Some of the Big Ideas in Quantum Mechanics

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$\{e_i\}$ gives Schrödinger and $\{Ue_i\}$ gives Heisenberg.

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Part II

Quantum Information and computation

Chapter 1

Circuit model

1.1 Qubits

A qubit is an element of $\mathbb{C}P^2$.

1.1.1 $\mathfrak{su}(2)$ and the Pauli matrices

The qubit Hamiltonians are elements of $\mathfrak{su}(2)$. Getting rid of the arbitrary global phase gives us elements of $\mathfrak{su}(2)$.

Lemma II.1. *For all $\sigma \in \mathfrak{su}(2)$, the eigenvalues λ_1, λ_2 are real and $\lambda_1 = -\lambda_2$.*

Proof. For all $\sigma \in \mathfrak{su}(2)$, σ is self-adjoint and $\mathrm{Tr}[\sigma] = \lambda_1 + \lambda_2 = 0$. □

Corollary II.1.1. *For all $\sigma \in \mathfrak{su}(2)$, we have $\|\sigma\|_2 = \sqrt{2}\|\sigma\|$, where $\|\cdot\|_2$ is the Hilbert-Schmidt norm.*

Proof. We have $\|\sigma\|_2 = \sqrt{\lambda_1^2 + \lambda_2^2} = \sqrt{2}|\lambda_1| = \sqrt{2}\|\sigma\|$. □

Corollary II.1.2. *The inner product*

$$\langle \cdot, \cdot \rangle : (\sigma_1, \sigma_2) \mapsto \frac{1}{2}\,\mathrm{Tr}[\sigma_1\sigma_2]$$

on $\mathfrak{su}(2)$ yields the operator norm as the norm associated with this inner product.

Corollary II.1.3. *Let σ be a unit vector in $\mathfrak{su}(2)$. Then σ has eigenvalues ± 1. This means σ is unitary.*

Corollary II.1.4. *There is a bijection between the unit vectors in $\mathfrak{su}(2)$ and the rank-1 projections on $\mathbb{C}^2$ given by $\mathfrak{su}(2)/\mathbb{R} \to \sigma \mapsto E_1^\sigma$, where E_1^σ is the eigenspace of σ associated with eigenvalue $+1$.*

Proof. We construct an inverse of the map. Let P_1 be the orthogonal projector on E_1^σ. Then $\sigma = 2P_1 - \mathrm{id}$. □

Proposition II.2. *Let $\sigma \in \mathfrak{su}(2)$. Then $\sigma^2 = \|\sigma\|^2\,\mathbf{1}$.*

Proof. We have

$$\sigma^2 = \|\sigma\|^2 \left(\frac{\sigma}{\|\sigma\|}\right)^2 = \|\sigma\|^2 \frac{\sigma}{\|\sigma\|} \left(\frac{\sigma}{\|\sigma\|}\right)^* = \|\sigma\|^2 \mathbf{1},$$

where we have used that $\frac{\sigma}{\|\sigma\|}$ is unitary by II.1.3. □

Corollary II.2.1. *The real algebra generated by* $\mathfrak{su}(2)$ *is the Clifford algebra* $\mathrm{Cl}_{3,0}$*. The unit pseudoscalar is* $i\mathbf{1}$*.*

Note that $\mathfrak{su}(2)$ is a Lie algebra and thus closed under the Lie bracket, but not an algebra under operator composition. Thus the algebra generated by $\mathfrak{su}(2)$ is larger than $\mathfrak{su}(2)$ (indeed $\sigma^2 = \|\sigma\|^2 \mathbf{1} \notin \mathfrak{su}(2)$).

Proposition II.3 (Pauli matrices)**.** *The Clifford algebra* $\mathfrak{su}(2)$ *has an orthonormal basis*

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \qquad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad \textit{and} \qquad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

1.1.2 The Bloch sphere

Because $\mathfrak{su}(2)$ is the Clifford algebra $\mathrm{Cl}_{3,0}$, we can use the unit sphere in $\mathbb{R}^3$ to represent the unit vectors in $\mathfrak{su}(2)$. By II.1.4 we can also use it to represent the rank-1 projections on $\mathbb{C}^2$. The unit sphere with as x, y, z axes the Pauli matrices $\sigma_x, \sigma_y, \sigma_z$ is called the Bloch sphere.
TODO image of Bloch sphere.
TODO spherical coordinates: $\cos\theta/2\,|0\rangle + e^{i\phi}\sin\theta/2\,|1\rangle$

Lemma II.4.

$$e^{\phi/2i\sigma}e^{\theta/2i\sigma^\perp}|1\rangle = \cos\theta/2\,|0\rangle + e^{i\phi}\sin\theta/2\,|1\rangle$$

1.2 Gates

1.2.1 Controlled gates

Let H_1, H_2 be two Hilbert spaces. Let P be a projector on H_1 and L an operator on H_2. The operation of L controlled by P is the operation $P \otimes L + (\mathrm{id}_{H_1} - P) \otimes \mathrm{id}_{H_2}$ in $H_1 \otimes H_2 \to H_1 \otimes H_2$.

Chapter 2

Eigenpath traversal

2.1 Quantum Zeno effect

Proposition II.5. *Consider a path of states $|\psi(s)\rangle$ where $s \in [0,1]$. Assume that, for fixed d and all δ,*

$$|\langle\psi(s)|\psi(s+\delta)\rangle|^2 \geq 1 - d^2\delta^2.$$

Then

2.2 Adiabatic quantum computation

2.3 Evolution through measurement

2.3.1 Phase randomisation

$|\psi_0\rangle = |E_0(0)\rangle = \sum_i \alpha_i |E_i(s_1)\rangle$

$$\begin{aligned}
\rho(s_1) &= \frac{1}{T}\int_0^T e^{-iH(s_1)t}|\psi_0\rangle\langle\psi_0|e^{iH(s_1)t}\,\mathrm{d}t \\
&= \sum_{i,j} \alpha_i\alpha_j^* \frac{1}{T}\left(\int_0^T e^{-i(E_i-E_j)t}\,\mathrm{d}t\right)|E_i\rangle\langle E_j| \\
&= \sum_{i,j} \alpha_i\alpha_j^* \left(\frac{i(e^{-i(E_i-E_j)T}-1)}{T(E_i-E_j)}\right)|E_i\rangle\langle E_j|
\end{aligned}$$

Theorem II.6 (Randomised dephasing)**.** *Let $|\psi(s)\rangle$ be a nondegenerate eigenstate of $H(s)$ and $\{\omega_j\}$ the energy differences to the other eigenstates $|\psi_j(s)\rangle$. Let T be a random variable. Then, for all states ρ, we have*

$$\left\|(M_l - e^{-iH(s)T}\rho e^{-iH(s)T}\right\|_{tr} \leq \epsilon = \sup_{\omega_j}|\Phi(\omega_j)|$$

Chapter 3

Variational quantum algorithms

Chapter 4

Algorithms

4.1 Deutsch's problem

4.2 Grover's search algorithm

Suppose we have a set $\mathcal{N}$ of N items, some of which are marked. WLOG we can take $\mathcal{N}$ to be the set of bit strings of length ν. The marked items form a subset $\mathcal{M}$ of size M. Suppose we have an oracle that tells us whether an object is marked or not:

$$f : \mathcal{N} \to \{0,1\} : x \mapsto \begin{cases} 0 & (x \in \mathcal{M}) \\ 1 & (x \notin \mathcal{M}) \end{cases}$$

Now we want to find a marked item. Classically we need to check $\Theta(N/M)$ items on average.

4.2.1 Circuit model

Let $\{|n\rangle \mid n \in \mathcal{N}\}$ be a basis of a Hilbert space $\mathcal{H}_N$ and let $\mathcal{H}_2$ be a qubit space.

4.2.1.1 The oracle

We would like to use the operator

$$U_f : \mathcal{H}_N \to \mathcal{H}_N : |n\rangle \mapsto (-1)^{f(n)} |n\rangle .$$

This can be constructed from the oracle

$$O_f : \mathcal{H}_N \otimes \mathcal{H}_2 \to \mathcal{H}_N \otimes \mathcal{H}_2 : |n\rangle \otimes |q\rangle \mapsto |n\rangle \otimes |f(n) \oplus q\rangle ,$$

where $\oplus$ is addition modulo 2, by preparing the qubit in the superposition $\frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$. Then

$$\begin{aligned} O_f\left(|n\rangle \otimes \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)\right) &= |n\rangle \otimes \frac{1}{\sqrt{2}}(|f(n)\rangle - |f(n) \oplus 1\rangle) \\ &= (-1)^{f(n)} |n\rangle \otimes \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle). \end{aligned}$$

The operator U_f can also be written

$$U_f = \mathrm{id}_{\mathcal{H}_N} - 2 \sum_{m \in \mathcal{M}} |m\rangle\langle m|.$$

4.2.1.2 The algorithm

We construct the an initial state which is a superposition of all possible solutions

$$|\mathcal{N}\rangle = \frac{1}{\sqrt{N}} \sum_{n\in\mathcal{N}} |n\rangle \,.$$

This can be prepared by applying a Hadamard gate W to each qubit in the register.
We also define the state

$$|\mathcal{M}\rangle = \frac{1}{\sqrt{M}} \sum_{m\in\mathcal{M}} |m\rangle \,.$$

We define the operation

$$U_0 = W^{\otimes\nu}(\mathrm{id} - 2|0\rangle\langle 0|)W^{\otimes\nu} = \mathrm{id} - 2|\mathcal{N}\rangle\langle\mathcal{N}|.$$

Now both U_0 and U_f leave span$\{\}$

4.2.2 Analogue Grover

Why does analogue Grover work?

4.2.3 Adiabatic Grover

$$\begin{aligned} H_0 &= \mathbf{1} - |\mathcal{N}\rangle\langle\mathcal{N}| = \mathbb{1} - \mathbb{J}/N \\ H_f &= \mathbf{1} - \sum_{m\in\mathcal{M}} |m\rangle\langle m| = \begin{pmatrix} 0 & 0 \\ 0 & \mathbb{1}_{N-M} \end{pmatrix}. \end{aligned}$$

Then

$$H(s) = (1-s)H_0 + sH_f = \begin{pmatrix} (1-s)\mathbb{1} + \frac{s-1}{N}\mathbb{J} & \frac{s-1}{N}\mathbb{J} \\ \frac{s-1}{N}\mathbb{J} & \mathbb{1} + \frac{s-1}{N}\mathbb{J} \end{pmatrix} = \begin{pmatrix} (1-s)\mathbb{1}_M & 0 \\ 0 & \mathbb{1}_{N-M} \end{pmatrix} + \frac{s-1}{N}\mathbb{J}.$$

Then, setting $A = \begin{pmatrix} (1-s-\lambda)\mathbb{1}_M & 0 \\ 0 & (1-\lambda)\mathbb{1}_{N-M} \end{pmatrix}$

$$\begin{aligned} \det(H(s)-\lambda) &= \det\left(A + \frac{s-1}{N}\mathbb{J}^{n\times 1}\mathbb{J}^{1\times n}\right) \\ &= \det(A)\det\left(\mathbb{1}_N + \frac{s-1}{N}A^{-1}\mathbb{J}^{n\times 1}\mathbb{J}^{1\times n}\right) \\ &= \det(A)\det\left(1 + \frac{s-1}{N}\mathbb{J}^{1\times n}A^{-1}\mathbb{J}^{n\times 1}\right) \\ &= (1-s-\lambda)^M(1-\lambda)^{N-M}\left(1 + \frac{M(s-1)}{(1-s-\lambda)N} + \frac{(N-M)(s-1)}{(1-\lambda)N}\right) \\ &= (1-s-\lambda)^{M-1}(1-\lambda)^{N-M-1}\left(\lambda^2 - \lambda + s(1-s)\frac{N-M}{N}\right), \end{aligned}$$

where we have used the matrix determinant lemma to simplify the calculation.

We see that there are four distinct eigenvalues:

$$\begin{aligned}
\lambda_{0,1} &= \frac{1}{2}\left(1 \pm \frac{\sqrt{N + 4(Ns^2 - Ns - Ms^2 + Ms)}}{\sqrt{N}}\right) && \text{with multiplicity } 1 \\
\lambda_2 &= 1 - s && \text{with multiplicity } M - 1 \\
\lambda_3 &= 1 && \text{with multiplicity } N - M - 1.
\end{aligned}$$

Next we are interested in the eigen vectors associated to $\lambda_{0,1}$. Let Q_1 be a unitary transformation that maps $\mathbb{J}^{M\times 1}$ to $\begin{pmatrix} \sqrt{M} \\ 0 \\ 0 \\ \vdots \end{pmatrix} \in \mathbb{C}^M$. Similarly let Q_2 be a unitary transformation that maps $\mathbb{J}^{(N-M)\times 1}$ to $\begin{pmatrix} \sqrt{N-M} \\ 0 \\ 0 \\ \vdots \end{pmatrix} \in \mathbb{C}^{(N-M)}$ and define $Q = \begin{pmatrix} Q_1 & 0 \\ 0 & Q_2 \end{pmatrix}$, which is also unitary.

Then we have

$$\begin{aligned}
QH(s)Q^{-1} &= \begin{pmatrix} (1-s)\mathbb{1}_M & 0 \\ 0 & \mathbb{1}_{N-M} \end{pmatrix} + \frac{s-1}{N} Q\mathbb{J}^{N\times 1}(\mathbb{J}^{N\times 1})^* Q^* \\
&= \begin{pmatrix} (1-s)\mathbb{1}_M & 0 \\ 0 & \mathbb{1}_{N-M} \end{pmatrix} + \frac{s-1}{N} \begin{pmatrix} \sqrt{M} \\ 0 \\ \vdots \\ 0 \\ \sqrt{N-M} \\ 0 \\ \vdots \end{pmatrix} \begin{pmatrix} \sqrt{M} \\ 0 \\ \vdots \\ 0 \\ \sqrt{N-M} \\ 0 \\ \vdots \end{pmatrix}^* .
\end{aligned}$$

All but two of the eigenvectors are just elements of $\mathcal{N}$. To study the other two we can simplify by "removing the zeros". Now the eigenvalue problem becomes

$$\left(\begin{pmatrix} 1 - s - \lambda_{0,1} & 0 \\ 0 & 1 - \lambda_{0,1} \end{pmatrix} + \frac{s-1}{N} \begin{pmatrix} \sqrt{M} \\ \sqrt{N-M} \end{pmatrix} \begin{pmatrix} \sqrt{M} \\ \sqrt{N-M} \end{pmatrix}^* \right) \mathbf{v} = 0.$$

Setting $\mathbf{v} = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$ gives us the equations

$$\begin{aligned}
0 &= (1 - s - \lambda_{0,1})x_1 + \frac{s-1}{N}(Mx_1 + \sqrt{M}\sqrt{N-M}x_2) \\
0 &= (1 - \lambda_{0,1})x_2 + \frac{s-1}{N}(\sqrt{M}\sqrt{N-M}x_1 + (N-M)x_2)
\end{aligned}$$

reshuffling and dividing these equations gives

$$\frac{(1 - s - \lambda_{0,1})x_1}{(1 - s - \lambda_{0,1})x_2} = \frac{-\frac{s-1}{N}(Mx_1 + \sqrt{M}\sqrt{N-M}x_2)}{-\frac{s-1}{N}(\sqrt{M}\sqrt{N-M}x_1 + (N-M)x_2)} = \frac{\sqrt{M}(\sqrt{M}x_1 + \sqrt{N-M}x_2)}{\sqrt{N-M}(\sqrt{M}x_1 + \sqrt{N-M}x_2)} = \frac{\sqrt{M}}{\sqrt{N-M}}.$$

So we have eigenvectors $\mathbf{v}_{0,1} = (\sqrt{M}(1-\lambda_{0,1}), \sqrt{N-M}(1-s-\lambda_{0,1}))^{\mathrm{T}}$ of $QH(s)Q^{-1}$. The corresponding eigenvectors of $H(s)$ are then given by

$$Q^*\mathbf{v}_{0,1} = \begin{pmatrix} (1-\lambda_{0,1})\mathbb{J}^{M\times 1} \\ (1-s-\lambda_{0,1})\mathbb{J}^{(N-M)\times 1} \end{pmatrix}.$$

For computational ease we will keep on working with the eigenvectors $\mathbf{v}_{0,1}$ of $QH(s)Q^{-1}$. We denote by $|0\rangle$ and $|1\rangle$ the normalisation of $\mathbf{v}_{0,1}$.

4.2.3.1 Poisson projective measurement

The dynamics of the system is governed by the differential equation

$$\frac{\mathrm{d}\rho}{\mathrm{d}s} = \Lambda(|0\rangle\langle 0|\rho|0\rangle\langle 0| + |1\rangle\langle 1|\rho|1\rangle\langle 1| - \rho).$$

Now we can rewrite $\frac{\mathrm{d}\rho}{\mathrm{d}t}$ in the basis $|0\rangle, |1\rangle$: let $i, j, k, l = 0, 1 \mod 2$ with implicit summation

$$\begin{aligned}
\tfrac{\mathrm{d}\rho}{\mathrm{d}s} &= \tfrac{\mathrm{d}}{\mathrm{d}s}\left(|i\rangle\langle i|\rho|j\rangle\langle j|\right) \\
&= \tfrac{\mathrm{d}}{\mathrm{d}s}(\langle i|\rho|j\rangle)|i\rangle\langle j| + \langle i|\rho|j\rangle\tfrac{\mathrm{d}}{\mathrm{d}s}(|i\rangle\langle j|) \\
&= \tfrac{\mathrm{d}}{\mathrm{d}s}(\langle i|\rho|j\rangle)|i\rangle\langle j| + \langle i|\rho|j\rangle|k\rangle\langle k|\tfrac{\mathrm{d}}{\mathrm{d}s}|i\rangle\langle j| - \langle i|\rho|j\rangle|i\rangle\langle j|\tfrac{\mathrm{d}}{\mathrm{d}s}|l\rangle\langle l| \\
&= \tfrac{\mathrm{d}}{\mathrm{d}s}(\langle i|\rho|j\rangle)|i\rangle\langle j| + \langle i|\rho|j\rangle|i+1\rangle\langle i+1|\tfrac{\mathrm{d}}{\mathrm{d}s}|i\rangle\langle j| - \langle i|\rho|j\rangle|i\rangle\langle j|\tfrac{\mathrm{d}}{\mathrm{d}s}|j+1\rangle\langle j+1| \\
&= \left(\tfrac{\mathrm{d}}{\mathrm{d}s}(\langle i|\rho|j\rangle) + \langle i+1|\rho|j\rangle\langle i|\tfrac{\mathrm{d}}{\mathrm{d}s}|i+1\rangle - \langle i|\rho|j+1\rangle\langle j+1|\tfrac{\mathrm{d}}{\mathrm{d}s}|j\rangle\right)|i\rangle\langle j|.
\end{aligned}$$

For each $|i\rangle\langle j|$ we get an equation, four in total. One of these is redundant by the zero trace requirement. Writing $y_{i,j} \coloneqq \langle i|\rho|j\rangle)$ and $\omega_{ij} \coloneqq \langle i|\frac{\mathrm{d}}{\mathrm{d}s}|j\rangle$ the three remaining equations are

$$\begin{aligned}
\tfrac{\mathrm{d}\rho_{00}}{\mathrm{d}s} &= -\rho_{10}\omega_{01} + \rho_{01}\omega_{10} \\
\tfrac{\mathrm{d}\rho_{01}}{\mathrm{d}s} &= -\Lambda\rho_{01} - (1-\rho_{00})\omega_{01} + \rho_{00}\omega_{01} \\
\tfrac{\mathrm{d}\rho_{10}}{\mathrm{d}s} &= -\Lambda\rho_{10} - \rho_{00}\omega_{10} + (1-\rho_{00})\omega_{10}
\end{aligned}$$

Setting $\omega = \omega_{10} = -\omega_{01}$ and $y = \rho_{00} - 1/2$we obtain the equation

$$\frac{\mathrm{d}^2 y}{\mathrm{d}s^2} = \left(\frac{\frac{\mathrm{d}\omega}{\mathrm{d}s}}{\omega} - \Lambda\right)\frac{\mathrm{d}y}{\mathrm{d}s} - 4\omega^2 y.$$

Setting $\mathbf{y} = \begin{pmatrix} y \\ y' \end{pmatrix}$ this second order differential equation is equivalent to the first order system

$$\begin{pmatrix} y \\ y' \end{pmatrix}' = \begin{pmatrix} 0 & 1 \\ -4 & -\Lambda/\omega \end{pmatrix},$$

which is in the form $\mathbf{y}' = A\mathbf{y}$. Now A is similar to $\begin{pmatrix} \omega/\Lambda & 0 \\ -4 & -\Lambda/\omega \end{pmatrix}$, so it is bounded if both Λ and Λ^{-1} are bounded functions.

Then by the Picard-Lindelöf theorem the initial value problem has a unique solution on $[0, 1]$. In addition let y_1 be the solution obtained using Λ_1 and y_2 using Λ_2. Then

$$\Lambda_1 \leq \Lambda_2 \implies y_1 \leq y_2.$$

To see this, we may first remark that

$$\{t \in [0,1] \mid y_1(t) \leq y_2(t) \wedge y_1'(t) \leq y_2'(t)\} = (y_2 - y_1)^{-1}[\,[0,+\infty[\,] \cap (y_2' - y_1')^{-1}[\,[0,+\infty[\,]$$

is a closed and bounded set that contains 0. Let t_1 be its supremum. This means that $y_1(t_1) \leq y_2(t_1)$ and $y_1'(t_1) \leq y_2'(t_1)$, but $y_1(t) > y_2(t)$ or $y_1'(t) > y_2'(t)$ on some open set $]t_1, t_1 + \delta[$.