Quantum Computing
Lecture 1

Bits and Qubits

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What is Quantum Computing?

Aim to use quantum mechanical phenomena that have no classical counterpart for computational purposes.

Central research tasks include:

- *Building devices* — with a specified behaviour.
- *Designing algorithms* — to use the behaviour.

Mediating these two are models of computation.

Bird's eye view

A computer scientist looks at Quantum Computing:

Algorithmic Languages

Theory/complexity

System Architecture

Specified Behaviour

Physics

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Why look at Quantum Computing?

- *The world is quantum*
  - classical models of computation provide a level of abstraction
  - discrete state systems
- *Devices are getting smaller*
  - Moore's law
  - the only descriptions that work on the very small scale are quantum
- *Exploit quantum phenomena*
  - using quantum phenomena may allow us to perform computational tasks that are not otherwise possible/efficient
  - understand capabilities/resources

Course Outline

A total of eight lecturers.

Useful Information

Some useful books:

- Nielsen, M.A. and Chuang, I.L. (2010). *Quantum Computation and Quantum Information*. 2nd ed. Cambridge University Press.
- Mermin, N.D. (2007). *Quantum Computer Science*. CUP.
- Kitaev, A.Y., Shen, A.H. and Vyalyi, M.N. (2002). *Classical and Quantum Computation*. AMS.

Course website:
`http://www.cl.cam.ac.uk/teaching/1516/QuantComp/`

Bits

A building block of classical computational devices is a two-state system.

$$0 \quad \longleftrightarrow \quad 1$$

Indeed, any system with a finite set of *discrete, stable* states, with controlled transitions between them will do.

Qubits

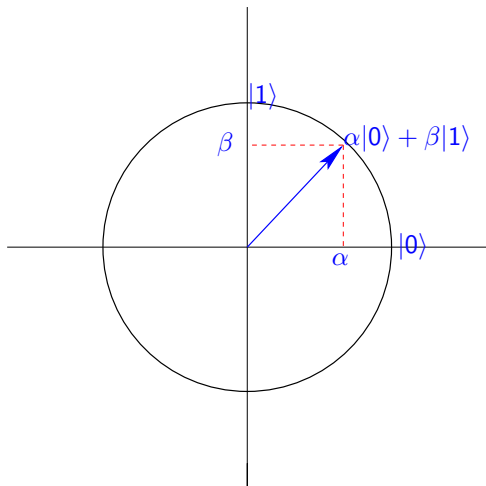Quantum mechanics tells us that any such system can exist in a *superposition* of states.

In general, the state of a *quantum bit* (or *qubit* for short) is described by:

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

where, α and β are complex numbers, satisfying

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

Qubits

A qubit may be visualised as a unit vector on the plane.

In general, however, α and β are *complex* numbers.

Measurement

Any attempt to measure the state

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

results in $|0\rangle$ with probability $|\alpha|^2$, and $|1\rangle$ with probability $|\beta|^2$.

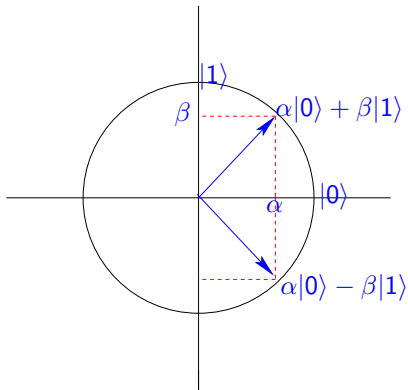*After the measurement, the system is in the measured state!*

That is, further measurements will always yield the same value.

We can only extract one bit of information from the state of a qubit.

Measurement

$\alpha|0\rangle + \beta|1\rangle$ and $\alpha|0\rangle - \beta|1\rangle$ have the same probabilities for their measurement

However, they are *distinct* states which behave differently in terms of how they evolve.

Vectors

Formally, the state of a qubit is a unit vector in $\mathbb{C}^2$—the 2-dimensional complex *vector space*.

The vector $\begin{bmatrix} \alpha \\ \beta \end{bmatrix}$ can be written as

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

where, $|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$ and $|1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$.

$|\phi\rangle$— a *ket*, Dirac notation for vectors.

Basis

Any pair of vectors $|\phi\rangle, |\psi\rangle \in \mathbb{C}^2$ that are linearly independent could serve as a basis.

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

The basis is determined by the measurement process or device.

Most of the time, we assume a standard (orthonormal) basis $|0\rangle$ and $|1\rangle$ is given.

This will be called the *computational basis*

Example

The vector $\begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix}$ measured in the computational basis gives either outcome with probability $1/2$.

Measured in the basis

$$\begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix}, \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{-1}{\sqrt{2}} \end{bmatrix}$$

it gives the first outcome with probability 1.

Entanglement

An n-qubit system can exist in any superposition of the 2^n *basis* states.

$$\alpha_0|000000\rangle + \alpha_1|000001\rangle + \cdots + \alpha_{2^n-1}|111111\rangle$$

$$\text{with } \sum_{i=0}^{2^n-1} |\alpha_i|^2 = 1$$

Sometimes such a state can be decomposed into the states of individual bits

$$\frac{1}{2}(|00\rangle + |01\rangle + |10\rangle + |11\rangle) = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \otimes \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

Entanglement

Compare the two (2-qubit) states:

$$\frac{1}{\sqrt{2}}(|00\rangle + |01\rangle) \quad \text{and} \quad \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

If we measure the first qubit in the first case, we see $|0\rangle$ with probability 1 and the state remains unchanged.

In the second case (*an EPR pair*), measuring the first bit gives $|0\rangle$ or $|1\rangle$ with equal probability. After this, the second qubit is also determined.