consider the circuit shown in Figure 8.5. Determine which Bell states are generated as output when $|b\rangle = |0\rangle$, $|b\rangle = |1\rangle$.

The Hadamard gate converts $|a\rangle = |1\rangle$ to $|-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$. Also the matrix representation of CNOT is

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

For the first case, we have $|b\rangle = |0\rangle$, so the input qubit is

$$|a\rangle |b\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) |0\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |10\rangle) = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix},$$

and

$$\begin{aligned} CNOT |ab\rangle &= \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix} \\ &= \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ -1 \end{pmatrix} \\ &= |\beta_{10}\rangle. \end{aligned}$$

For the second case, we have $|b\rangle = |1\rangle$, so the input qubit is

$$|a\rangle |b\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) |1\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |11\rangle) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ 0 \\ -1 \end{pmatrix},$$

and

$$\begin{aligned} CNOT |ab\rangle &= \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 0 \\ -1 \end{pmatrix} \\ &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ -1 \\ 0 \end{pmatrix} \\ &= |\beta_{11}\rangle. \end{aligned}$$

QCE 8.6

Write down the matrix representation for the controlled Z gate. Then write down its representation using Dirac notation.

The matrix representation is

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

and in Dirac notation this is $|00\rangle\langle 00| + |01\rangle\langle 01| + |10\rangle\langle 10| - |11\rangle\langle 11|$.

QCE 8.7

$$\begin{aligned} X^2 &= \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\ &= I, \end{aligned}$$

$$\begin{aligned} Y^2 &= \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\ &= I, \end{aligned}$$

$$\begin{aligned}
Z^2 &= \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\
&= I,
\end{aligned}$$

$$\begin{aligned}
S^2 &= \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \\
&= Z,
\end{aligned}$$

$$\begin{aligned}
T^2 &= \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} e^{i\pi/4} \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 \\ 0 & e^{2i\pi/4} \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/2} \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 \\ 0 & \cos \frac{\pi}{2} + i \sin \frac{\pi}{2} \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix} \\
&= S.
\end{aligned}$$

QCE 8.10

By using the tensor product methods developed in chapter 4, show that the controlled-NOT matrix can be generated from $P_0 \otimes I + P_1 \otimes X$.

$$\begin{aligned}
P_0 \otimes I + P_1 \otimes X &= \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \otimes \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \otimes \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \\
&= CNOT.
\end{aligned}$$

QCE 8.11

The operator matrix of the left circuit is that of CNOT:

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

The two “parallel” Hadamard gates may be represented as

$$H^{\otimes 2} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix},$$

so

$$\begin{aligned}
H^{\otimes 2} \times CNOT \times H^{\otimes 2} &= \frac{1}{4} \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix} \\
&= \frac{1}{4} \begin{pmatrix} 4 & 0 & 0 & 0 \\ 0 & 4 & 0 & 0 \\ 0 & 0 & 0 & 4 \\ 0 & 0 & 4 & 0 \end{pmatrix} \\
&= CNOT.
\end{aligned}$$

QCE 8.12

$$\begin{aligned}
V &= (1-i) \frac{I+iX}{2} \\
&= \frac{(1-i)}{2} \left(\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix} \right) \\
&= \frac{(1-i)}{2} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix} \\
&= \frac{1}{2} \begin{pmatrix} 1-i & 1+i \\ 1+i & 1-i \end{pmatrix}
\end{aligned}$$

Now, the conditional CV gate is

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1-i & 1+i \\ 0 & 0 & 1+i & 1-i \end{pmatrix},$$

and the conditional CV^\dagger is

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1+i & 1-i \\ 0 & 0 & 1-i & 1+i \end{pmatrix}.$$

Now the entire circuit can be represented as

$$(I \otimes CV)(CNOT \otimes I)(I \otimes CV^\dagger)(CNOT \otimes I)(I \otimes CV).$$

$$\begin{aligned}
I \otimes CV &= \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \otimes \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1-i & 1+i \\ 0 & 0 & 1+i & 1-i \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1-i & 1+i & 0 & 0 & 0 & 0 \\ 0 & 0 & 1+i & 1-i & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1-i & 1+i \\ 0 & 0 & 0 & 0 & 0 & 0 & 1+i & 1-i \end{pmatrix}.
\end{aligned}$$

$$= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1-i & 1+i & 0 & 0 & 0 & 0 \\ 0 & 0 & 1+i & 1-i & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1-i & 1+i \\ 0 & 0 & 0 & 0 & 0 & 0 & 1+i & 1-i \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}.$$

$$= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & -2i & 0 & 0 & 0 & 0 \\ 0 & 0 & -2i & 2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1+i & 1-i \\ 0 & 0 & 0 & 0 & 0 & 0 & 1-i & 1+i \\ 0 & 0 & 0 & 0 & 1-i & 1+i & 0 & 0 \\ 0 & 0 & 0 & 0 & 1+i & 1-i & 0 & 0 \end{pmatrix}.$$

Finally,

$$\begin{aligned}
& (I \otimes CV)(CNOT \otimes I)(I \otimes CV^\dagger)(CNOT \otimes I)(I \otimes CV) \\
&= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & -2i & 0 & 0 & 0 & 0 \\ 0 & 0 & -2i & 2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1+i & 1-i \\ 0 & 0 & 0 & 0 & 0 & 0 & 1-i & 1+i \\ 0 & 0 & 0 & 0 & 1-i & 1+i & 0 & 0 \\ 0 & 0 & 0 & 0 & 1+i & 1-i & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1-i & 1+i & 0 & 0 & 0 & 0 \\ 0 & 0 & 1+i & 1-i & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1-i & 1+i \\ 0 & 0 & 0 & 0 & 0 & 0 & 1+i & 1-i \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} = \\
& \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2(1-i) - 2i(1+i) & 2(1+i) - 2i(1-i) & 0 & 0 & 0 & 0 \\ 0 & 0 & -2i(1-i) + 2(1+i) & -2i(1+i) + 2(1-i) & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1+i & 1-i & 0 & 0 \\ 0 & 0 & 0 & 0 & 1-i & 1+i & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & (1-i)^2 + (1+i)^2 & 2(1-i)(1+i) \\ 0 & 0 & 0 & 0 & 0 & 0 & 2(1+i)(1-i) & (1+i)^2 + (1-i)^2 \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2-2i-2i+2=4-4i & 0 & 4(1-i) & 0 & 0 & 0 & 0 & 0 \end{pmatrix}
\end{aligned}$$

Problems not solved

- QCE 7.1
- (Ask about QCE 7.9)
- (Ask about QCE 7.14)
- (Ask about QCE 8.1)
- QCE 8.12