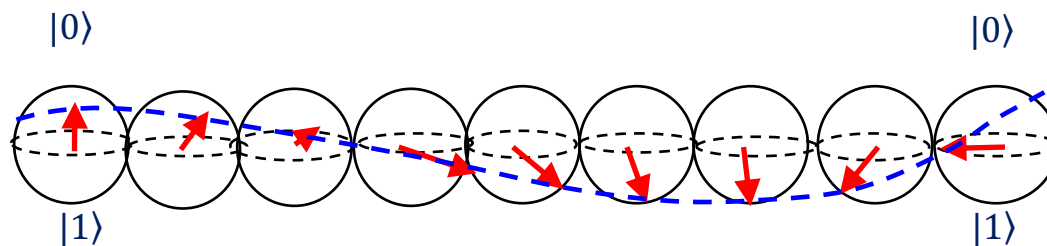


量子科技的崛起、實現的挑戰與機會



國立清華大學物理系
前瞻量子科技研究中心

<http://cqt.site.nthu.edu.tw>

牟中瑜



大綱:

- 量子科技(Quantum Technology)發展的背景
- 量子科技的基本理論與應用
- 量子科技發展概況、產品實現的挑戰
- 世界各國的投入與台灣的發展

量子技術(Quantum Technology) 的突破

量子電腦 [qubit, 量子位元]

HARDWARE > NEWS 之前：幾個量子位元

IBM Inches Closer To Quantum Supremacy With 16- And 17-Qubit Quantum Computers

by Lucian Armasu May 17, 2017 at 9:00 AM



IBM Raises the Bar with a 50-Qubit Quantum Computer

by Will Knight November 10, 2017

CES 2018: Intel's 49-Qubit Chip Shoots for Quantum Supremacy

By Jeremy Hsu (/author/jeremy-hsu)
Posted 9 Jan 2018 | 0:00 GMT

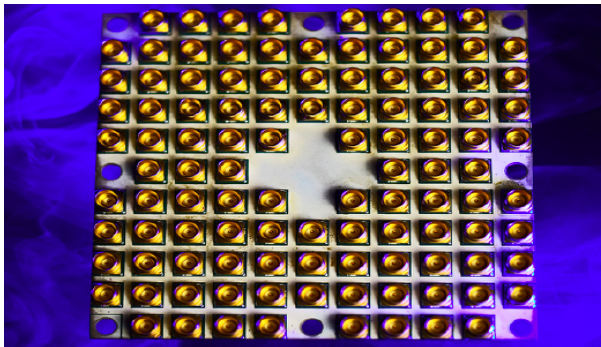


Photo: Intel
Intel's new 49-qubit superconducting quantum test chip is named Tangle Lake.

Intel Roadmap: 1000 qubits 5-7 years

ScienceNews

MAGAZINE OF THE SOCIETY FOR SCIENCE & THE PUBLIC

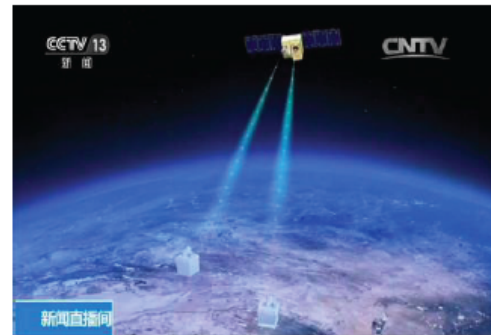
Google moves toward quantum supremacy with 72-qubit computer

Google contends its Bristlecone chip demos 1% error rates for readout, 0.1% for single-qubit gates, and 0.6% for two-qubit gates.



(中央社台北18日電) 2017/06/18 13:52

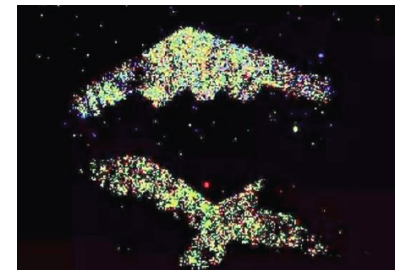
陸首顆量子衛星墨子號 可全球秘密通訊



光子：飛行量子位元

2017年09月07日 07:51 中時電子報

陸量子雷達再突破 F35隱形戰機藏不住

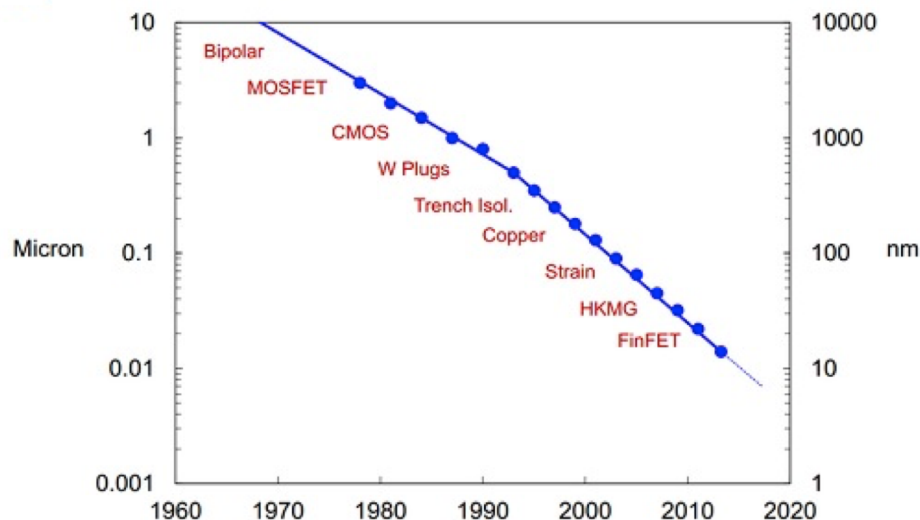


早期的發展：以理論為主

- 1982 R. P. Feynman proposed the idea of a 'quantum computer', a computer that uses the effects of quantum mechanics
- 1984 BB84 Quantum key distribution
- 1994 Shor's algorithm (fast prime factorization)
- 1995 Quantum error correction (Shor and Steane)
- 1996 Grover's searching algorithm
- ...

奈米科技發展的促進

Moore's Law Challenges Below 10nm: Technology, Design and Economic



找尋後半導體時代的技術平台 ➡ 量子資訊 (quantum information science) (~2000年)

所有網頁 圖片 新聞 網上論壇 網誌搜尋 Gmail 更多 ▼

登入



quantum information science

搜尋

進階搜尋 | 使用偏好

☒ 所有網頁 ☐ 中文網頁 ☐ 繁體中文網頁 ☐ 台灣的網頁

所有網頁

約有 **4,440,000** 項符合 quantum information science 的查詢結果，以下是第 1-10 項。共費 0.51 秒。

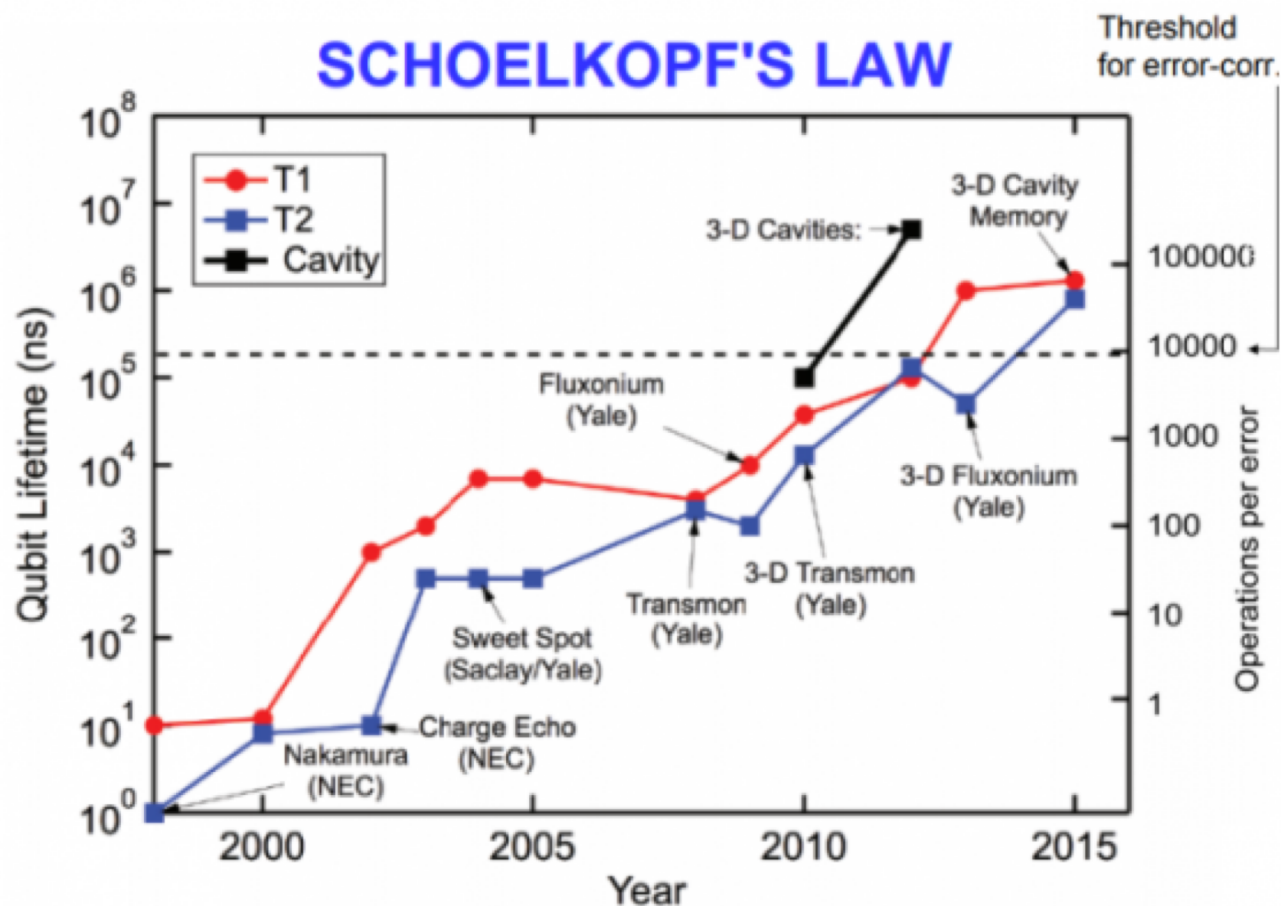
提示：在 [只要搜尋中文（繁體）的結果](#)，在 [使用偏好](#) 可以指定搜尋語言。

[Quantum Information Science](#) - [[翻譯此頁](#)]

Quantum Information Science (QIS) is an emerging field with the potential to cause revolutionary advances in fields of science and engineering involving ...

www.nsf.gov/pubs/2000/nsf00101/nsf00101.htm - 120k - 頁庫存檔 - 類似網頁

超導量子為元的突破



Devoret & Schoelkopf, Science 339, 1169 (2013)

量子科技發展臨界點

量子技術：直接利用量子物理波函數特性進行資訊處理與計算的技術

量子電腦的實現可用以解決傳統電腦難以解決的問題

絕對安全的通訊網路、新藥的研發、新材料的設計、新型態的人工智慧帶來革命性改變

Berkeley Lab Supercomputer Breaks New Ground in
Quantum Computing Simulation

[Michael Feldman](#) | April 12, 2017 11:26 CEST

Cori, the fifth fastest supercomputer in the world, has been used to model a 45-qubit circuit

Classical computers

50 qubit

Quantum supremacy



量子位元數

50量子位元的製作

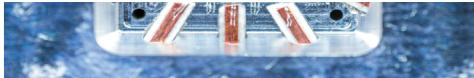


二次量子革命的來臨

因應可能的二次量子革命的來臨...

各國投入大量經費成立相關研究中心或執行大計畫(如 Europe Quantum Manifesto, UK National Quantum Technologies Programme, Centre for Quantum Technologies in Singapore, 美國 DARPA call program ,...)

426 | NATURE | VOL 532 | 28 APRIL 2016



A €1-billion (US\$1.1-billion) European flagship project could advance the state of quantum computing.

Billion-euro boost for quantum tech

Microsoft just upped its multi-million bet on quantum computing

Microsoft pours millions into a new Station Q outpost in Copenhagen.

By Liam Tung | September 7, 2017 -- 13:38 GMT (21:38 GMT+08:00) | Topic: Innovation

The DOE Is Giving Berkeley Lab \$3 Million Annually for Quantum Computing Research

PH Images/Getty Images (http://www.gettyimages.ca/license/68693261)

繼施堯耘之後，又一重量級量子計算學者入職阿里巴巴達摩院

作者 雷鋒網 | 發布日期 2018 年 01 月 18 日 17:35 | 分類 AI 人工智慧, 人力資源, 科技教育 | [Follow](#) [G+](#) [5](#) [分享](#)

2018年03月08日 10:17 [時報資訊](#) 綜合外電報導

新浪財經消息，百度今日宣布成立量子計算研究所，開展量子計算軟件和信息技術應用業務研究，百度計畫在五年內組建世界一流的量子計算研究所，並逐步將量子計算融入到業務中。

量子計算機在金融、醫藥、化學、材料、人工智能等領域具有廣闊的應用空間，有望應用於人工智能（如自動駕駛軟件）等領域。



The Quantum Manifesto calls upon Member States and the European Commission to launch a €1 billion Flagship-scale Initiative in Quantum Technology, preparing for a start in 2018 within the European H2020 research and innovation framework programme.

This initiative aims to place Europe at the forefront of the second quantum revolution now



UNSW
SYDNEY

Newsroom

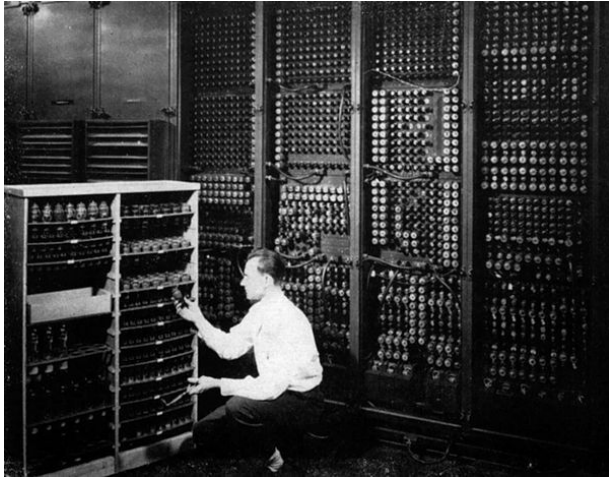
Australia's first quantum computing company launches at UNSW

23 AUG 2017 | UNSW MEDIA

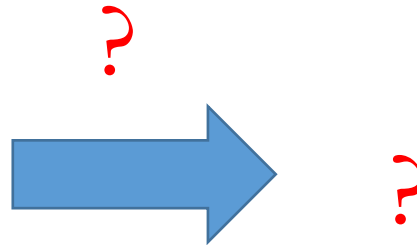
Australia's first quantum computing company, Silicon Quantum Computing Pty Ltd, has been launched to advance the development and commercialisation of UNSW Sydney's world-leading quantum computing technology.

量子技術的憧憬

Eniac 1943



量子技術 (Quantum Technology)



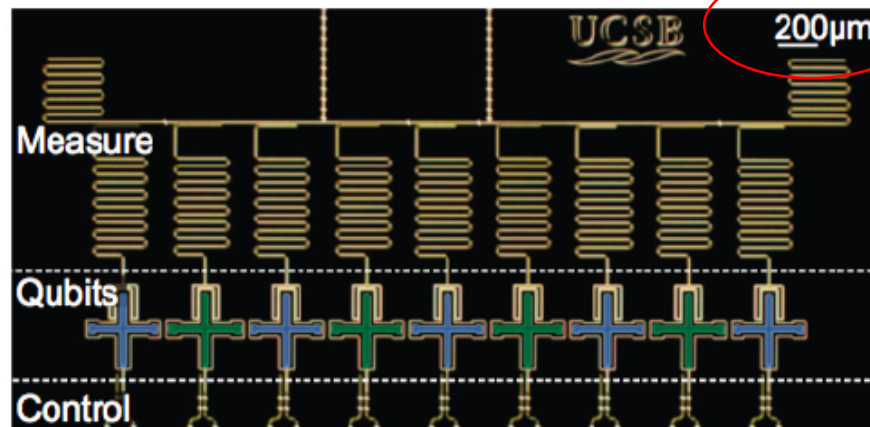
量子技術憧憬的迷失與誤解

台積電3奈米赴美？關鍵在量子電腦

發稿時間：2017/03/20 14:40 最新更新：2017/03/20 15:18

（中央社記者鍾榮峰台北20日電）台積電傳出考量3奈米赴美設廠。工研院IEK主任室計畫副組長楊瑞臨指出，台積電3奈米選址非常關鍵，牽涉布局量子電腦1奈米以下的次奈米新技術和材料。

UCSB/Google nine X-mon qubit processor



➡ 需了解什麼是量子力學能做什麼？

什麼是量子科技？ 量子電腦？

量子科技的基本理論與應用

費因曼最早提出利用量子力學做計算(1982)



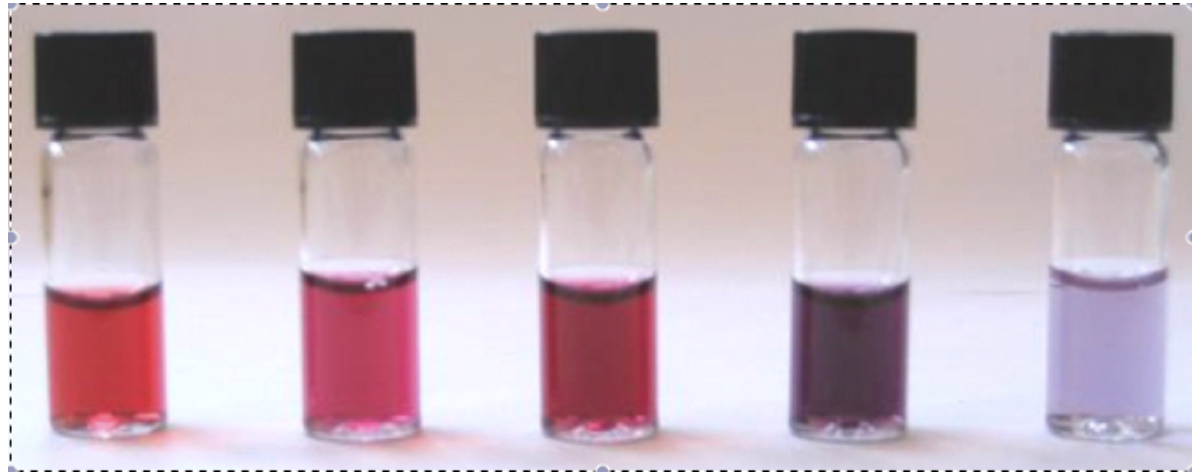
費因曼
(1965 諾貝爾物理獎)

但費因曼也說過

I think that it is fair to say that no one understands the quantum theory...

典型的量子現象

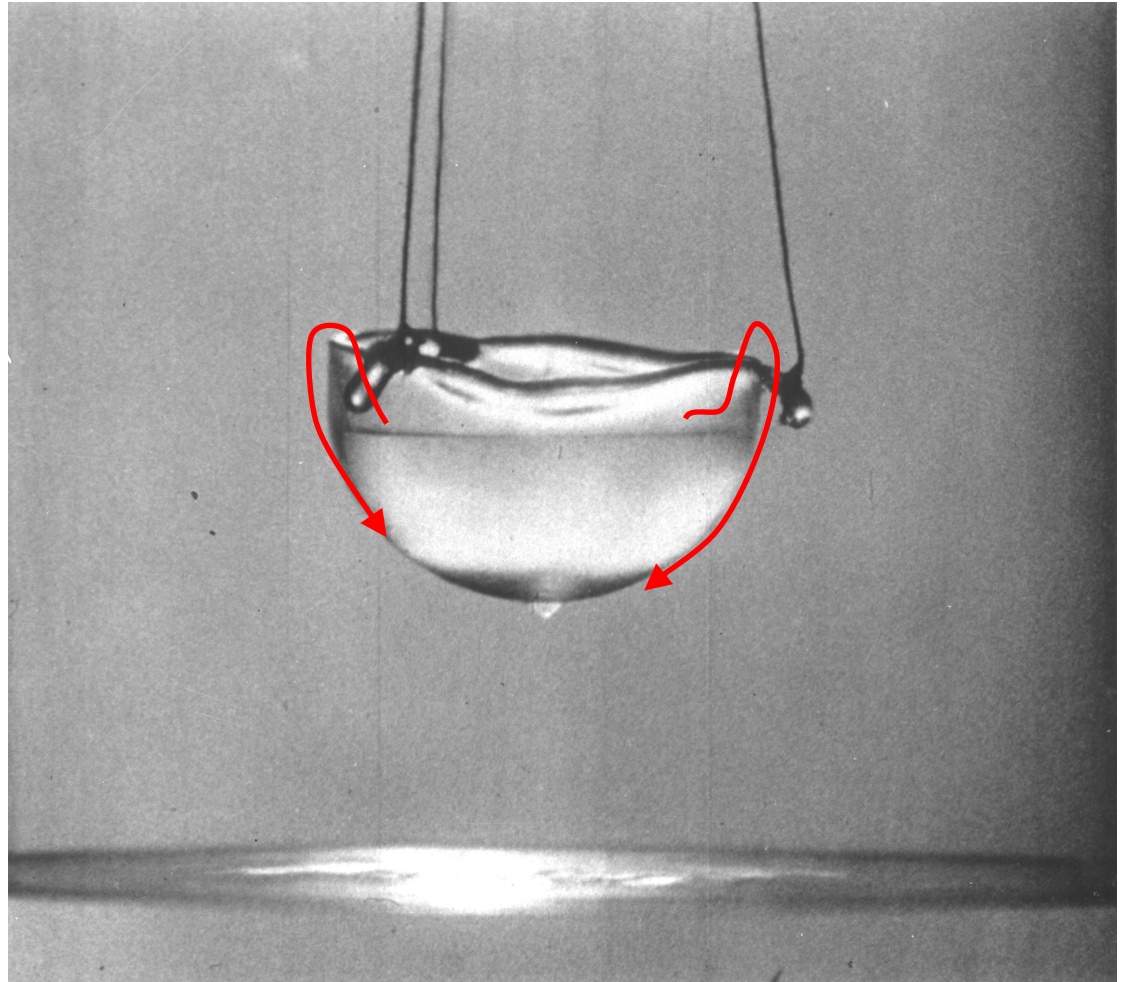
金子不再
閃閃發亮



→ 不是二次量子革命的重點

巨觀的量子現象：需低溫、同調

自動爬出的液態氦



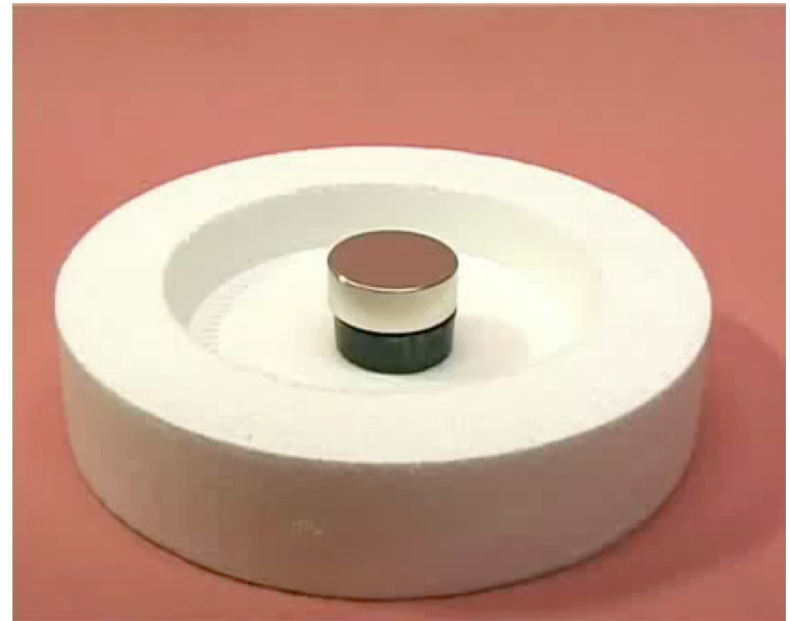
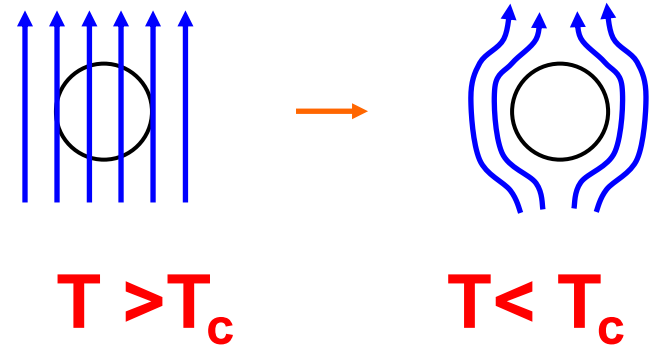
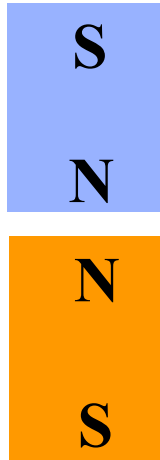
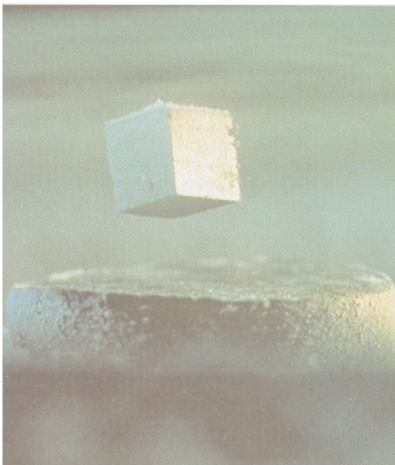
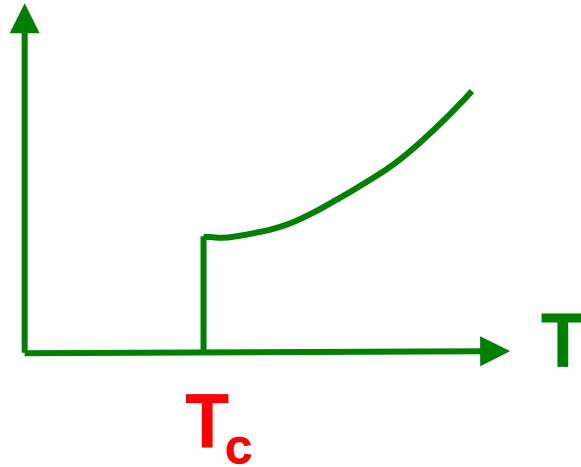
<http://www.youtube.com/watch?v=2Z6UJbwxBZI>

<https://youtu.be/2Z6UJbwxBZI>



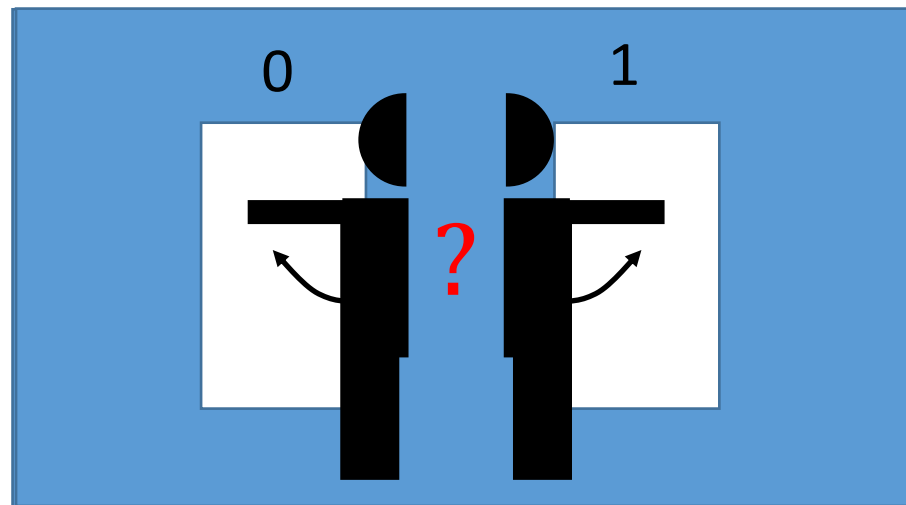
巨觀量子現象：超導

電阻



什麼是量子力學？

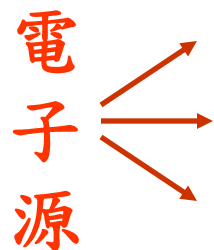
用以描述同時通過兩個門
(量子位元)的質點力學



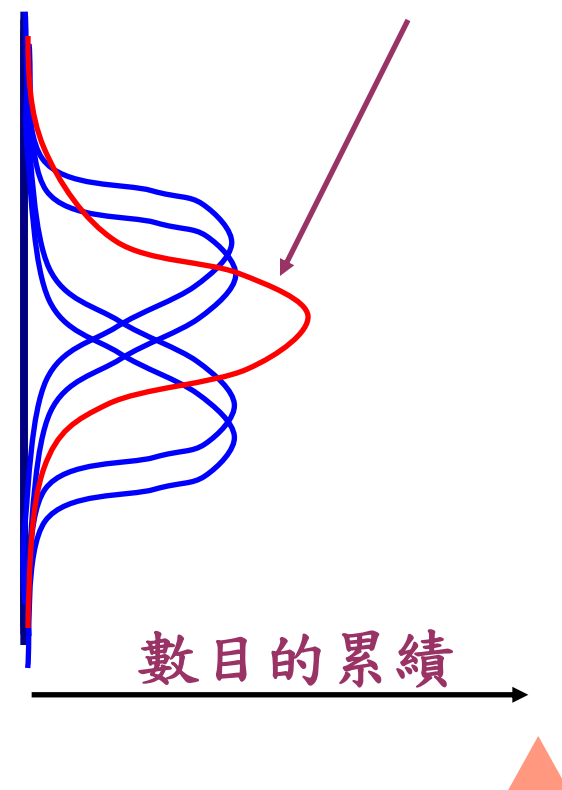
讓我們來檢驗同時通過兩個門這件事：

通過其中一個門的期待(相加)

電子源

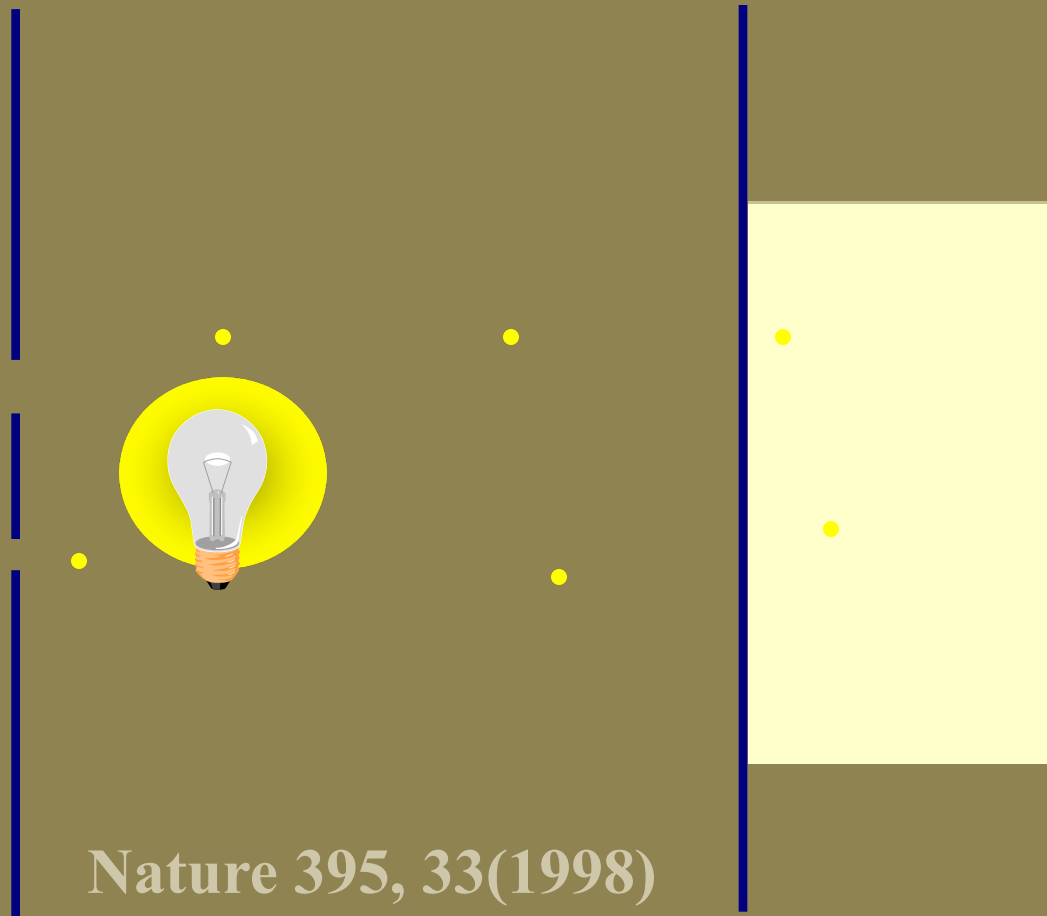


The diagram shows a vertical blue line representing a barrier. To its left, the text '電子源' (Electron Source) is written vertically in red. Three red arrows point from this text towards the barrier, indicating the direction of particle emission.



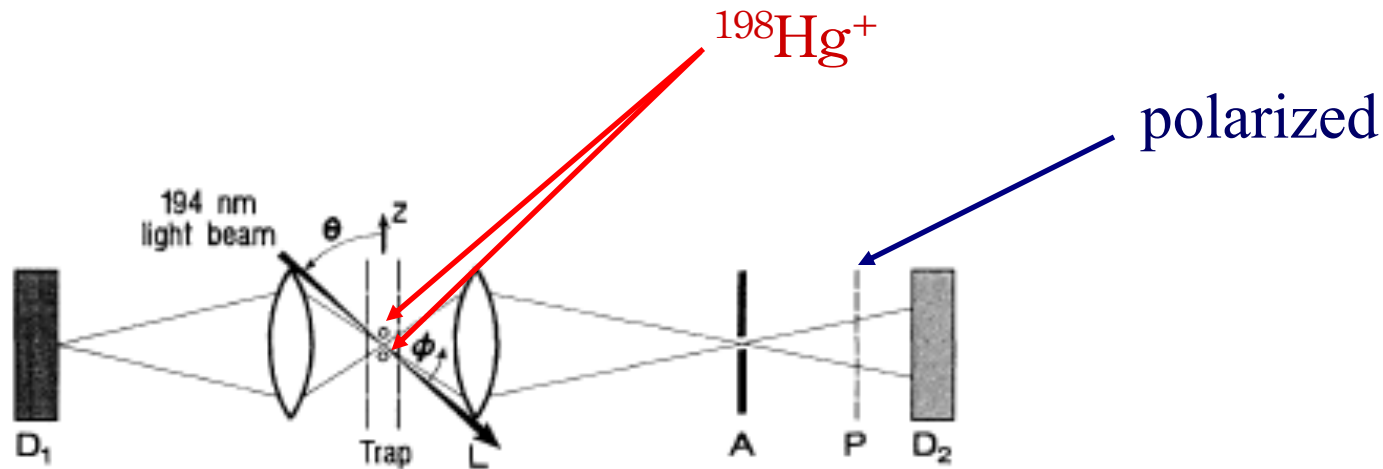
走哪個門實驗(which-way experiment)

電
子
源



Nature 395, 33(1998)
PRL70,2359(1993)

走哪一個門實驗



Phys. Rev. Lett. 70,2359(1993)

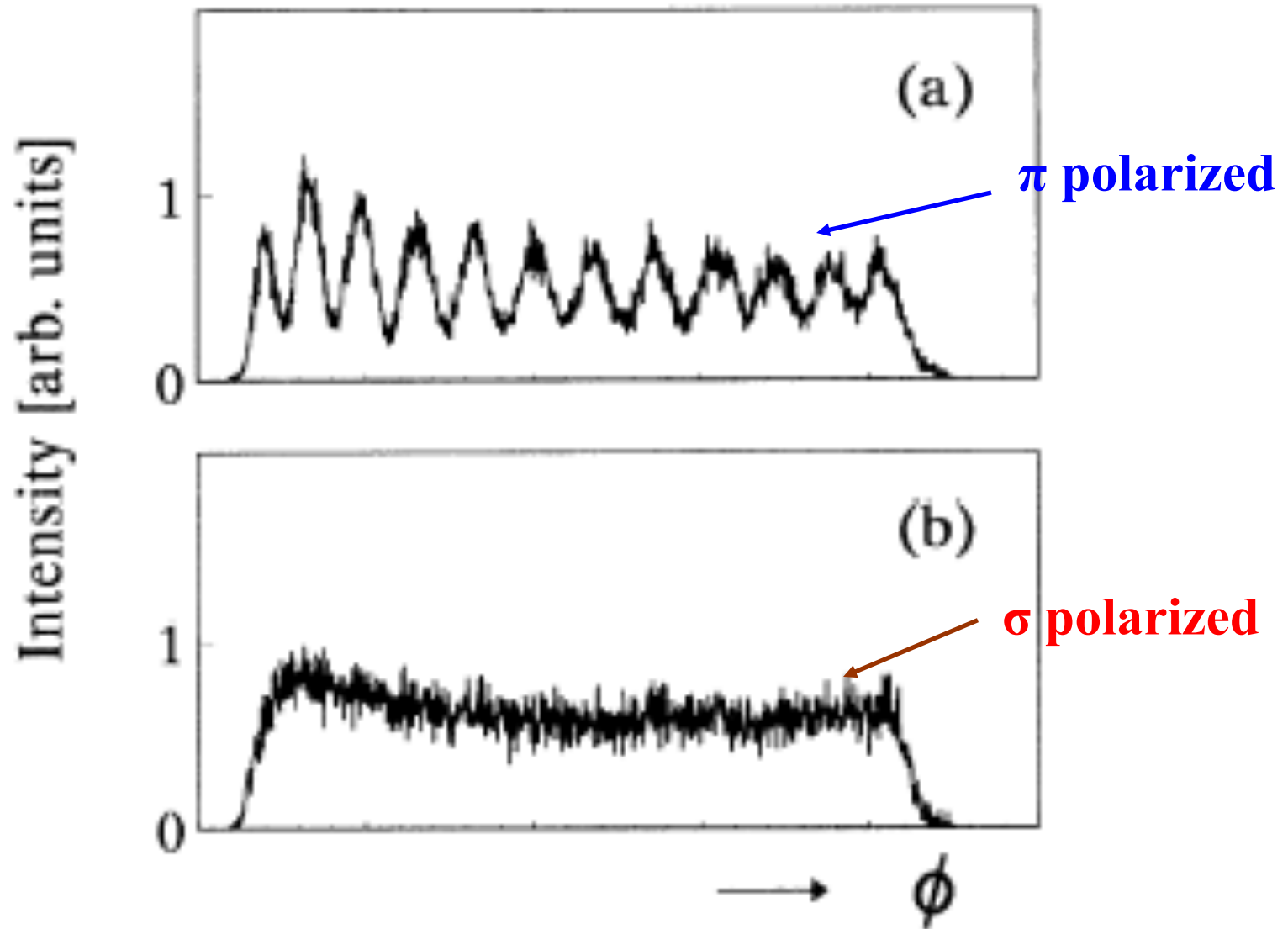
**Ground state: $6s^2S_{1/2}$, Excited state: $6p^2P_{1/2}$
degenerate: m_J**

Photons: σ & π polarized

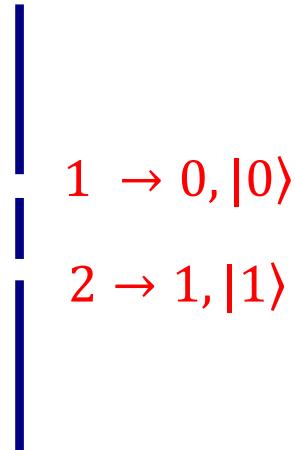
π : $\Delta m_J = 0$ two atoms are in the same state

σ : $\Delta |m_J| = 1$ two atoms are not in the same state

測量時只能測到通過其中一個門



全新的概念：量子位元



古典電腦位元：不是 0 就是 1

量子位元：可同時是1 也是 0

測量時只能測到 0或1

雙狹縫 $\Rightarrow \frac{|1\rangle + |0\rangle}{\sqrt{2}}$



疊加原理 $\Psi = \Psi_1 + \Psi_2$

量子位元的優勢

* 更寬廣的操作空間：

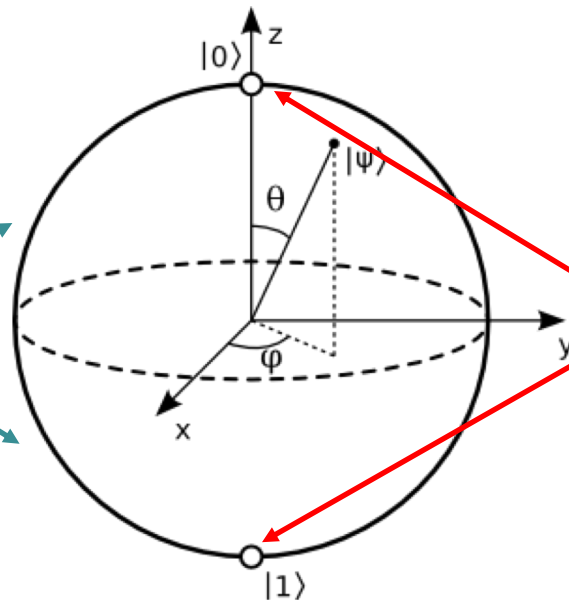
古典電腦位元：不是 0 就是 1

量子位元：可同時是 1 也是 0

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle = \cos\frac{\theta}{2}|1\rangle + e^{i\phi}\sin\frac{\theta}{2}|0\rangle$$

$|\alpha|^2$ 為出現 0 的機會
 $|\beta|^2$ 為出現 1 的機會
 $|\alpha|^2 + |\beta|^2 = 1$

量子：整個球面

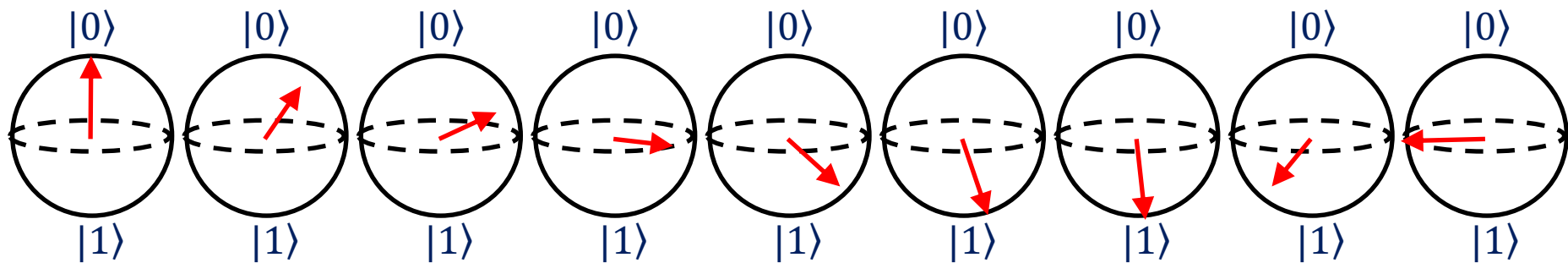


古典位元：2點

50 個量子位元：量子科技發展臨界點

50 個量子位元

$$(\alpha_1|0\rangle + \beta_1|1\rangle) \times (\alpha_2|0\rangle + \beta_2|1\rangle) \times \cdots \times (\alpha_{50}|0\rangle + \beta_{50}|1\rangle) \\ = c_1|00 \dots 000\rangle + c_2|00\dots 001\rangle + c_3|00\dots 010\rangle + \cdots + c_{2^{50}}|11\dots 111\rangle$$



運作的空間： 2^{50} 個實數 $c_1, c_2, \cdots, c_{2^{50}}$

每一個 floating point number 需 4 個 byte
 $\Rightarrow$ 需 $4 \times 2^{50} = 4.5$ petabyte (10^6 Gbyte) 描述

五大量子效應與量子技術

第一次量子革命

干涉 ▲

量子化 - 能階：半導體 ▲

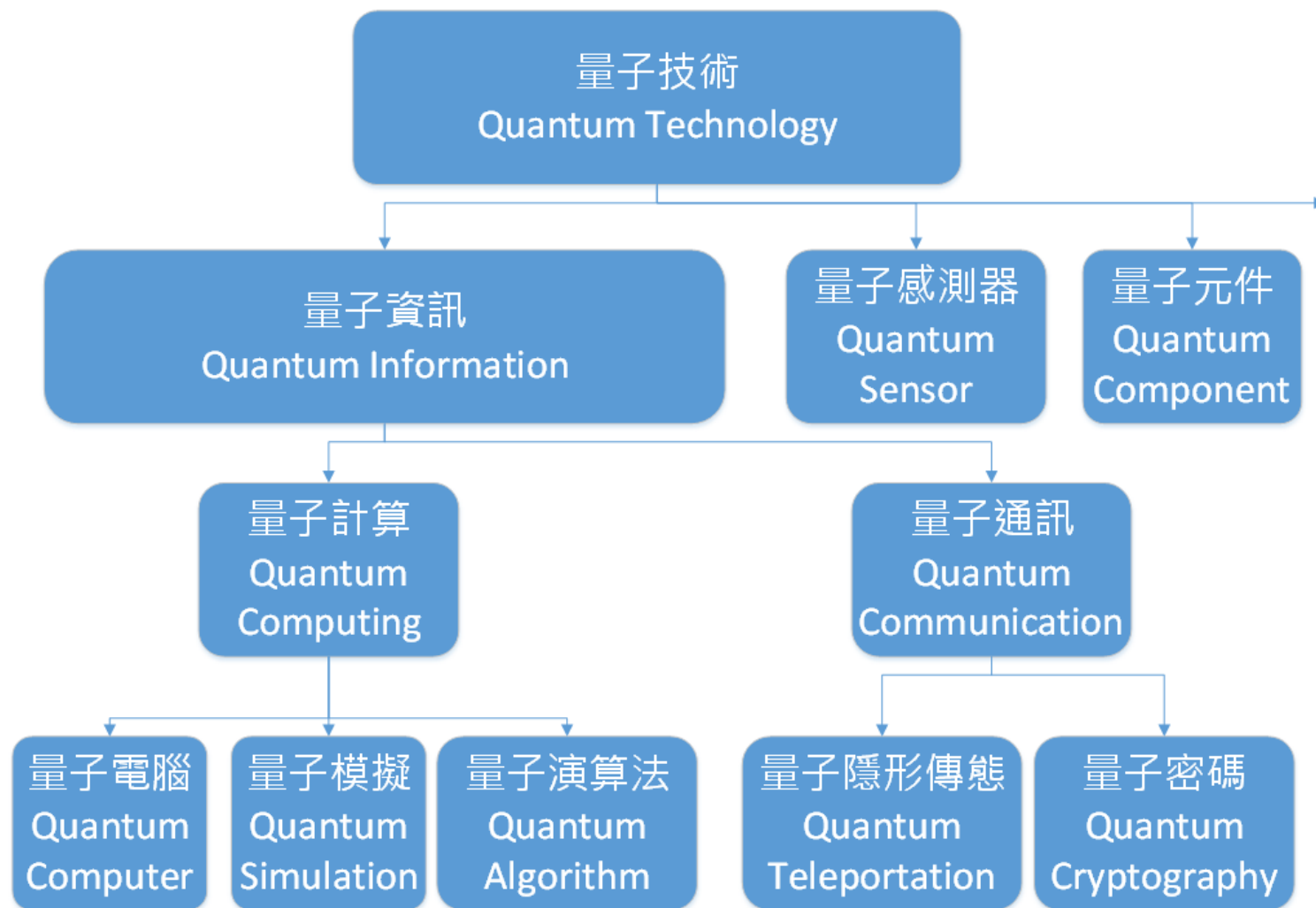
穿隧效應 ▲

自旋：自旋電子學(spintronics) ▲

糾纏 (entanglement) ▲

2次
量子革命

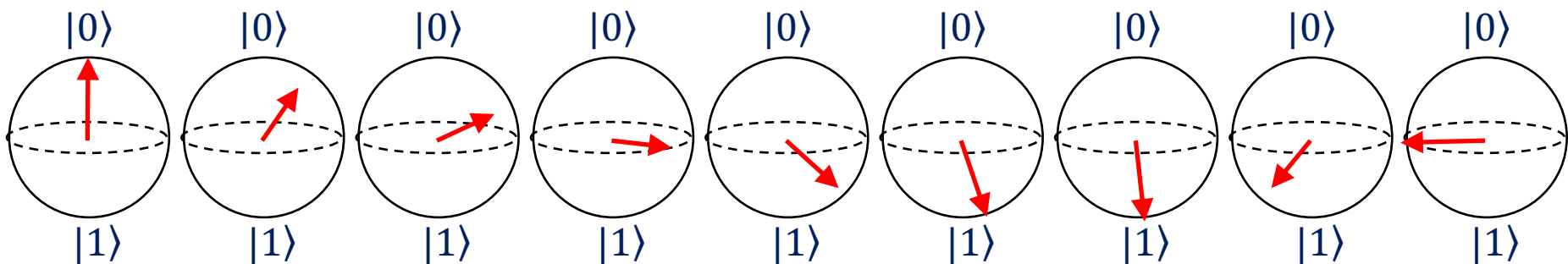
量子科技



量子演算法與計算

----利用巨大的向量空間加速找尋答案 (quantum speed up)

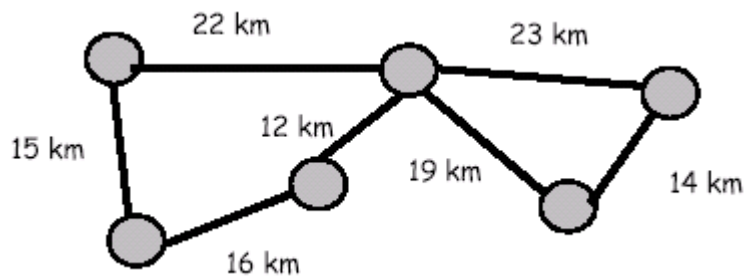
$$\begin{aligned} &(\alpha_1|0\rangle + \beta_1|1\rangle) \times (\alpha_2|0\rangle + \beta_2|1\rangle) \times \cdots \times (\alpha_{50}|0\rangle + \beta_{50}|1\rangle) \times \cdots \\ &= c_1|00 \dots 000\rangle + c_2|00..001\rangle + c_3|00..010\rangle + \cdots \end{aligned}$$



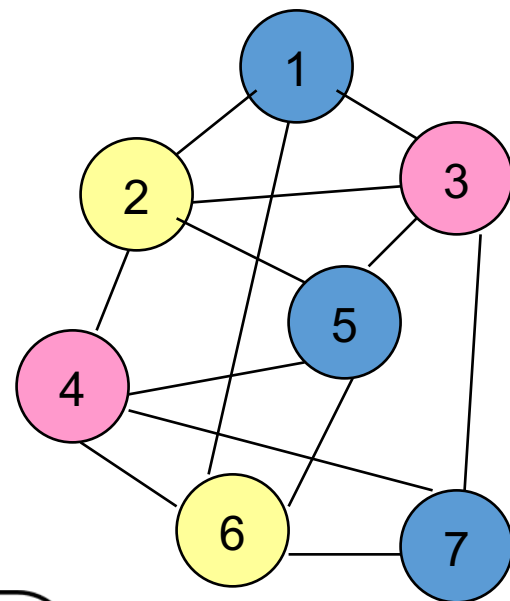
運作的向量空間： $(c_1, c_2, \cdots)$

可能的應用...

推銷員的旅程問題 (Traveling Salesperson Problem)



圖色問題

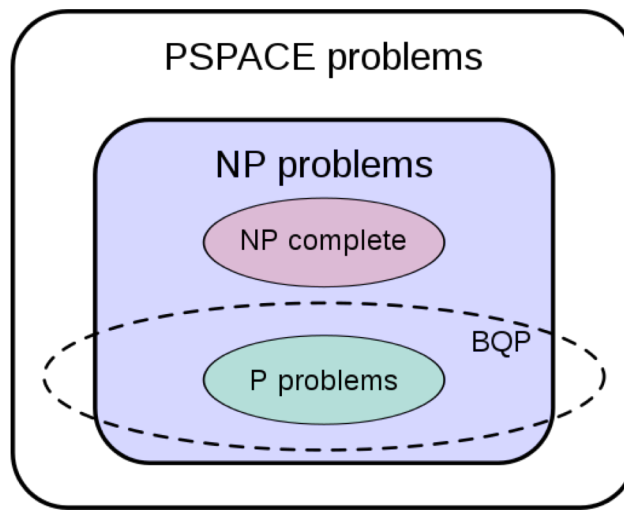


量子計算：判斷大質數問題、破解密碼
判斷 $2^{50} + 1 = \text{質數?}$ 156 versus 1.8×10^6

Computation complexity classes

NP = nondeterministic polynomial time

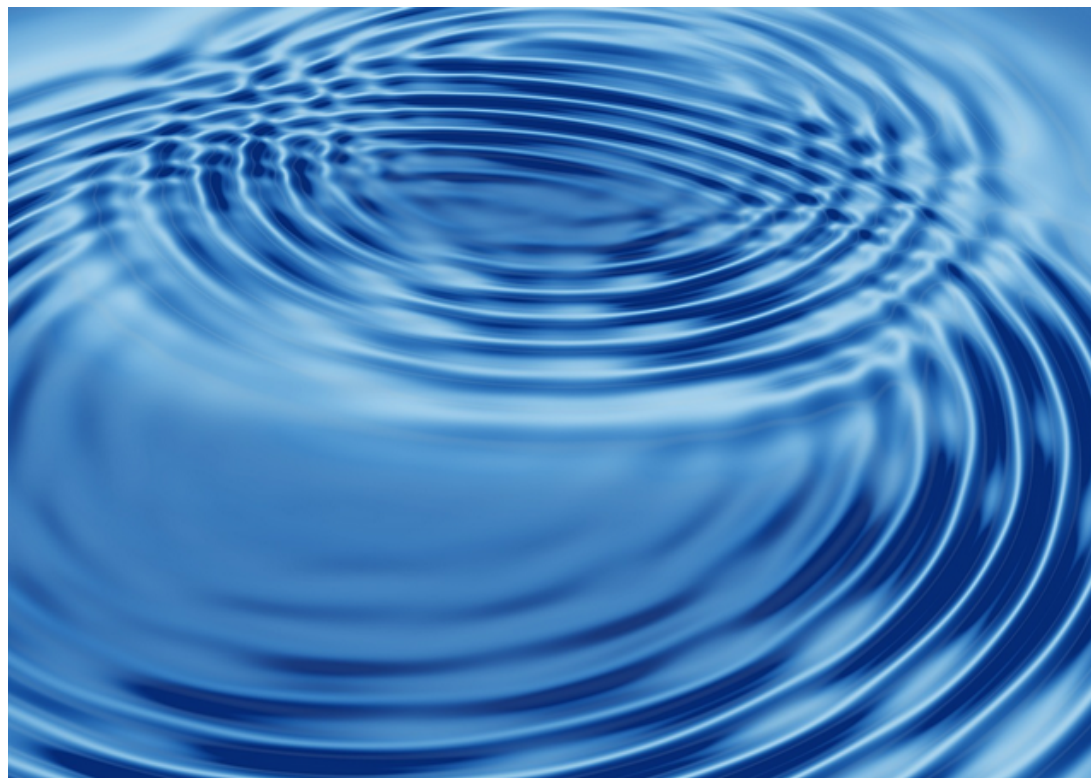
BQP = bounded-error (correct probability at least $2/3$) quantum polynomial time



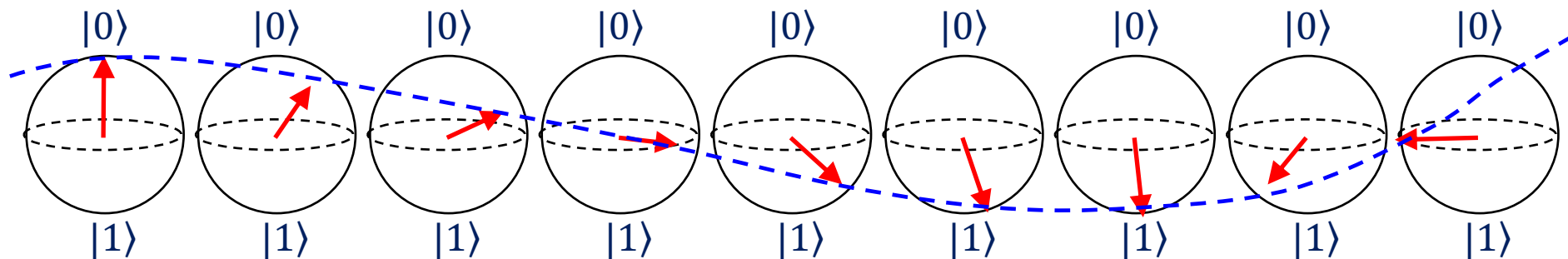
給定一著色及給定 x
著色規則： $f(x) = 1$ or $f(x) = 0$

量子力學：

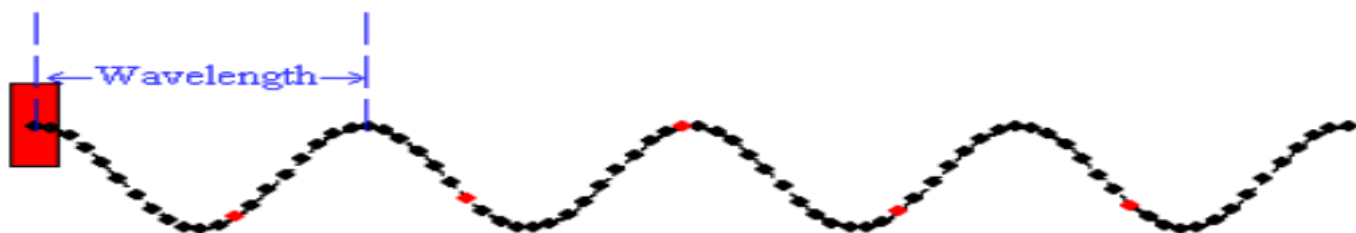
物質皆須以波描述 - 物質波



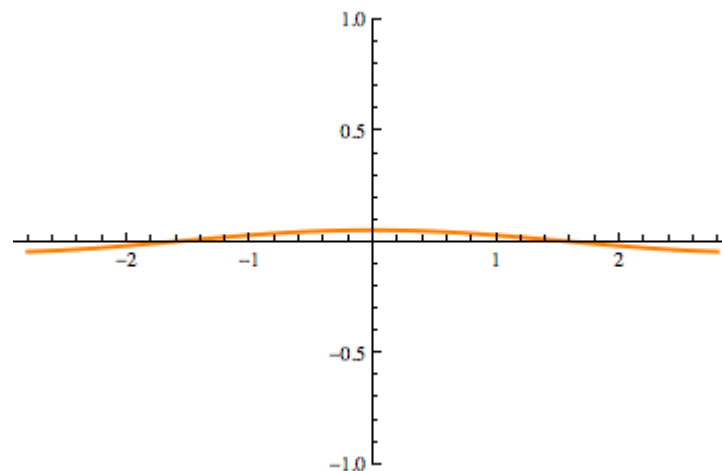
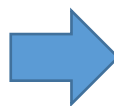
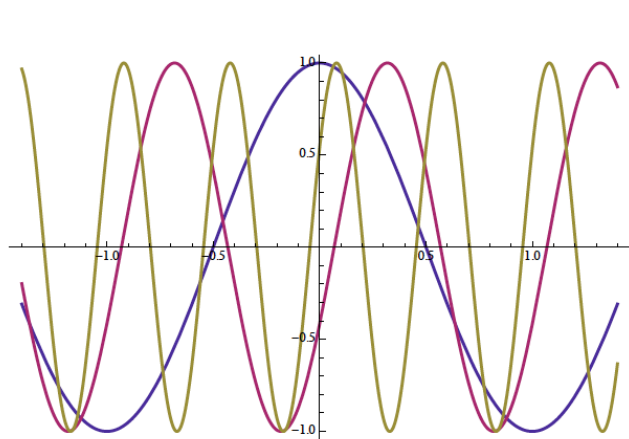
波動：集體處理、可疊加



Transverse Wave

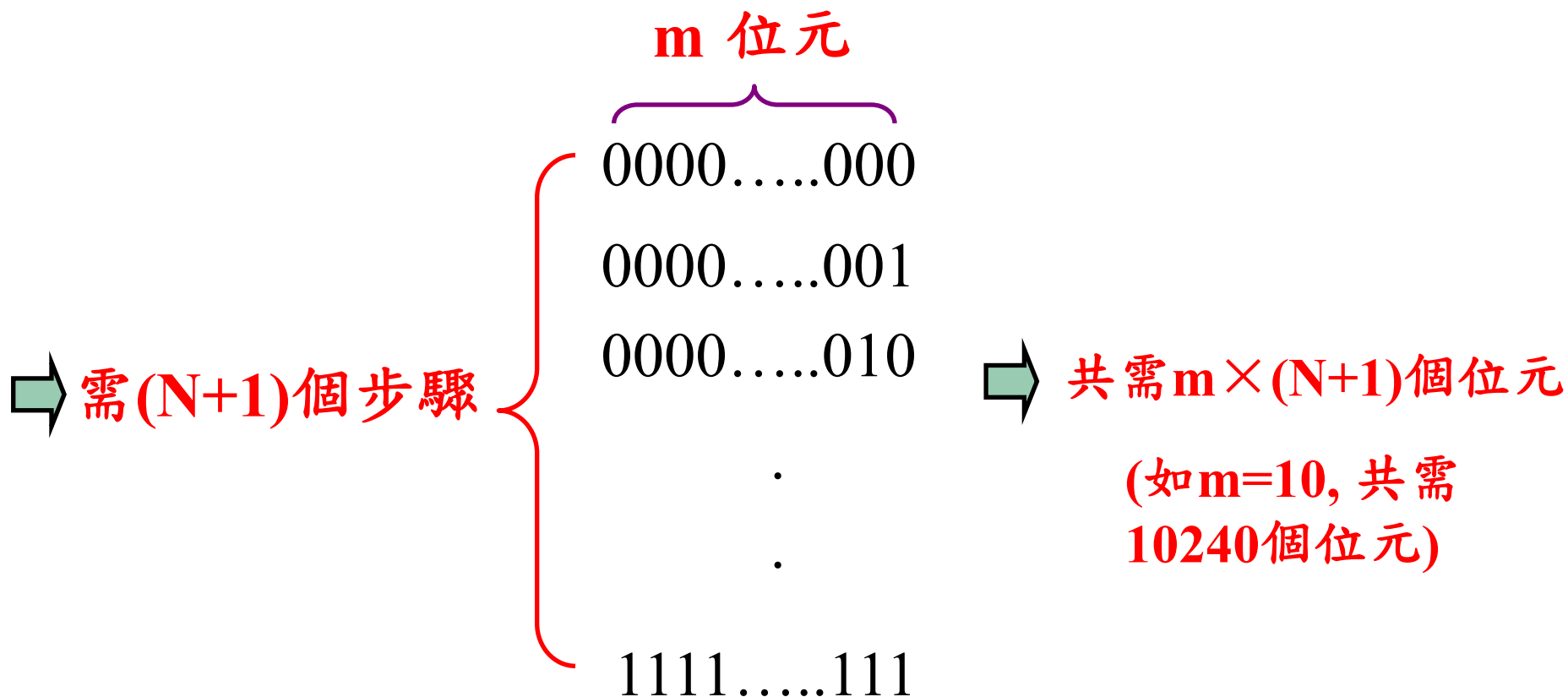


isvr



牽一髮動全身的量子平行處理

古典平行化: 產生 $0, 1, 2, 3, \dots, N=2^m-1$



量子平行化：只需m個量子位元

m組
雙狹縫

$$\left\{ \begin{array}{l} | \quad = \frac{|1\rangle + |0\rangle}{\sqrt{2}} \\ | \quad = \frac{|1\rangle + |0\rangle}{\sqrt{2}} \\ \cdot \quad \cdot \\ \cdot \quad \cdot \\ | \quad = \frac{|1\rangle + |0\rangle}{\sqrt{2}} \end{array} \right.$$

可用

$$\frac{|1\rangle + |0\rangle}{\sqrt{2}} \times \frac{|1\rangle + |0\rangle}{\sqrt{2}} \times \dots \times \frac{|1\rangle + |0\rangle}{\sqrt{2}}$$

代表

一次產生 $0,1,2,3,\dots,N=2^m-1$

m 組量子位元

$$\frac{|1\rangle+|0\rangle}{\sqrt{2}} \times \frac{|1\rangle+|0\rangle}{\sqrt{2}} \times \frac{|1\rangle+|0\rangle}{\sqrt{2}} \times \dots \times \frac{|1\rangle+|0\rangle}{\sqrt{2}} \times \frac{|1\rangle+|0\rangle}{\sqrt{2}}$$
$$= \frac{1}{2^m} [|000\dots000\rangle + |000\dots001\rangle + |000\dots010\rangle + \dots + |111\dots111\rangle]$$

$0,1,2,3,\dots,N=2^m-1$

量子平行處理：可集體處理 $0,1,2,3,\dots,N=2^m-1$

$$Q = \frac{1}{2^m} [|\underline{000}\dots000\rangle + |\underline{000}\dots001\rangle + |\underline{000}\dots010\rangle + \dots + |111\dots111\rangle]$$
$$= \frac{1}{2^m} [|0\rangle + |1\rangle + |2\rangle + \dots + |N\rangle]$$

第一位元 $|0\rangle \Rightarrow \left| \begin{array}{c} | \\ \vdots \\ | \end{array} \right\rangle = \frac{|1\rangle + |0\rangle}{\sqrt{2}} \Rightarrow \text{牽一髮動全身!}$

$$Q \Rightarrow \frac{1}{2^m} \left[\frac{1}{\sqrt{2}} |0\rangle + \frac{1}{\sqrt{2}} |1\rangle + \frac{1}{\sqrt{2}} |2\rangle + \dots + \left(1 + \frac{1}{\sqrt{2}}\right) |N\rangle \right]$$

量子演算法較有效率!

例：3 個量子位元的量子平行運算

$$c_1|000\rangle + c_2|001\rangle + c_3|010\rangle + c_4|011\rangle + c_5|100\rangle + c_6|101\rangle + c_7|110\rangle + c_8|111\rangle$$

代表 $c_1, c_2, c_3, \dots, c_8$ 8個數

σ_x 運作第一個位元： $0 \rightarrow 1, 1 \rightarrow 0$

$$(c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8) \rightarrow (c_5, c_6, c_7, c_8, c_1, c_2, c_3, c_4)$$

$$\text{旋轉45度: } |0\rangle \rightarrow \frac{|0\rangle + |1\rangle}{\sqrt{2}}, |1\rangle \rightarrow \frac{-|0\rangle + |1\rangle}{\sqrt{2}}$$

$$(c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8) \rightarrow \frac{1}{\sqrt{2}}(c_1 - c_5, c_2 - c_6, c_3 - c_7, c_4 - c_8, c_1 + c_5, c_2 + c_6, c_3 + c_7, c_4 + c_8)$$

Universal Quantum Gates

古典電腦 : AND, OR, NOT (combination of NAND) 建構所有邏輯運算

量子電腦: any U ($UU^\dagger = 1$) can be decomposed into ..

$$\frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \quad (\text{Hadamard}) \quad \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix} \quad (\pi/8)$$

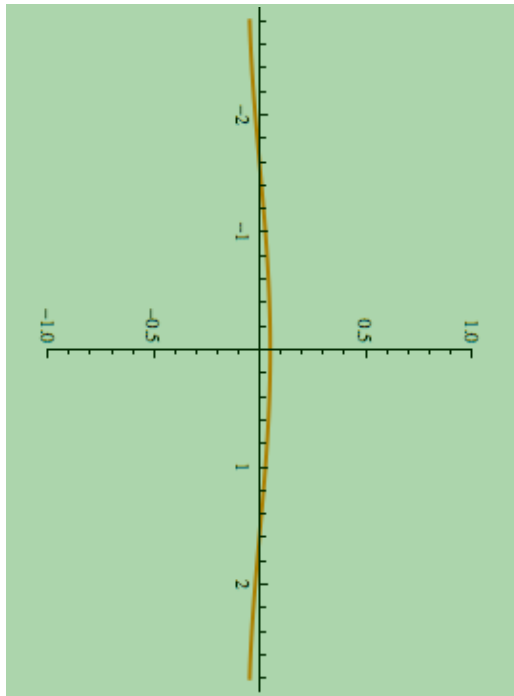
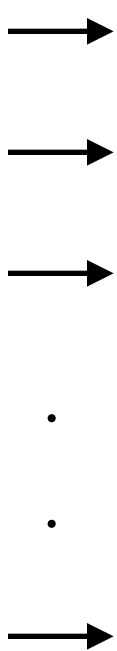
$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \quad (\text{control-not})$$

$|00\rangle \rightarrow |00\rangle \quad |01\rangle \rightarrow |01\rangle$
 $|10\rangle \rightarrow |11\rangle \quad |11\rangle \rightarrow |10\rangle$

量子演算法

=量子平行處理+機率

量子平行
處理器



正確答案的機率最大



$|0000\dots000\rangle$



$|0000\dots001\rangle$



$|0000\dots010\rangle$

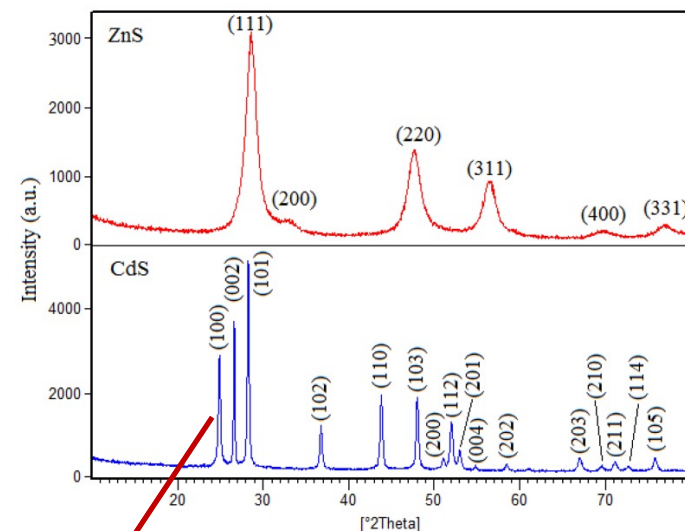
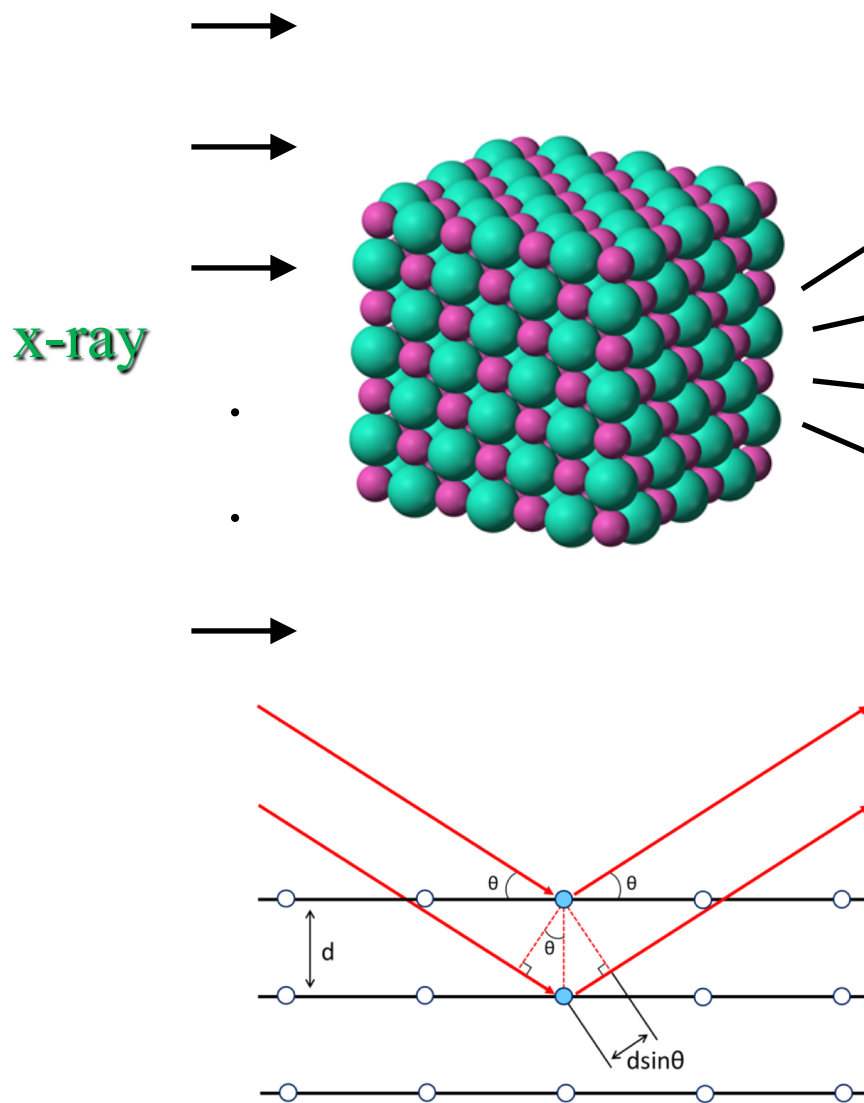


$|0110\dots010\rangle$



$|1111\dots111\rangle$

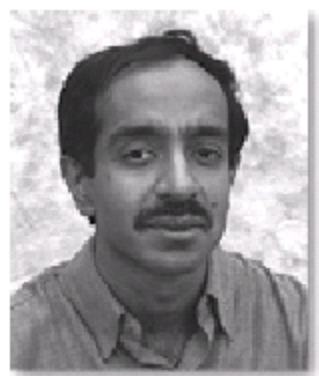
X-ray 繞射：最早的量子計算



peak : 建設性干涉

$$d \sin \theta = n \lambda \quad e^{i \vec{k} \cdot \vec{r}} \text{ 同相位}$$

決定晶體的週期 d



例：量子搜索術 (Grover algorithm)

Lov K. Grover

在 $x=0,1,2,3,\dots,N$ (如電話簿) 中找出所要的資料

設所要的資料可以 $f(x) = 1$ (標示函數) 標示, 其他的資料則滿足 $f(x) = 0$

$$Q = \frac{1}{2^m} [|0\rangle + |1\rangle + |2\rangle + \dots + |N\rangle]$$

$$\Rightarrow \frac{1}{2^m} \left[\underbrace{(-1)^{f(0)} |0\rangle + (-1)^{f(1)} |1\rangle + (-1)^{f(2)} |2\rangle + \dots + (-1)^{f(N)} |N\rangle}_{\text{Grover's iteration}} \right]$$

古典一個一個搜查： $O(N)$

量子搜索策略

標示函數(oracle)

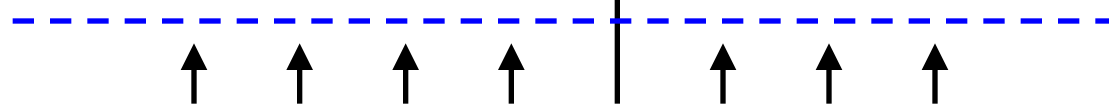
$|Q\rangle$

已知的狀態, 找出↓

平均值



對平均值
值翻轉

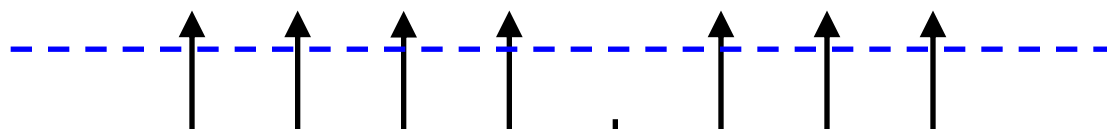


量子搜索：可集體處理 $0,1,2,3,\dots,N$

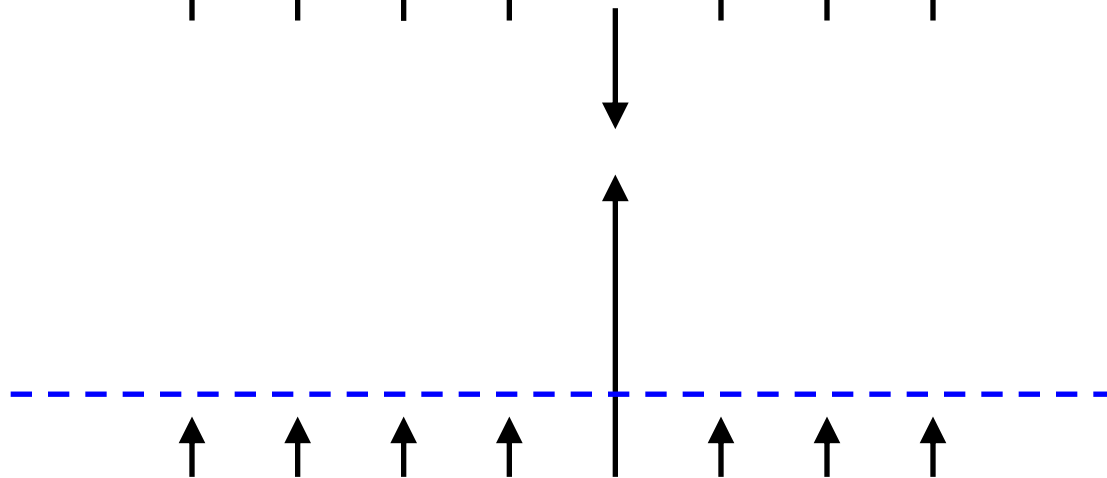
可證明：只需翻轉 $\sqrt{N}$ 次，

如 $\sqrt{10000} = 100 < N = 10000$

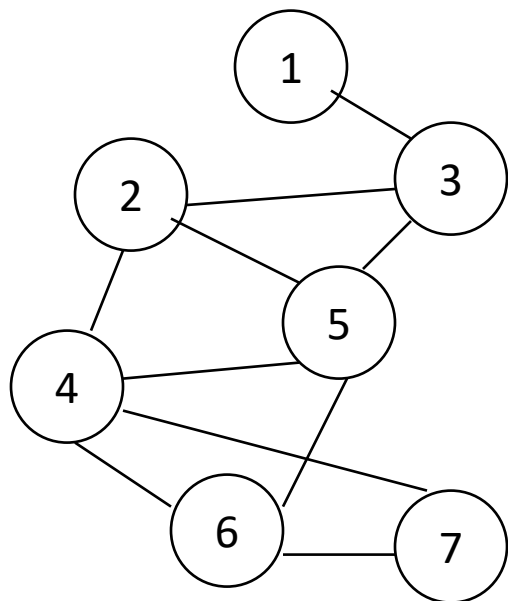
平均值



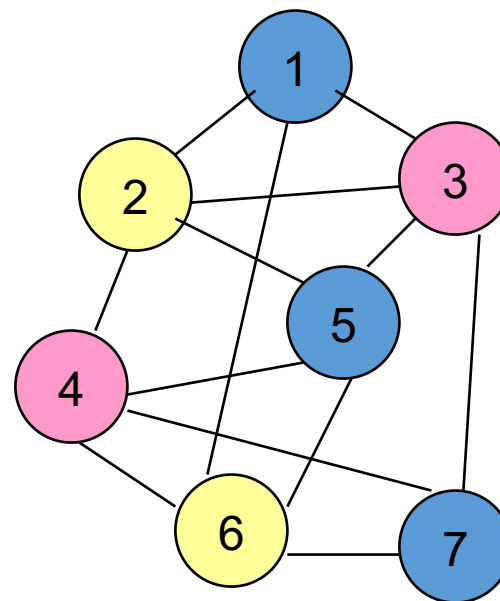
對平均值
翻轉



應用：圖色問題



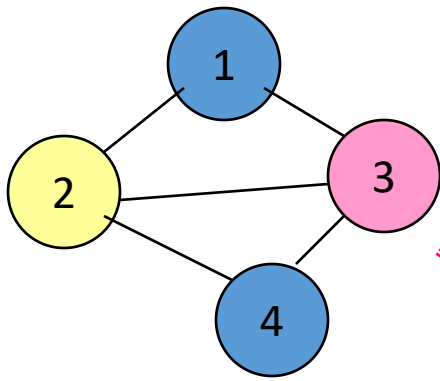
給每一節點上色.
任二相連之節點必
須不同色求所需最
小顏色數



上圖最少需3個顏色

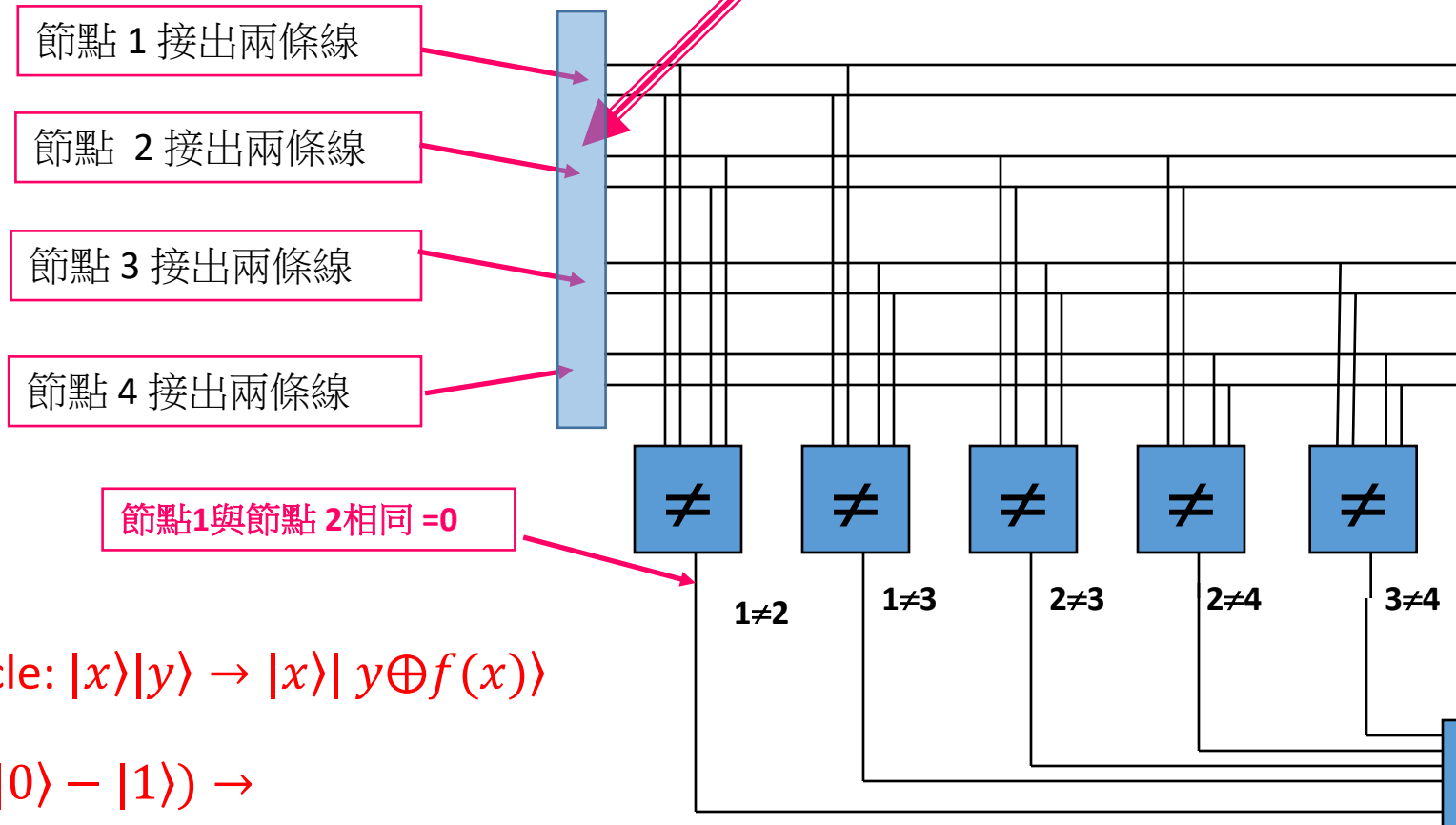
只要能建構標示函數(oracle) 即可用量子收尋：
給定一個圖色 x , 能決判定此圖色滿足規則 $f(x)=1$
或不滿足規則 $f(x)=0$

標示函數 (Oracle)



$$\frac{|0\rangle+|1\rangle}{\sqrt{2}} \times \frac{|0\rangle+|1\rangle}{\sqrt{2}} \times \frac{|0\rangle+|1\rangle}{\sqrt{2}} \times \dots$$

$$= \frac{1}{2^{(n+1)/2}} \sum_{x=0}^{x=2^n-1} |x\rangle$$



Oracle: $|x\rangle|y\rangle \rightarrow |x\rangle|y \oplus f(x)\rangle$

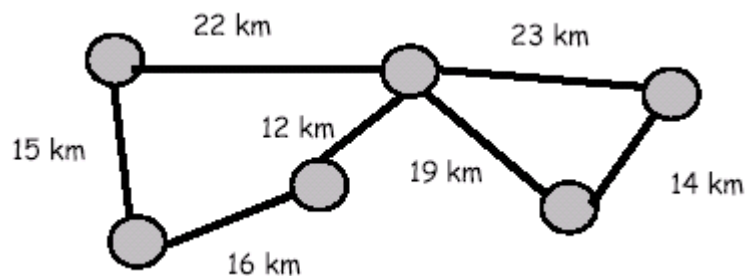
$|x\rangle(|0\rangle - |1\rangle) \rightarrow$

$|x\rangle(|f(x)\rangle - |1 \oplus f(x)\rangle) = (-1)^{f(x)} |x\rangle(|0\rangle - |1\rangle)$

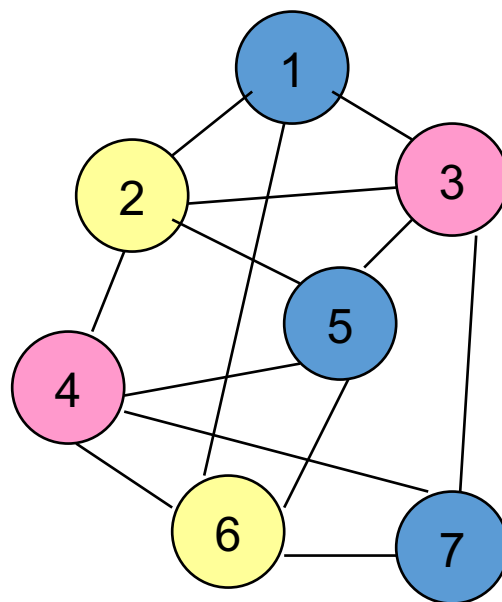
Value 1 for good coloring

量子收尋其他可能的應用...

推銷員的旅程問題 (Traveling Salesperson Problem)

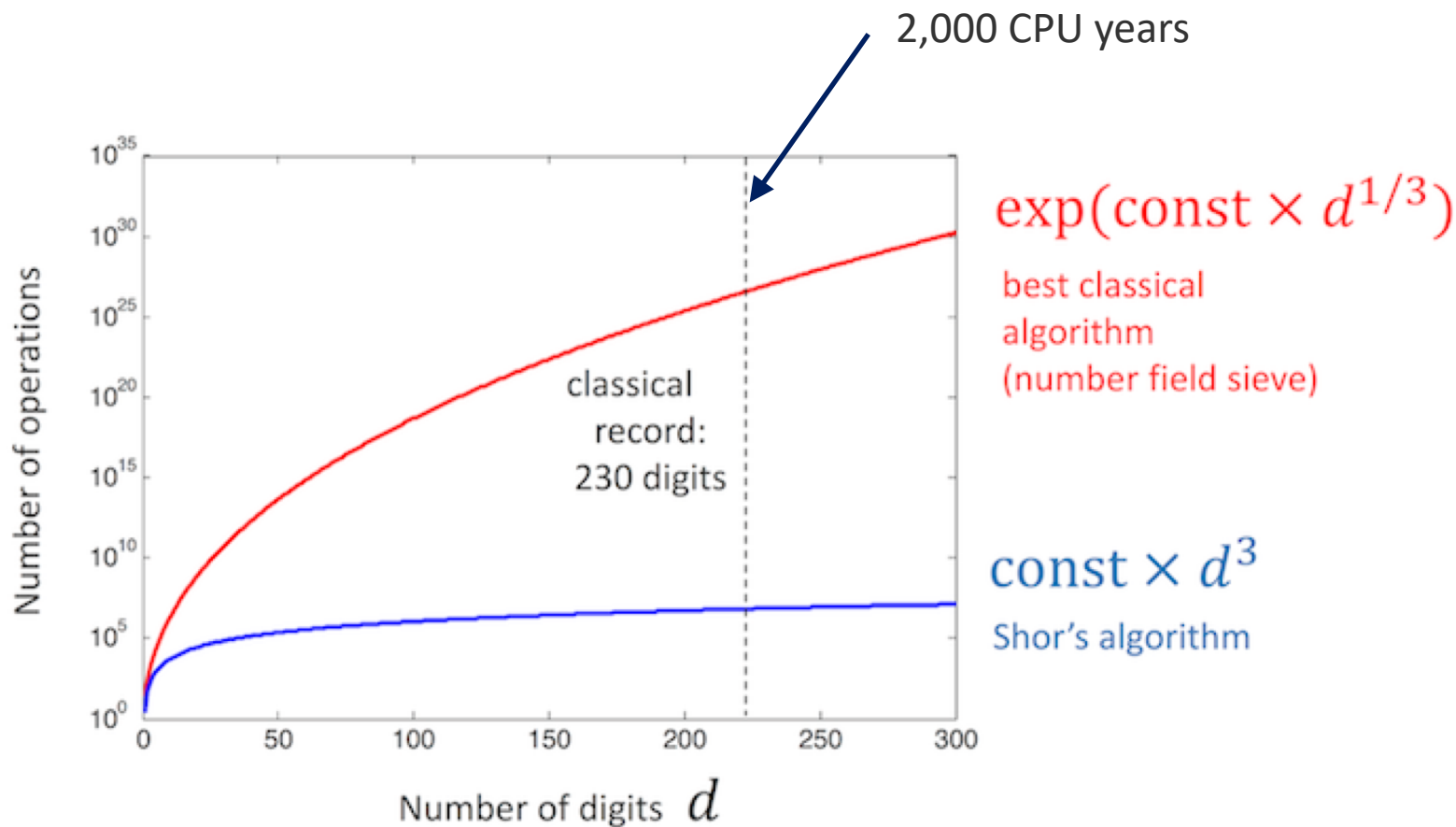


圖色問題

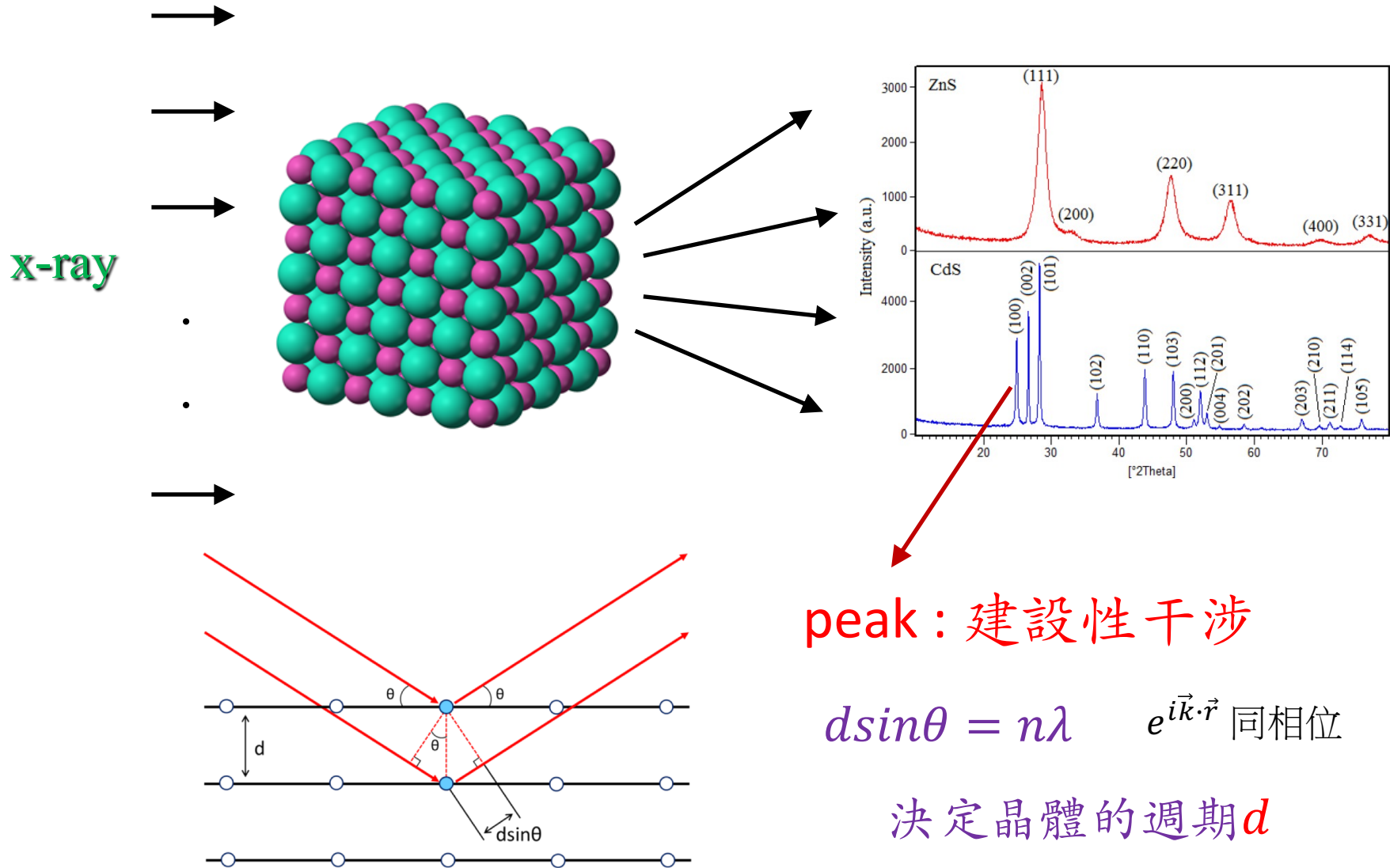


量子計算：

大數因數分解問題—化簡為找週期(波動特性)的問題
(Shor's algorithm) ▲

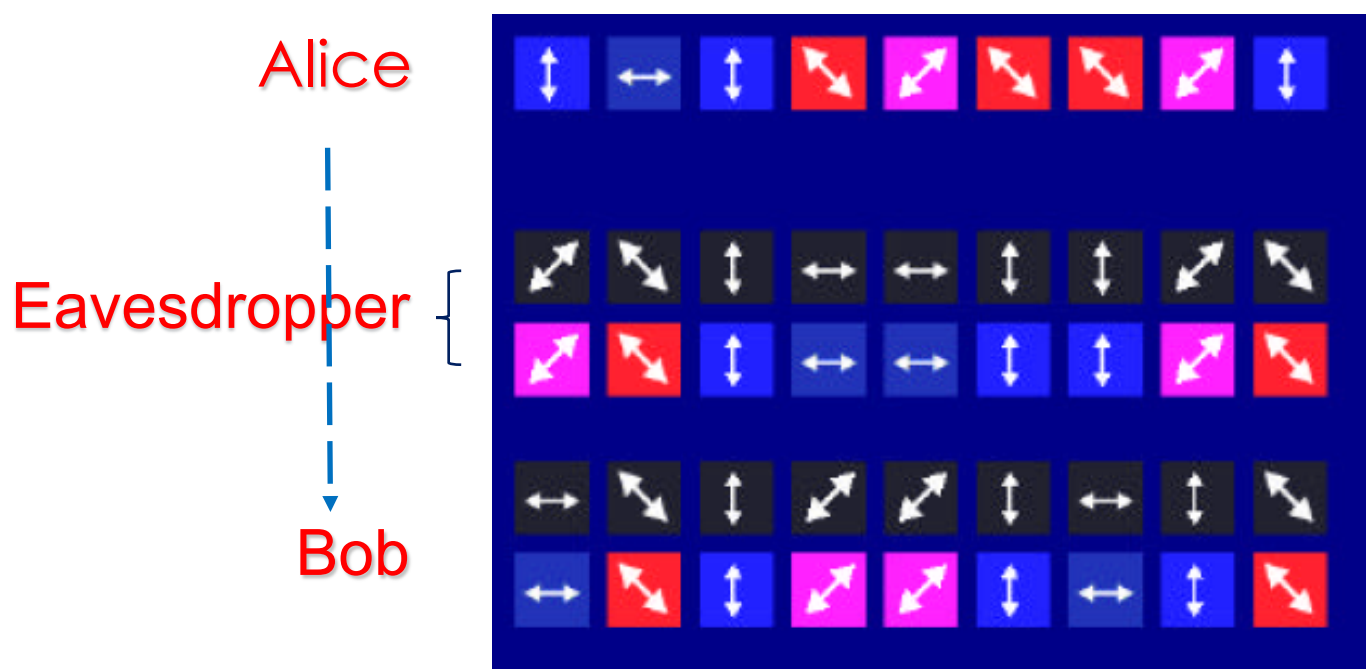


尋找週期的方法與x-ray繞射相似



量子通訊

利用量子態的脆弱性(Fragility)作秘密通訊



量子通訊：不會被竊聽的秘密通訊

為了通訊安全不被竊聽, 訊息傳遞加密碼

不管是那種密碼(如聖經密碼,...)

➔ 需要所謂的密碼鑰匙(key)

1 1 0 0 1 0



0 1 1 0 1 0

XOR 1 1 0 0 1 0

1 0 1 0 0 0

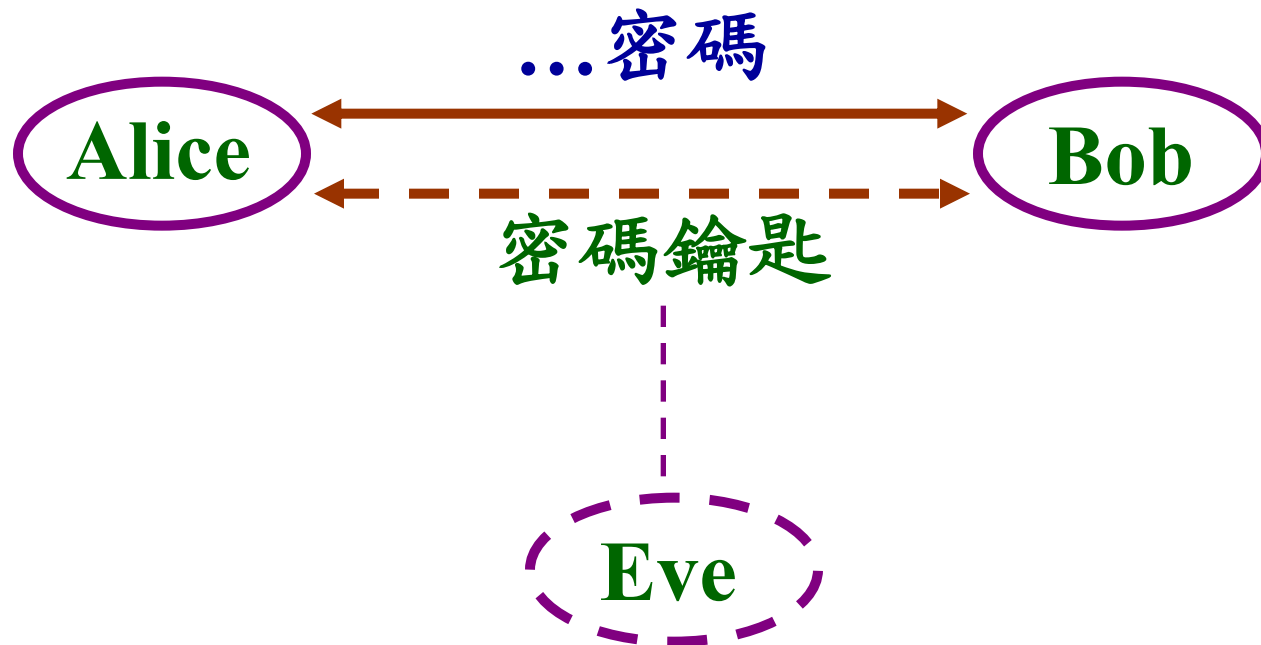
transmission

1 0 1 0 0 0

XOR 1 1 0 0 1 0

0 1 1 0 1 0

如何安全傳達密碼鑰匙呢?



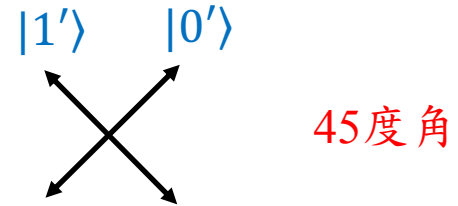
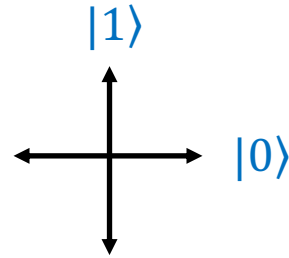
典型的古典方法:

由公告的密碼鑰匙找密碼必須會作**非**
常大的數之因式分解(RSA)才行

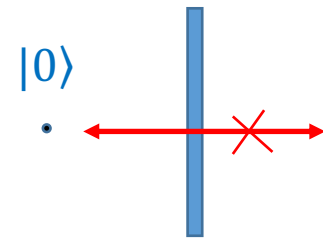
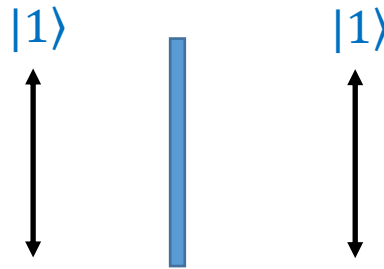


量子密碼學：不會被竊聽的秘密通訊

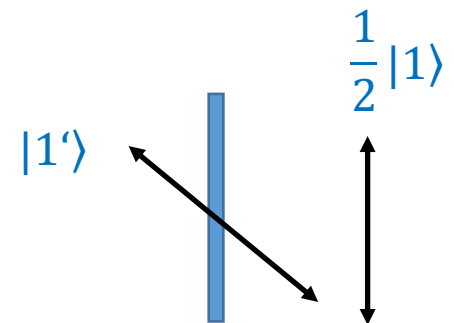
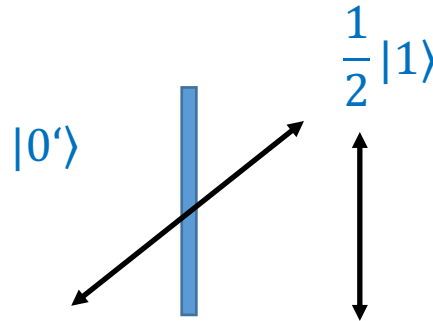
兩組光子的正交偏極化
(電場方向)



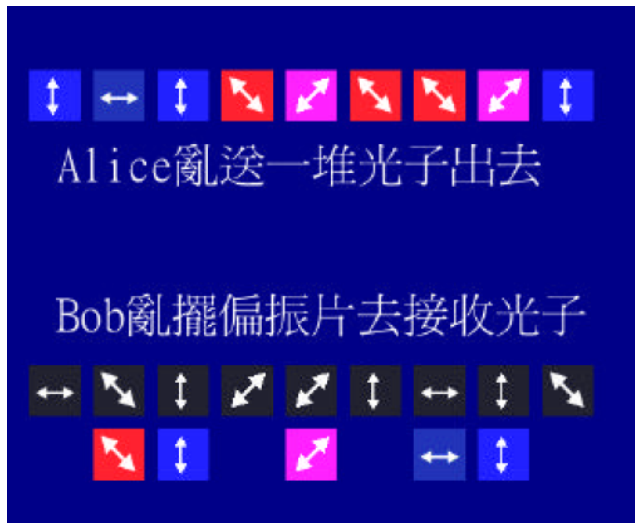
偏振板與偏極化同一組
排斥性通過(只讓垂直
水平單一方向通過)



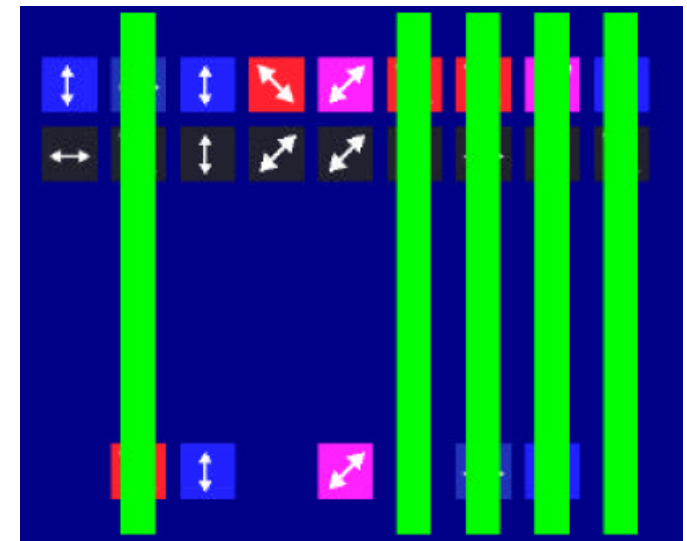
偏振板與偏極化不同組
可通過一半



單光子量子密碼傳送: BB84 (by Bennett and Brassard)

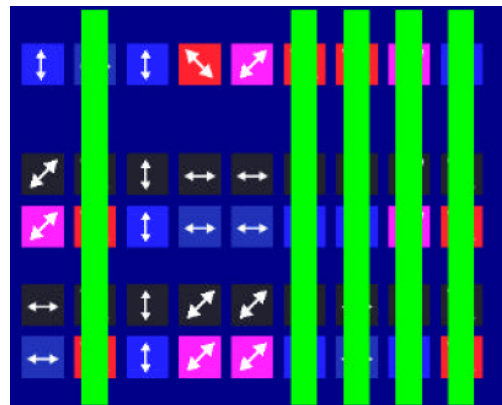


Alice打電話公開通知Bob只有1,3,4,5可以使用



Alice與Bob使用剩餘的資訊做key

如果有竊聽者



Bob犧牲一些key(如1,5..)傳給Alice比較

咩? 1號測量怎麼會出現水平?

不被發現的機率: $\frac{1}{2}$ (選對偏振) + $\frac{1}{2} \times \frac{1}{2}$ (選錯偏振) = $\frac{3}{4}$

犧牲比較的key數目(n)愈多, 不被發現的機率, $\left(\frac{3}{4}\right)^n$, 趨近0!

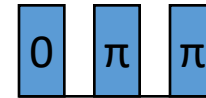
目前有四種通訊協定的選擇

使用環境、通訊距離、駭客攻擊

④ Decoy-state BB84 

Free space, satellite-based

④ DPS (Differential Phase-Shifted)



Optical fiber

④ E91 (Entanglement-based)



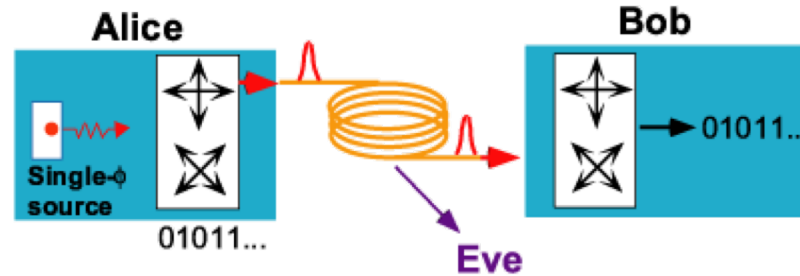
Longer distance, verification of QM

④ MDI (Measurement-Device-Independent)

Against hacking on detectors



量子密碼學：不會被竊聽的秘密通訊

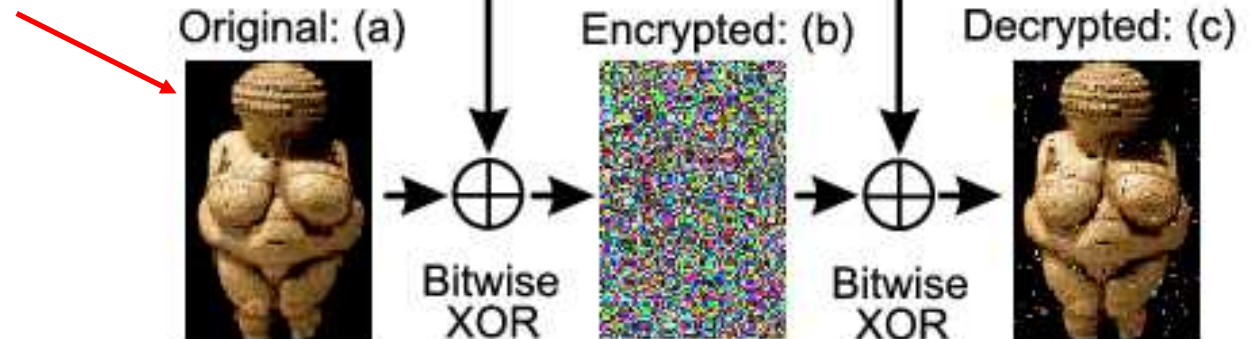


60x90 pixels

8 bit color information
per pixel + header

= 49984bits

Venus von Willendorf effigy



Phys. Rev. Lett. 84, 4729-4732 (2000)

(Ekert scheme, using entangled photons, E91 協定)

Quantum Teleportation



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

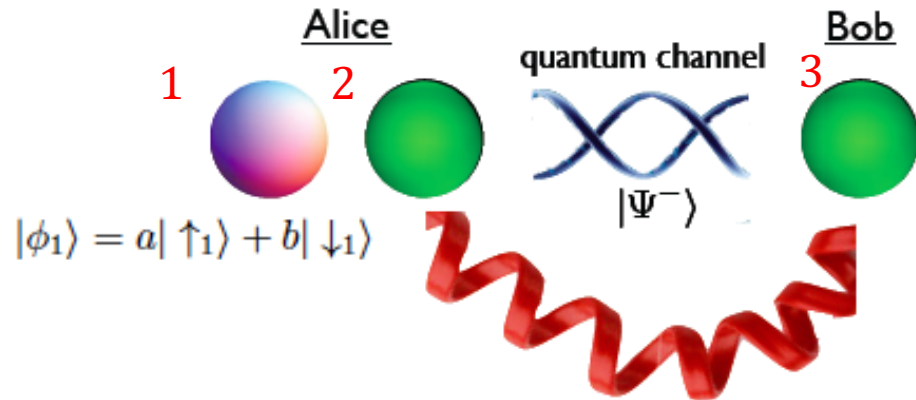


$$\alpha|1\rangle + \beta|0\rangle$$

量子隱傳(Quantum teleportation)

(Bennet et al. Phys. Rev. Lett. 70, 1895–1899 (1993);

Nielsen, Knill. & Laflamme, Nature 395, 5 Nov, (1998), record 102KM over optical fibre)



$$|\Psi_{23}^{(-)}\rangle = \frac{1}{\sqrt{2}}(|\uparrow_2\rangle|\downarrow_3\rangle - |\downarrow_2\rangle|\uparrow_3\rangle).$$

classical channel

$$|\Psi_{123}\rangle = |\phi_1\rangle \otimes |\Psi_{23}^{(-)}\rangle = \frac{a}{\sqrt{2}}(|\uparrow_1\rangle|\uparrow_2\rangle|\downarrow_3\rangle - |\uparrow_1\rangle|\downarrow_2\rangle|\uparrow_3\rangle) + \frac{b}{\sqrt{2}}(|\downarrow_1\rangle|\uparrow_2\rangle|\downarrow_3\rangle - |\downarrow_1\rangle|\downarrow_2\rangle|\uparrow_3\rangle)$$

Recombined 1 & 2 using Bell basis

$$|\Psi_{12}^{(\pm)}\rangle = \frac{1}{\sqrt{2}}(|\uparrow_1\rangle|\downarrow_2\rangle \pm |\downarrow_1\rangle|\uparrow_2\rangle)$$

$$|\Phi_{12}^{(\pm)}\rangle = \frac{1}{\sqrt{2}}(|\uparrow_1\rangle|\uparrow_2\rangle \pm |\downarrow_1\rangle|\downarrow_2\rangle)$$

$$|\Psi_{123}\rangle = \frac{1}{2} [|\Psi_{12}^{(-)}\rangle (-a|\uparrow_3\rangle - b|\downarrow_3\rangle) + |\Psi_{12}^{(+)}\rangle (-a|\uparrow_3\rangle + b|\downarrow_3\rangle) \\ + |\Phi_{12}^{(-)}\rangle (a|\downarrow_3\rangle + b|\uparrow_3\rangle) + |\Phi_{12}^{(+)}\rangle (a|\downarrow_3\rangle - b|\uparrow_3\rangle)].$$

$-I$ $-\sigma_z$
 $-\sigma_x$ $-i\sigma_y$

➡ Bell measurement on 1&2



量子計算與量子通訊之終極目標

建立量子網路：量子計算、量子位元、
量子資訊傳遞



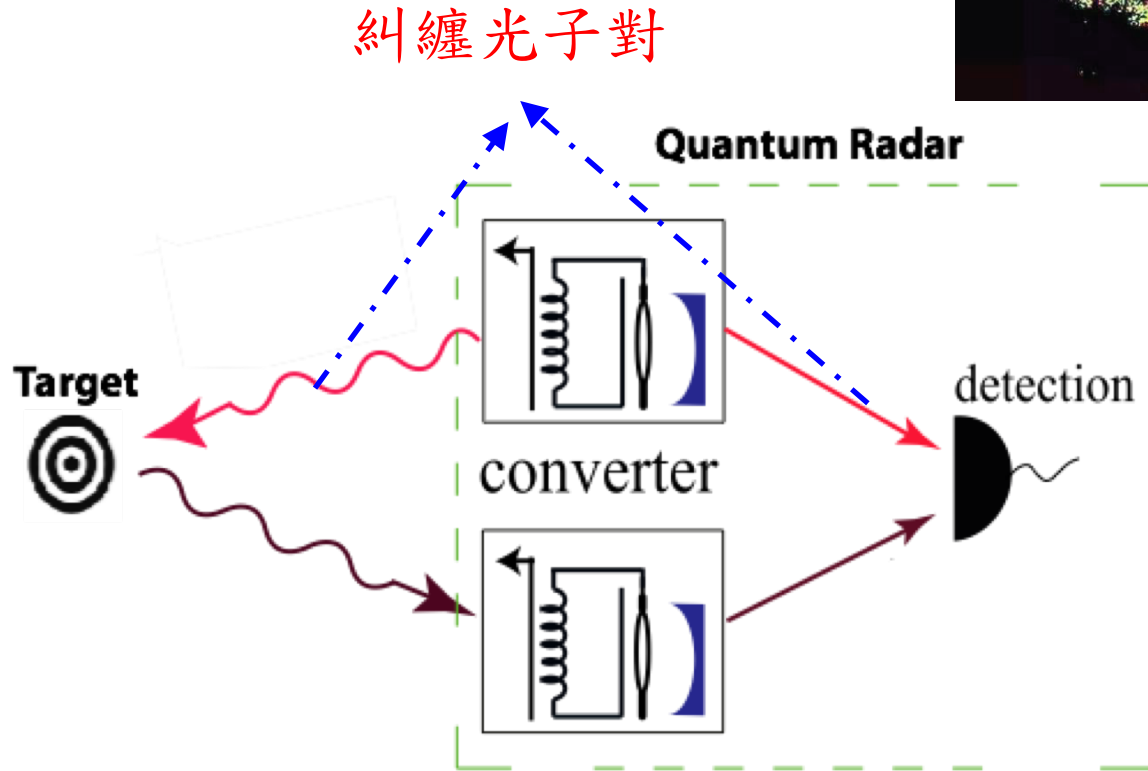
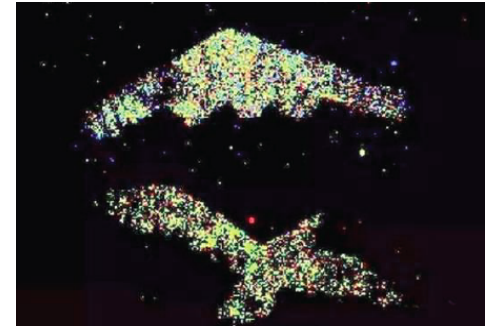
硬體的實現：工程問題

量子感測/計量

2017年09月07日 07:51 中時電子報

陸量子雷達再突破 F35隱形戰機藏不住

超靈敏的測量: ultra-sensitive camera...



比較相關性
可以移除
噪音

S. Lloyd, Science 321, 1463 (2008); S. Barzanjeh et al., Phys. Rev. Lett. (2015)

量子感測/計量

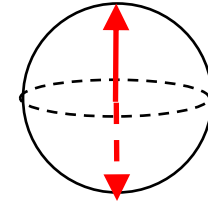
Clock synchronization

目前時鐘的同步只能做到每天差1奈秒

$$\begin{array}{c} \text{---} E_1 \\ \text{---} E_0 \end{array} \quad \begin{array}{c} |\uparrow\rangle \\ |\downarrow\rangle \end{array} \quad \frac{E_1 - E_0}{\hbar} = \omega$$

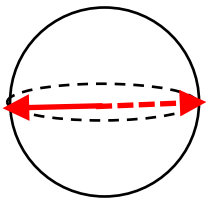
Initial Bell state shared between Alice & Bob

$\begin{array}{cc} \uparrow & \downarrow \\ \downarrow & \uparrow \end{array}$



$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|\uparrow\rangle_A |\downarrow\rangle_B - |\downarrow\rangle_A |\uparrow\rangle_B) = \frac{1}{\sqrt{2}} (|-\rangle_A |+\rangle_B - |+\rangle_A |-\rangle_B)$$

Alice measures in different basis



$$|+\rangle = \frac{1}{\sqrt{2}} (|\uparrow\rangle + |\downarrow\rangle) \quad |-\rangle = \frac{1}{\sqrt{2}} (|\uparrow\rangle - |\downarrow\rangle)$$

$$|+, t\rangle = \frac{1}{\sqrt{2}} (e^{-iE_0 t} |\uparrow\rangle + e^{-iE_1 t} |\downarrow\rangle) \quad |-, t\rangle = \frac{1}{\sqrt{2}} (e^{-iE_0 t} |\uparrow\rangle - e^{-iE_1 t} |\downarrow\rangle)$$

Alice/Bob

$$P(+, t) = \frac{1}{2} (1 + \cos \omega t)$$

Bob/Alice

$$P(-, t) = \frac{1}{2} (1 - \cos \omega t)$$

量子模擬

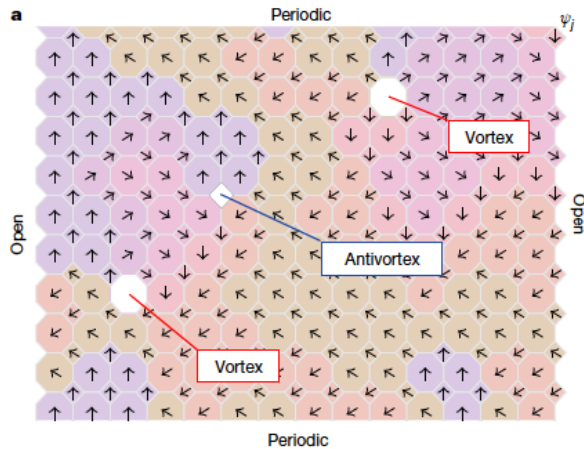
模擬真實的量子系統或模型 (Feynman)

Programmable quantum simulation

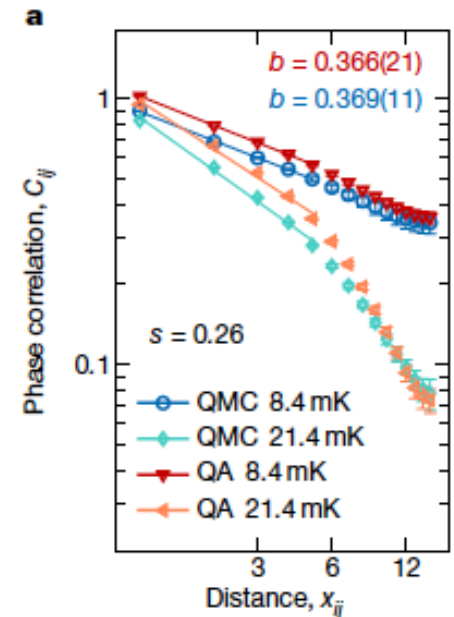
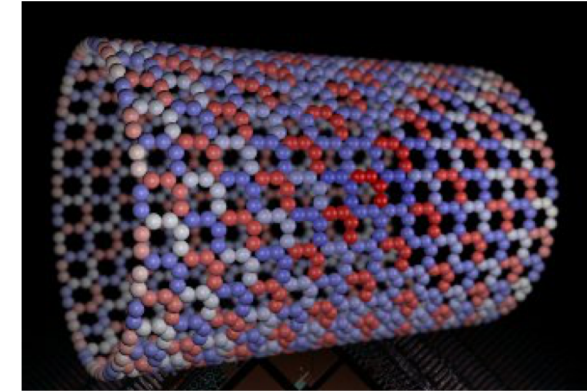
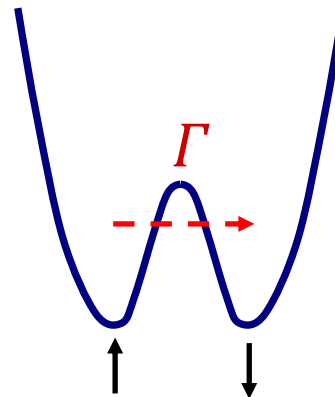
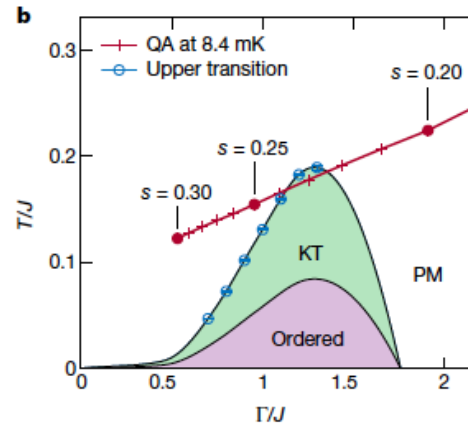
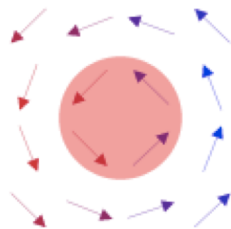
Large-Scale (**1800 qubits**) Quantum Simulation of Topological State of Matter

(D-wave, Nature 560, 457, 2018)

$$H = \sum_i h_i \sigma_i^z + \sum_{i < j} J_{ij} \sigma_i^z \sigma_j^z - \Gamma \sum_i \sigma_i^x$$



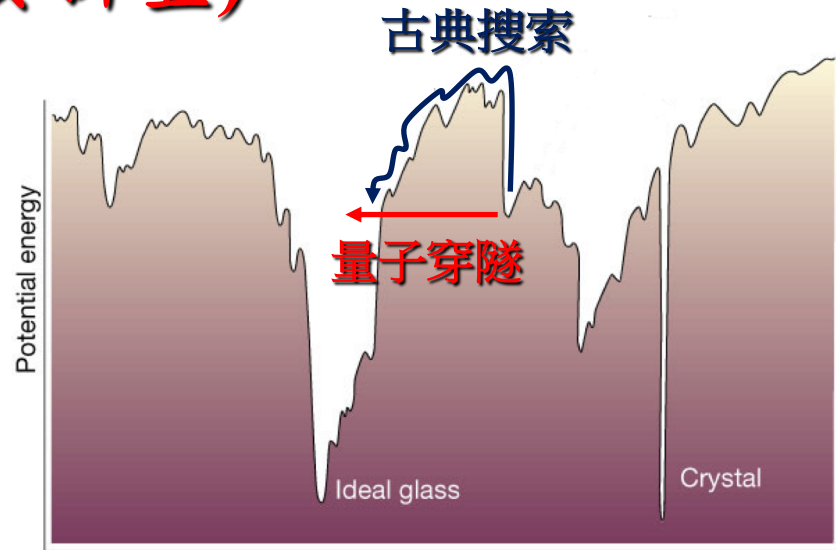
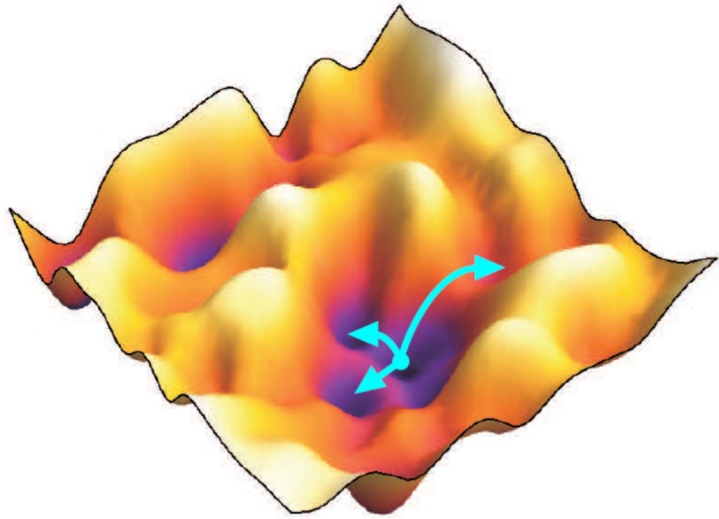
successfully
generating quantum
vortices



量子模擬

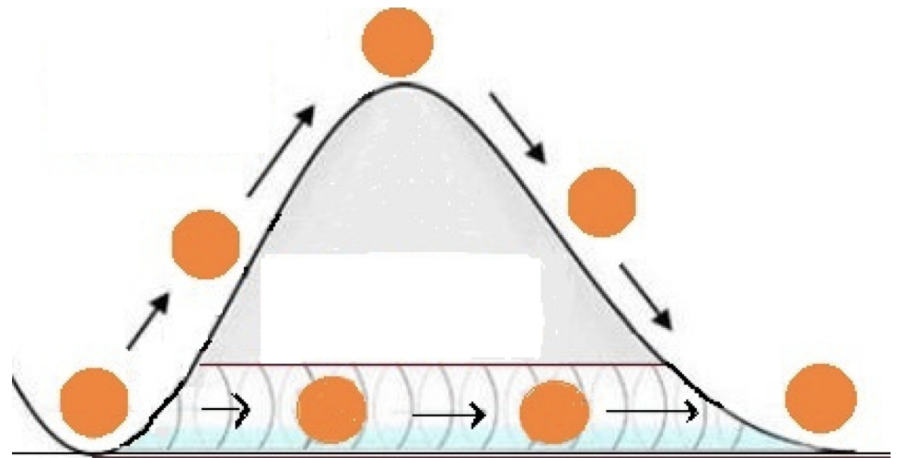
量子穿隧與量子退火搜索

古典退火(如模擬蛋白質折疊)

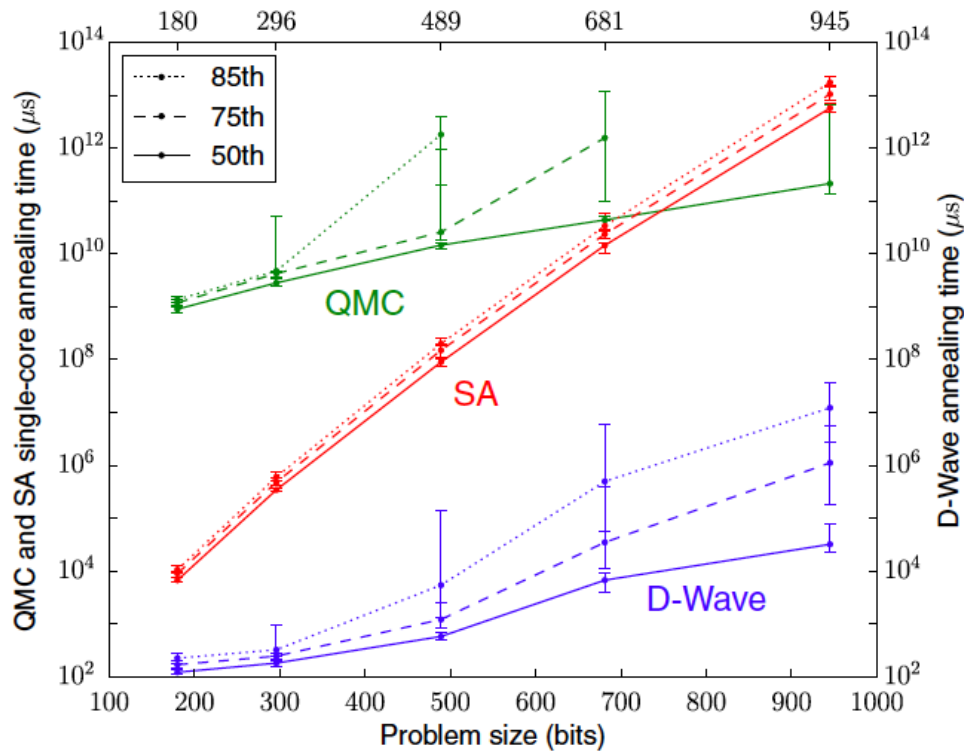


量子穿隧效應

新藥的研發(蛋白質折疊)、最佳化收尋....



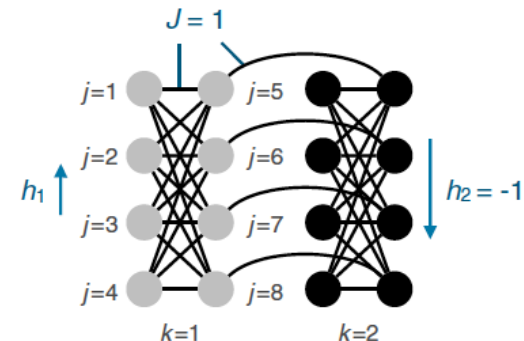
對特定類別問題：量子退火極具優勢



加快 10^8 倍

$$H_P^k = -J \sum_{\langle j,j' \rangle \in \text{intra}} \sigma_{k,j}^z \sigma_{k,j'}^z - \sum_{j=1}^8 h_k \sigma_{k,j}^z,$$

$$H_P^{1,2} = -J \sum_{j \in \text{inter}} \sigma_{1,j}^z \sigma_{2,j}^z.$$



量子模擬費米子(Quantum simulation of Fermions)

Any state α : occupied $n_\alpha = 1$ ➡ Naturally form a qubit $|1\rangle$
 unoccupied $n_\alpha = 0$ $|0\rangle$

+ Jordan-Wigner transformation:

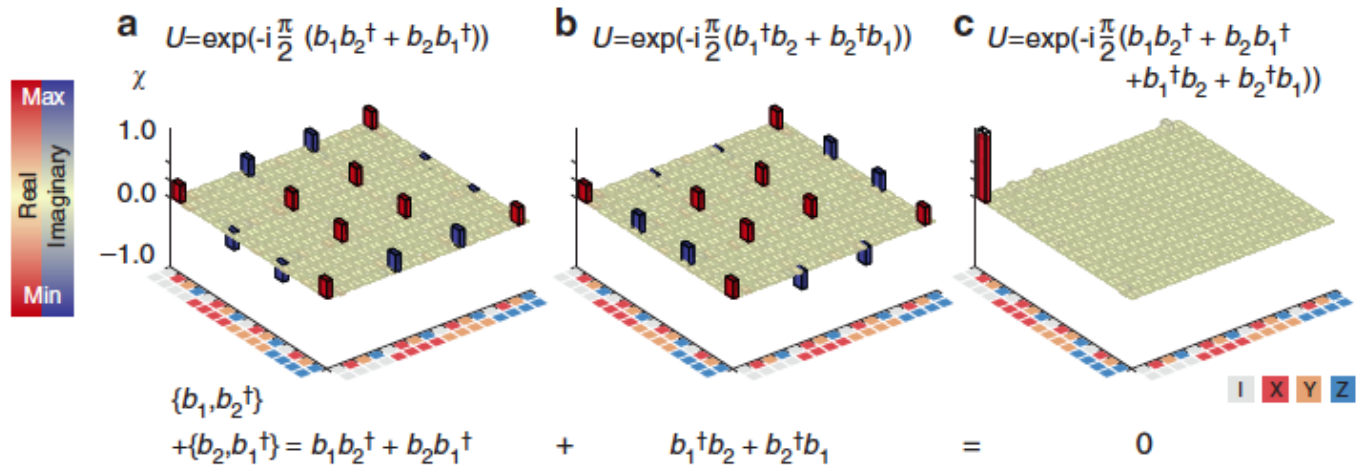
00000000
11111111

$b_i b_j + b_j b_i = 0$

$b_i^\dagger b_j + b_j b_i^\dagger = \delta_{ij}$

費米子性質驗證

$$H = -V \sum_{\langle i,j \rangle} b_i^\dagger b_j + b_j b_i^\dagger + U \sum_i n_{i\uparrow} n_{i\downarrow}$$



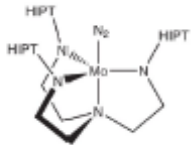
Noisy-intermediate **hybrid** quantum simulation

--Energies of small molecules, small size of spin systems,
fermions

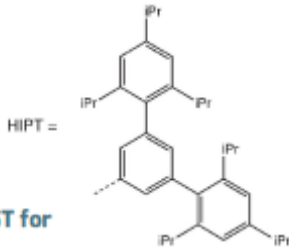
1. MOLECULAR DESCRIPTION

e.g. Electronic Structure Hamiltonian

$$H = \sum_{i,j}^{N_a} \frac{Z_i Z_j}{|R_i - R_j|} + \sum_i^{N_e} \frac{-\nabla_{r_i}^2}{2} - \sum_{i,j}^{N_a, N_e} \frac{Z_i}{|R_i - r_j|} + \sum_{i,j < i}^{N_e} \frac{1}{|r_i - r_j|}$$



e.g. SCHROCK CATALYST for NITROGEN FIXATION



2. MAP TO QUBIT REPRESENTATION

e.g. Bravyi-Kitaev or Jordan-Wigner Transform

e.g. HYDROGEN

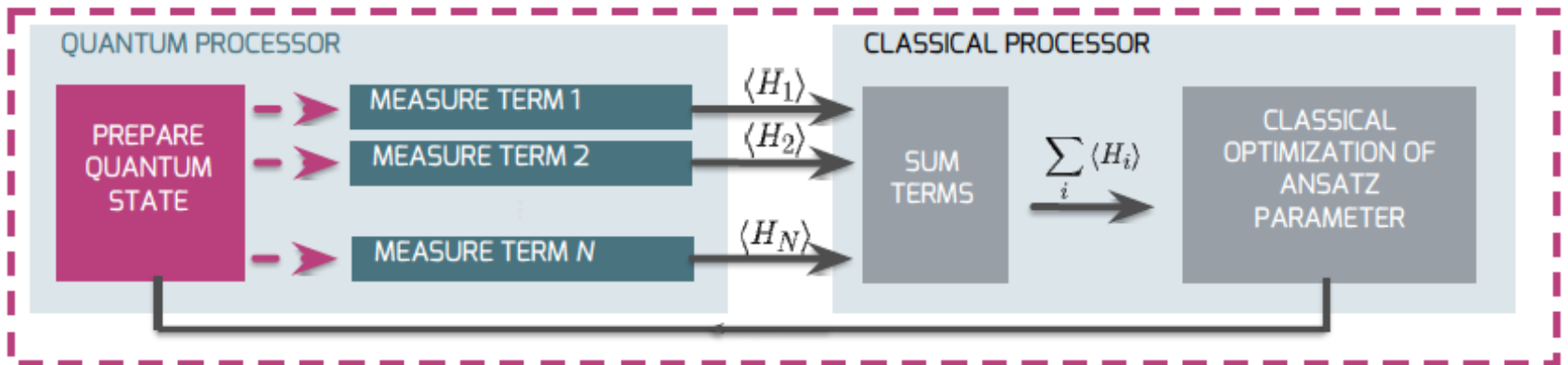
$$\begin{aligned} H = & f_0 \mathbb{1} + f_1 Z_0 + f_2 Z_1 + f_3 Z_2 + f_4 Z_0 Z_1 \\ & + f_4 Z_0 Z_2 + f_5 Z_1 Z_3 + f_6 X_0 Z_1 X_2 + f_6 Y_0 Z_1 Y_2 \\ & + f_7 Z_0 Z_1 Z_2 + f_4 Z_0 Z_2 Z_3 + f_3 Z_1 Z_2 Z_3 \\ & + f_6 X_0 Z_1 X_2 Z_3 + f_6 Y_0 Z_1 Y_2 Z_3 + f_7 Z_0 Z_1 Z_2 Z_3 \end{aligned}$$

3. PARAMETERIZED ANSATZ

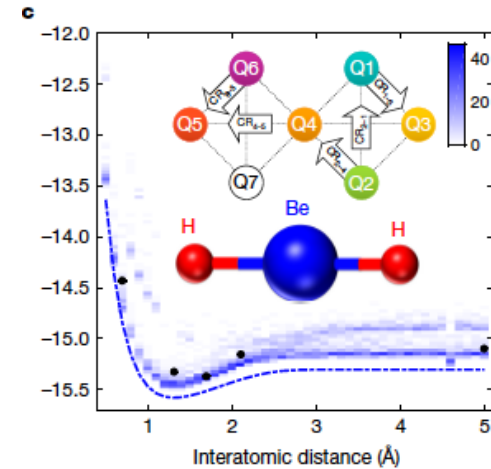
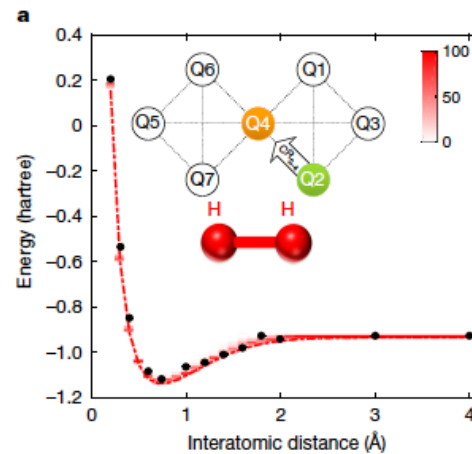
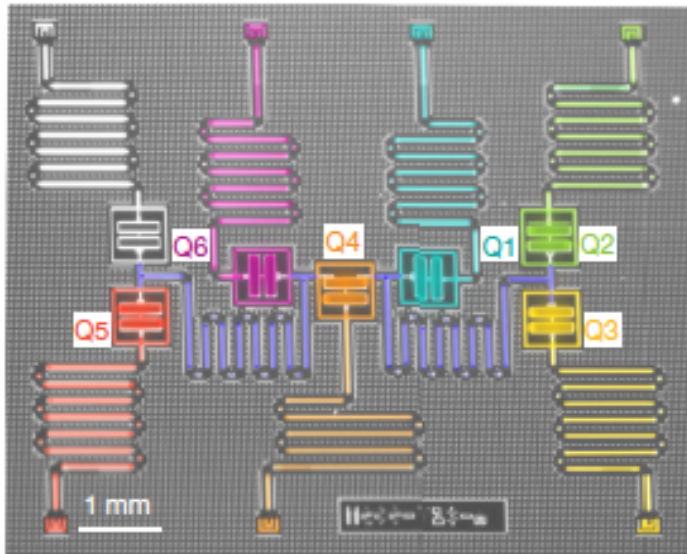
e.g. Unitary Coupled Cluster Variational Adiabatic Ansatz

$$\frac{\langle \varphi(\vec{\theta}) | H | \varphi(\vec{\theta}) \rangle}{\langle \varphi(\vec{\theta}) | \varphi(\vec{\theta}) \rangle} \geq E_0$$

4. RUN Q.V.E. QUANTUM-CLASSICAL HYBRID ALGORITHM

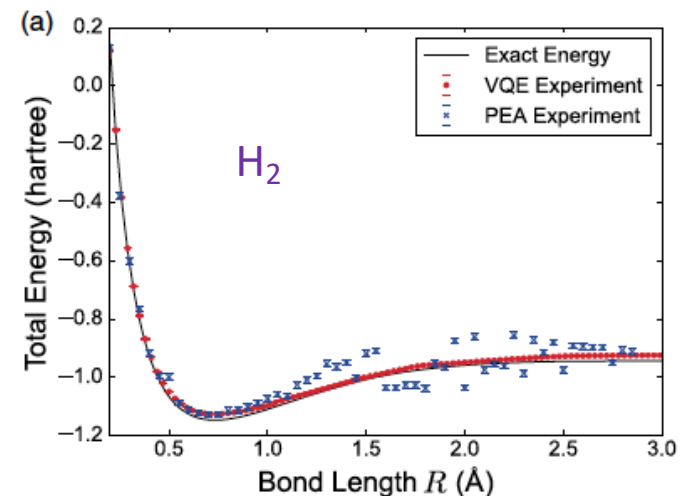


Noisy-intermediate quantum simulation



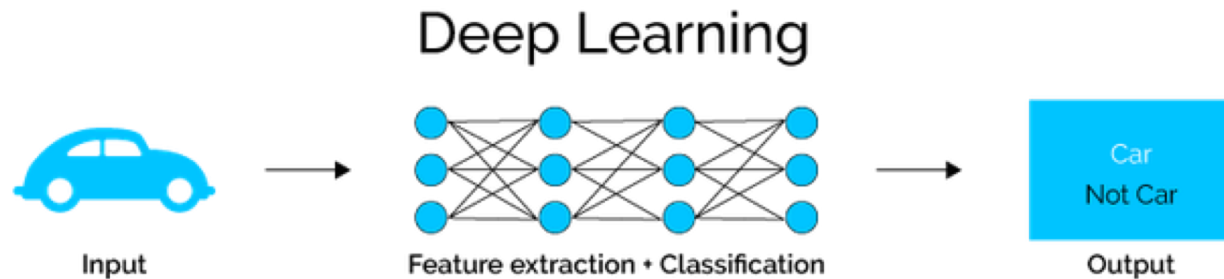
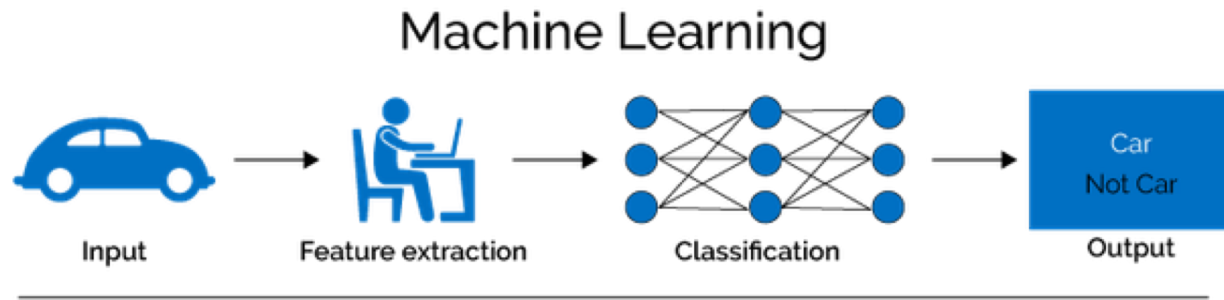
A. Kandala et al. Nature 549, 242 (2017)

O' Malley et al. Phys Rev. X 6 , 037007(2016)



Machine learning: quantum speed up?

Classical supervise learning



Source of image: <https://www.quora.com/What-is-the-difference-between-deep-learning-and-usual-machine-learning>

$$Ax_{input} = x_{output}$$

Trained more efficiently ?

$$x_{input} \rightarrow |x_{input}\rangle = Car |000 \dots 1\rangle + cat |00010\dots 0\rangle + \dots$$

Exponential quantum speedups: given A & x_{output} find x_{input} (HHL algorithm, PRL 103, 150502, 2009)

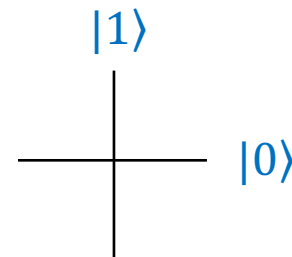
量子科技發展概況、實現產品化的 挑戰與機會

量子位元與量子電腦

任意兩個狀態($|0\rangle, |1\rangle$)皆可成為量子位元

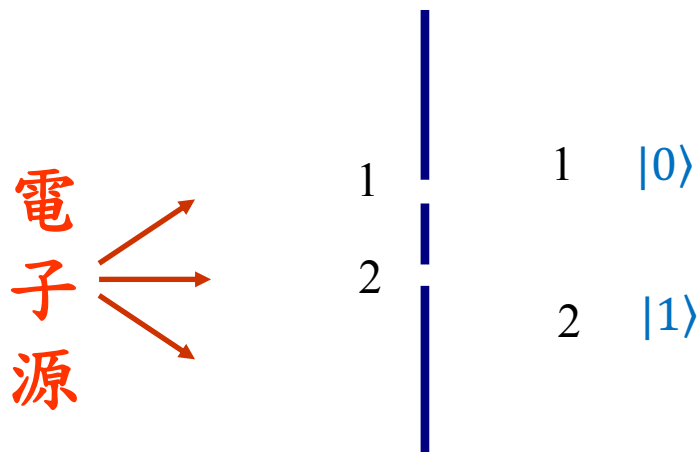
*2 能階 (two level): $\begin{array}{c} \text{—————} E_1 \\ \text{—————} E_0 \end{array} \begin{array}{l} |1\rangle \\ |0\rangle \end{array}$

*光子：飛行量子位元, 如偏極化



*自旋 $\frac{1}{2}$: $\uparrow |0\rangle \quad \downarrow |1\rangle$

電子源



量子技術最大的困難

量子態特性：脆弱、不能被複製

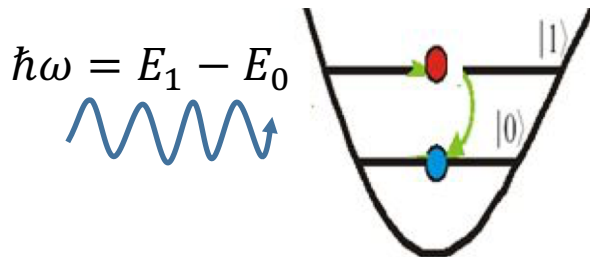
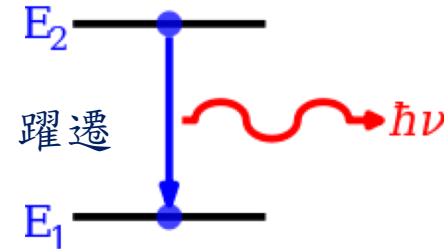
第一個考慮：

量子態的存活時間

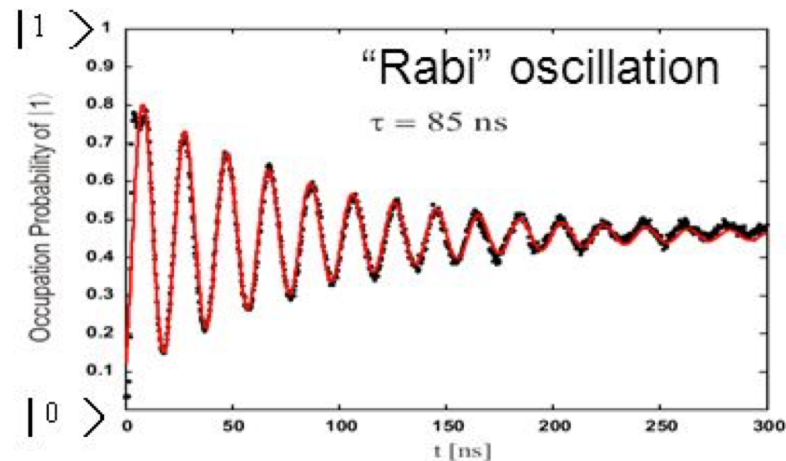
(decoherence time)

↔ 同調光與非同調光

要求：存活時間 $\gg$ 操作一步(操作gate)的時間



$E_1 - E_0$ 決定了操作溫度



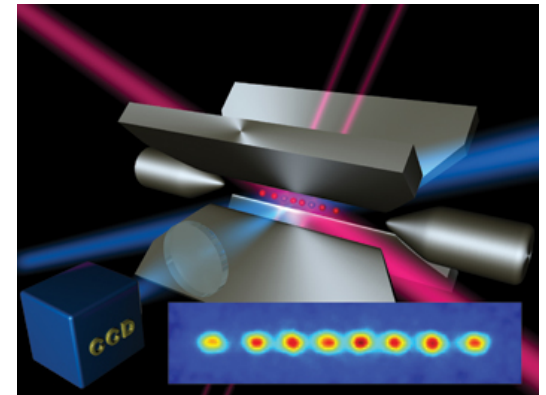
候選量子位元系統

- 光子的偏振方向：飛行量子位元 degrade $\sim 200\text{km}$ ，用於量子通訊

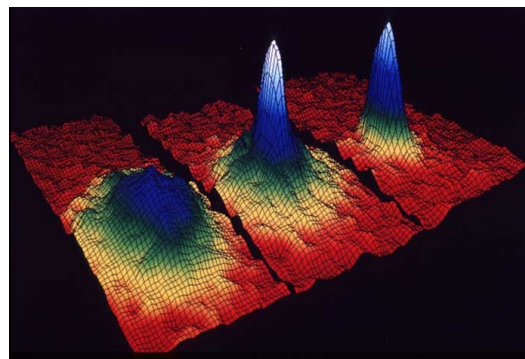


- 液態NMR(原子核自旋共振)：早期發展、最近發現 $\sim$ no entanglement

- Trapped ion, 束縛離子中的電子能階 (IonQ)
Hyperfine qubits (thousands to millions of years)
Optical qubits (the order of a second)
operation time (microseconds)



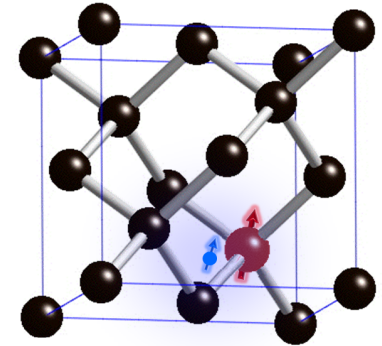
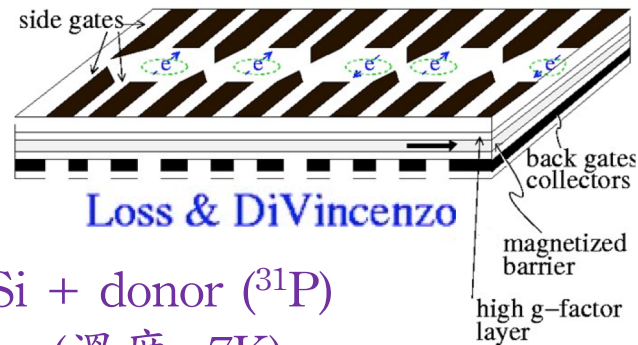
- 超冷原子 (BEC, $\sim \mu\text{K}$, the order of a second)



Cornell&Wieman

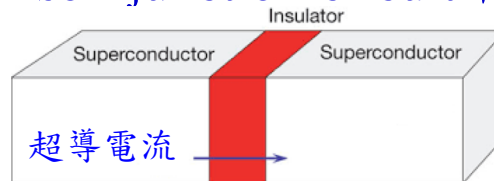
- Diamond nitrogen-vacancy ($\text{NV} + {}^{13}\text{C} + \text{other } {}^{12}\text{C}$ spinless) : 10 s (room temperature); Science 336, 1283 (2012)

- 矽半導體量子點的電子自旋(Intel)
或電荷(Hitachi Cambridge Lab.)



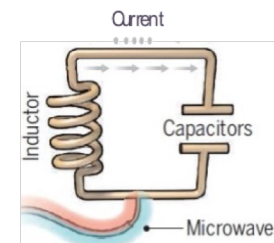
Spin qubit : 純化 ${}^{28}\text{Si}$ + donor (${}^{31}\text{P}$)
最佳存活時間 : 30ms (溫度~7K)

- 超導體Josephson junction circuit中的磁通量 (D-Wave) ▲



- 超導體的電荷(Al/Si or Sapphire Al_2O_3) (Google, Rigetti, IBM)

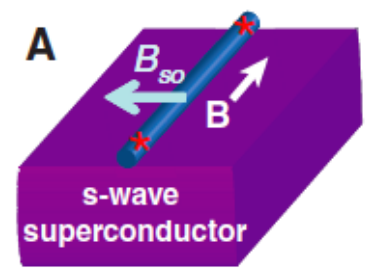
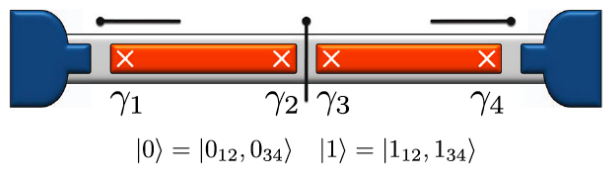
存活時間 : 30-140 μs (溫度~10mK)
操作時間~ 10 ns



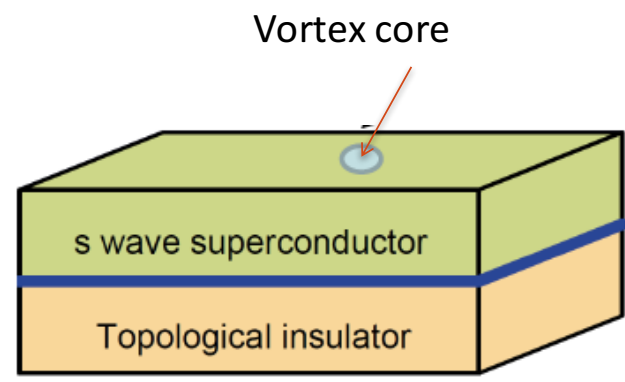
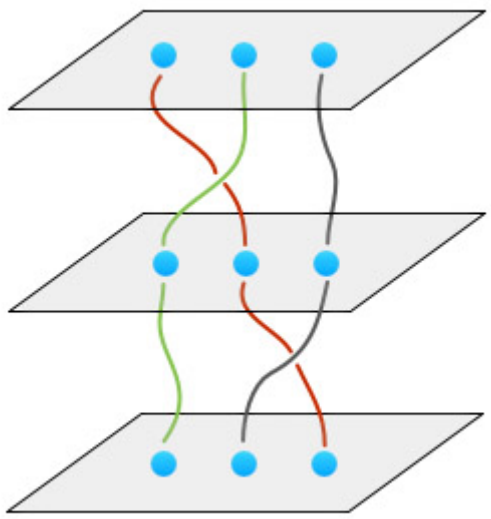
與半導體
製程相容

與半導體
製程相容

- 超導+半導體 (InAs+Al)：拓樸量子位元 (Microsoft)
Majorana zero mode: no dynamical dephasing
存活時間：10 μ s



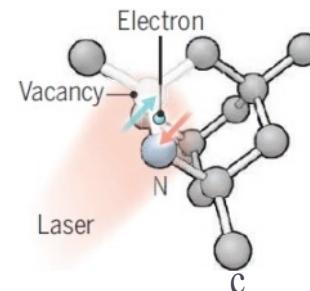
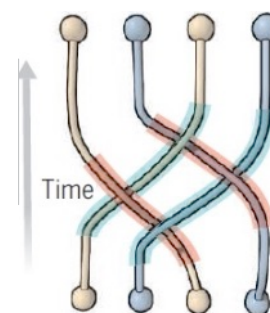
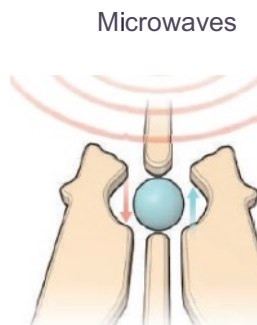
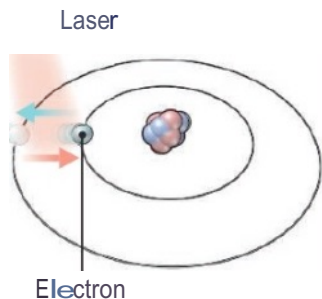
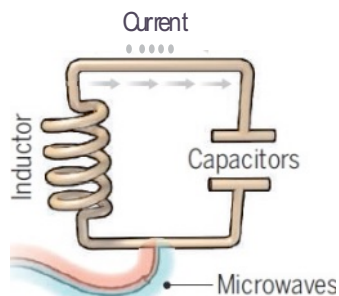
Science 336, 1003 (2012)
PRX 6, 031016 (2016)



A bit of the action

Science (Dec. 1, 2016) DOI: 10.1126/science.aal0442

In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.



Superconducting loops

A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.

Longevity (seconds)
0.00005

Logic success rate
99.4%

Number entangled

49 – 72 now, 1000

Company support

Google, IBM, Quantum Circuits

Pros

Fast working. Build on existing semiconductor industry.

Cons

Collapse easily and must be kept cold.

Trapped ions

Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.

>1000

99.9%

10 -- 60

ionQ

Very stable. Highest achieved gate fidelities.

Slow operation. Many lasers are needed.

Silicon quantum dots

These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.

0.03

~99%

10

Intel

Stable. Build on existing semiconductor industry.

Only a few entangled. Must be kept cold.

Topological qubits

Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.

N/A

N/A

N/A

Microsoft.
Bell Labs

Greatly reduce errors.

Existence not yet confirmed.

Diamond vacancies A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.

10

99.2%

6

Quantum Diamond
Technologies

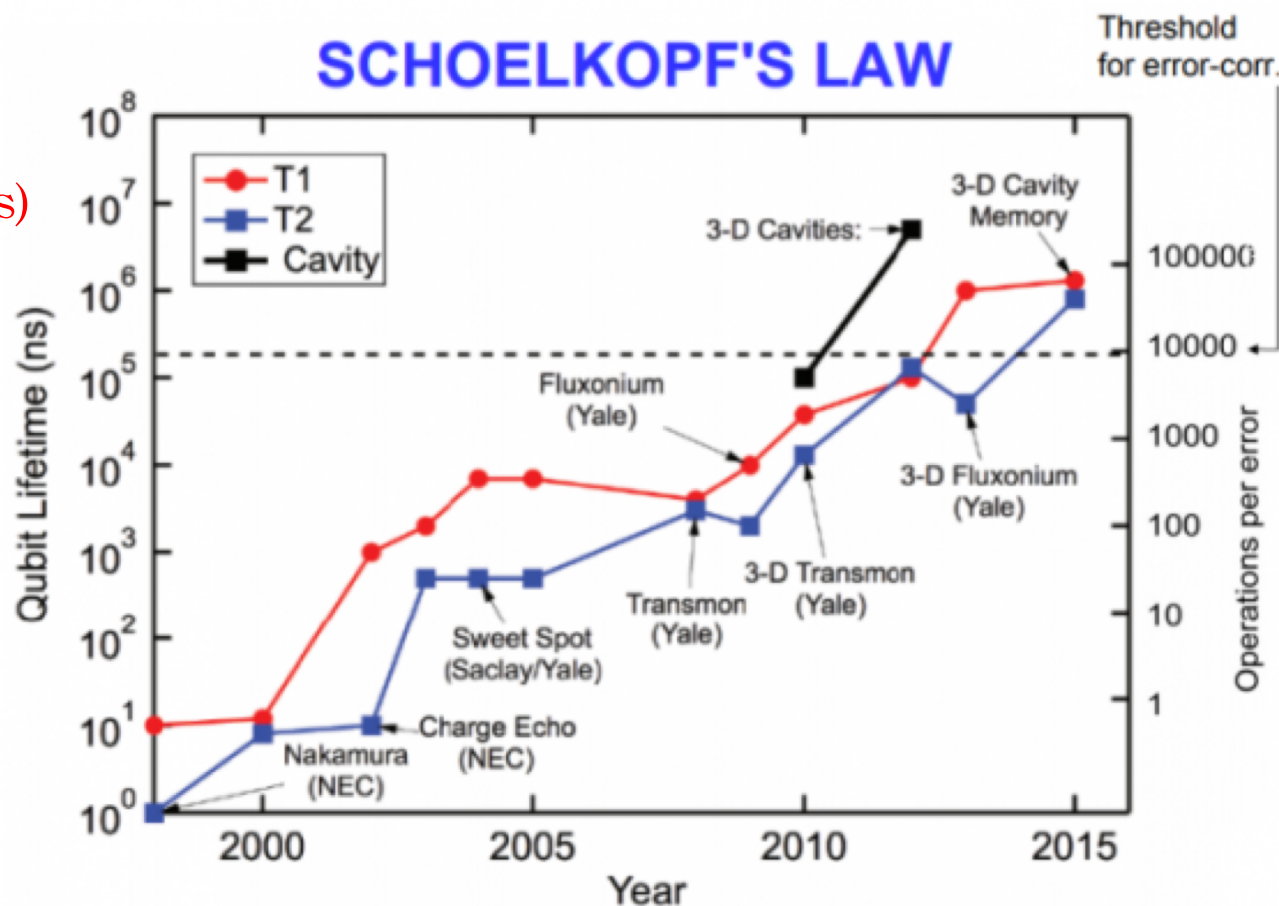
Can operate at room temperature.

Difficult to entangle.

0.01 K domestic researchers: 2-5 qubits

超導量子位元的突飛猛進

存活時間(ns)



Devoret & Schoelkopf, Science 339, 1169 (2013)

建立量子網路(quantum network)

硬體的實現：工程問題

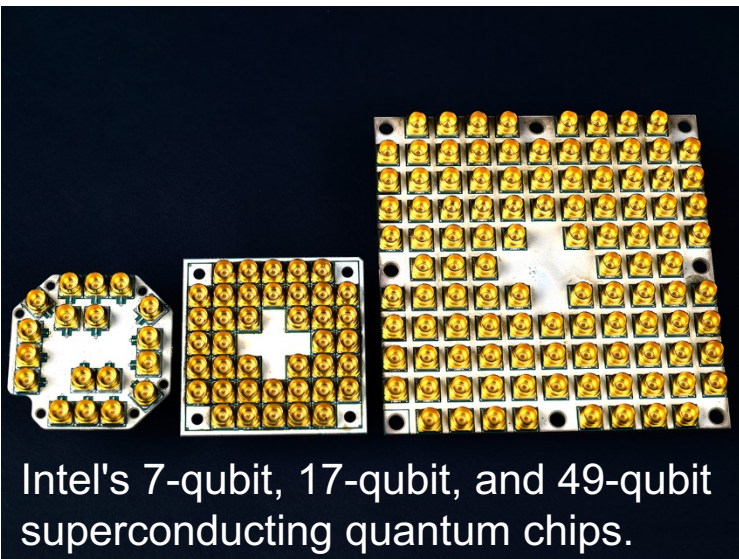


DiVincenzo criteria

- A **scalable** physical system with well characterized qubits. ?
- The ability to **initialize** the state of the qubits to a simple fiducial state. ✓
- **Long** relevant **decoherence times** ($> 10^4$ operation time) ✓
- A “**universal**” set of quantum gates. ✓
- A **qubit-specific measurement** capability. ✓
- The ability to interconvert stationary and flying qubits.
- The ability to faithfully transmit flying qubits between specified locations.

CES 2018: Intel's 49-Qubit Chip Shoots for Quantum Supremacy

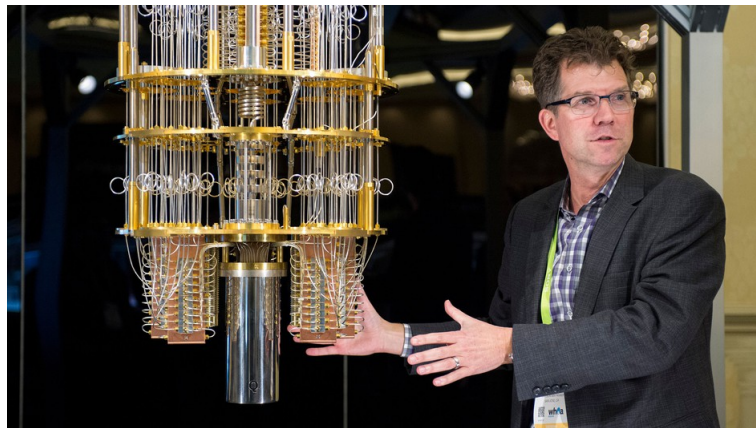
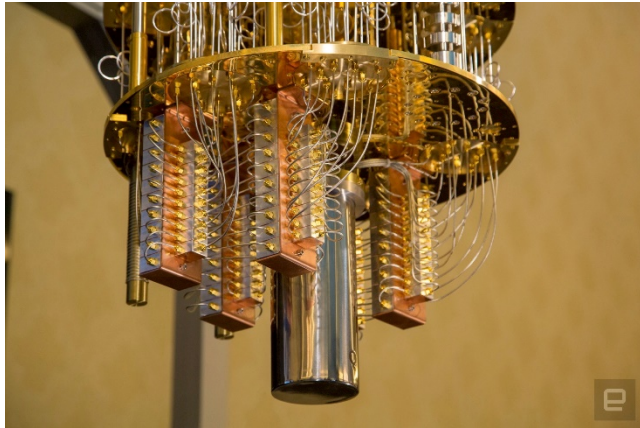
- Intel has passed a key milestone while running alongside Google and IBM in the marathon to build quantum computing systems. The tech giant has **unveiled a superconducting quantum test chip with 49 qubits (code-named Tangle Lake)**: enough qubits to possibly enable quantum computing that begins to exceed the practical limits of modern classical computers, i.e., the so-called **“quantum supremacy.”**
- But practical quantum computing also requires much more than ever-larger arrays of qubits. **One important step involves implementing “surface code” error correction that can detect and correct for disruptions in the fragile quantum states of individual qubits.** **Another step involves figuring out how to map software algorithms to the quantum computing hardware.** A third crucial issue involves engineering the local electronics layout necessary to control the individual qubits and read out the quantum computing results.



- Intel's roadmap suggests researchers could achieve 1,000-qubit systems within 5 to 7 years.
- 17-qubit arrays have the minimum number of qubits necessary to perform surface code error correction.
- Intel has developed packaging to prevent radio-frequency interference with the qubits, and uses flip chip technology, enabling smaller and denser connections to get signals on and off the chips.

CES 2018: IBM Shows Off The World's Largest Quantum Computer

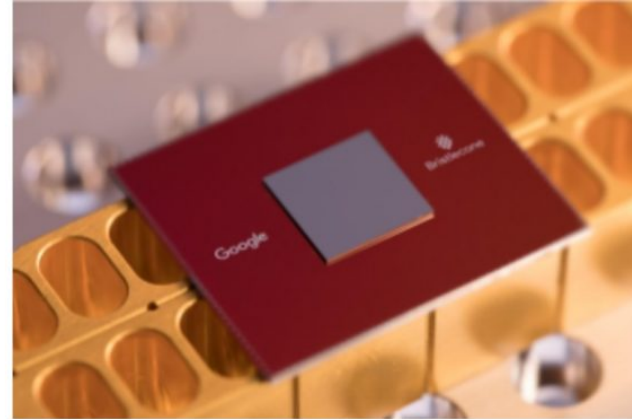
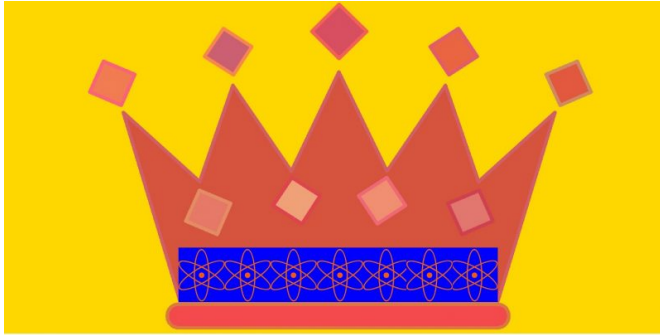
- The promise of the quantum computer is to solve problems that typical computers will never be able to tackle, by bringing unheard-of power and speed to computing through leveraging the principles of quantum physics.
- Developing new synthetic materials, allowing for faster machine learning, and providing an advanced back-end to power consumer apps. These are just some of the potential applications of the **first ever 50-qubit quantum computer prototype** displayed at this year's CES conference in Las Vegas, Nevada.



IBM is also working with commercial partners in the finance, materials, automotive, and chemistry industries by allowing them access to the groundbreaking computing power these devices offer.

Google reclaims quantum computer crown with 72 qubit processor

by [TRISTAN GREENE](#) — in [ARTIFICIAL INTELLIGENCE](#) 2018 March 6



- Google unveiled the world's largest quantum computer processor to date. Dubbed **Bristlecone**, it's a 72-qubit gate-based superconducting system that blows the previous best, [IBM's 50-qubit processor](#), out of the water. The race to build the world's first useful quantum computer is nearing its end.
- The Mountain View company's [Research at Google](#) team created the 72-qubit processor by scaling its previous 9-qubit system. Its obvious goal is to provide the power and stability necessary for quantum computers to become functionally useful.

Prototype quantum computers

Rigetti: 8-qubit and 19-qubit superconducting quantum processors, accessible to users over the cloud through our open source software platform [Forest](#)

IBM Q: 5-qubit and 16-qubit (open free), 20-qubit & 50-qubit (paid)

Available to Taiwan users in 2019

The screenshot displays the Forest quantum computing interface. At the top, there's a 'New experiment' section with buttons for 'New', 'Save', and 'Save as'. Below this is a toolbar with a '< >' button, a 'Switch to Qasm Editor' button, and status information: 'Backend: ibmqx4', 'My Units: 15', and 'Experiment Units: 3'. To the right of the toolbar are 'Run' and 'Simulate' buttons. The main area shows a quantum circuit diagram with five qubits, q[0] through q[4], each initialized to $|0\rangle$. The circuit includes an X gate on q[0], an H gate on q[1], a T gate on q[2], and an H gate on q[4]. A classical control line labeled 'c 0' is shown at the bottom. On the right, a 'GATES' panel lists various quantum gates: id, X, Y, Z, H, S, $S^\dagger$, T, and $T^\dagger$. There is also an 'Advanced' checkbox. Below the gates is a 'BARRIER OPERATIONS' section with icons for a barrier and a π^2 phase gate.



Synced

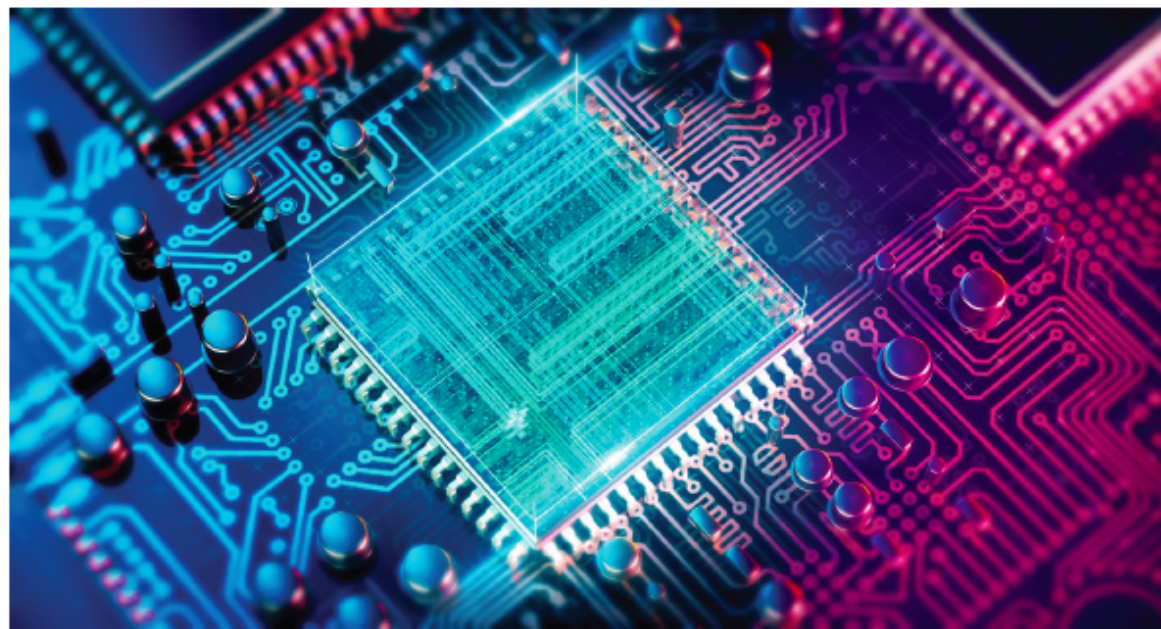
Follow

AI Technology & Industry Review - www.syncedreview.com || www.jiqizhixin.com ||

Subscribe: <http://goo.gl/Q4cP3B>

Feb 23 · 3 min read

Alibaba Launches 11-Qubit Quantum Computing Cloud Service



D-Wave Launches Free Quantum Cloud Service

Canadian company joins IBM and Rigetti in offering online access to pricey hardware

By **Mark Harris** (/author/mark-harris)

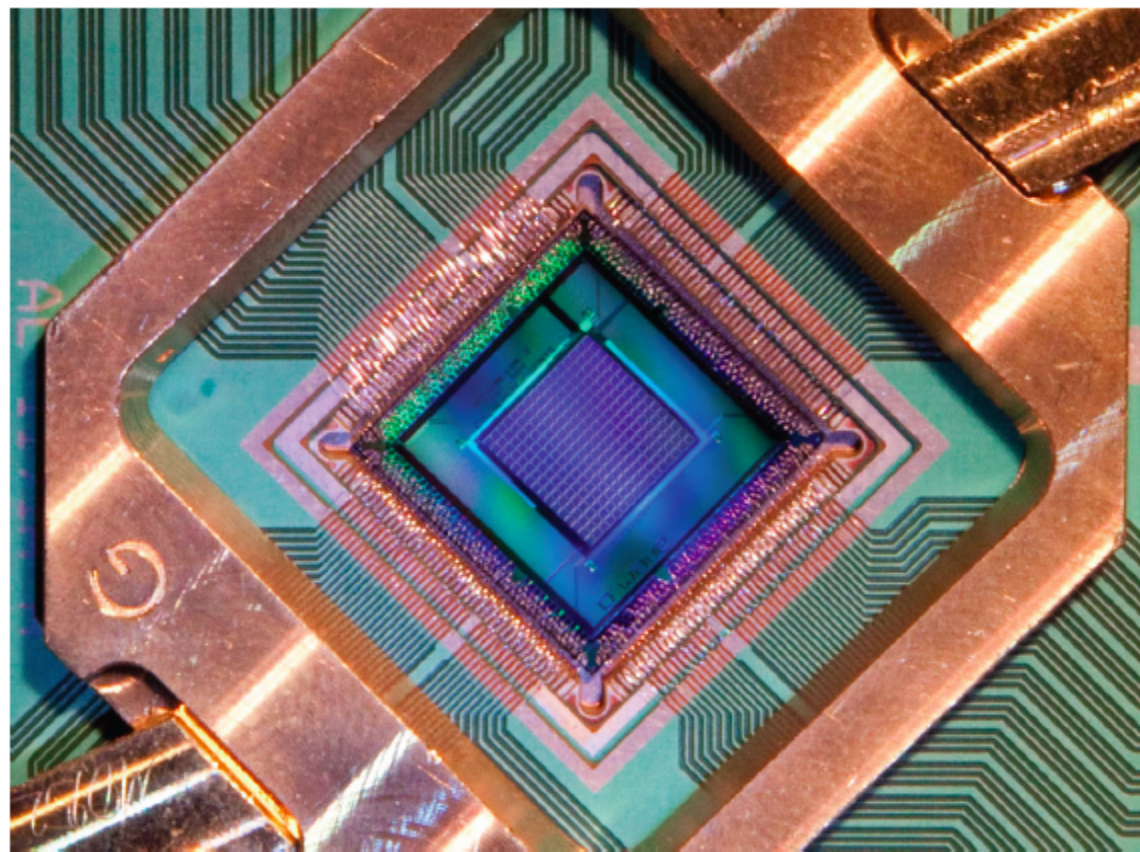


Photo: D-Wave Systems

D-Wave's latest 2,048-qubit processor has to be kept close to absolute zero to function.

Quantum computing could someday supercharge artificial intelligence, accelerate drug discovery, and even reduce traffic jams. But existing quantum computers, which have only a modest, if any, advantage over their classical brethren, are expensive, finicky beasts. Even if you could afford the US \$15 million to buy a D-Wave 2000Q quantum annealer (https://www.dwavesys.com/sites/default/files/D-Wave%202000Q%20Tech%20Collateral_0117F.pdf) [PDF], for example, you would need experts to maintain the ultracold operating conditions its processor requires.

Until today, that is, when Canadian startup D-Wave Systems Inc (<https://www.dwavesys.com/home>) launched a real-time online quantum computing environment called Leap (<https://cloud.dwavesys.com/leap/>). Leap is the latest addition to the quantum cloud—services that virtualize quantum computing for almost anyone with a computer and a broadband connection to use.

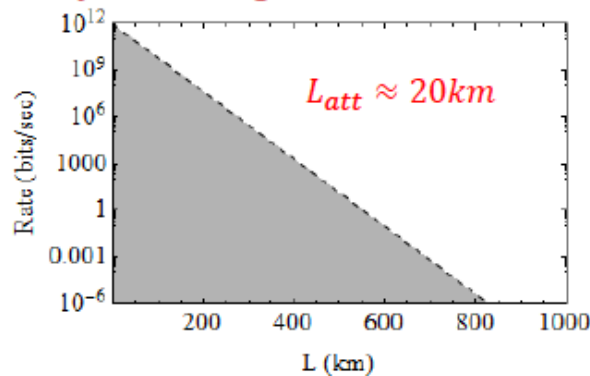
Leap allows anyone to sign up, giving them one minute of time on a cloud-connected 2000Q each month. That might not sound like much, but a key advantage of quantum computing is to be able to solve in milliseconds

problems like factoring large numbers, optimizing routes, or calculating molecular structures that could take traditional computers days or weeks.

量子通訊主要的挑戰

光纖傳輸衰減

Major Challenge – Fiber Attenuation



No clone theorem !

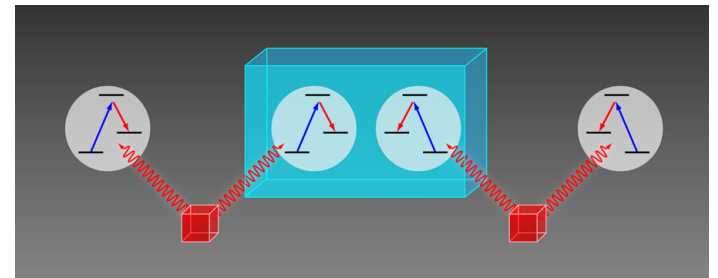
(量子態無法複製)

需發展量子中繼器(quantum repeater)以突破200km限制

關鍵技術: 量子記憶體、量子隱傳、entanglement

swapping

國內過去儲存效率領先國際的光子量子記憶體(Phys. Rev. Lett. 110, 083601, 2013)



光子：飛行量子位元, 200km 衰減 ➡ 衛星量子通訊

European scientists propose world's largest quantum network, between Earth and the ISS

April 9, 2013 at 8:50 am

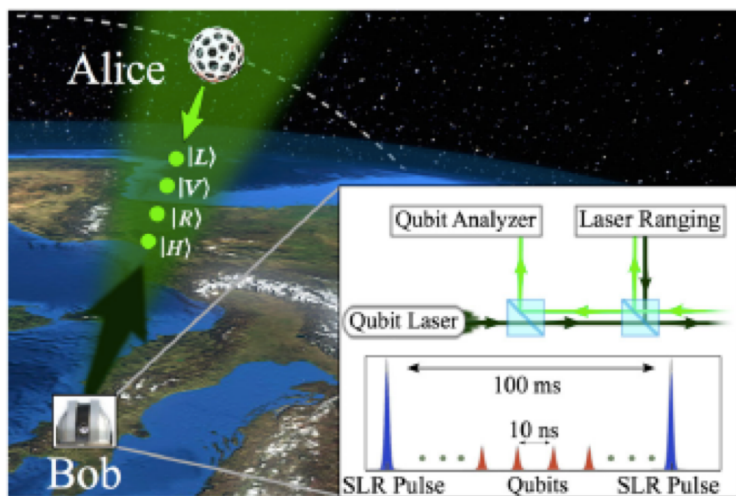


FIG. 1 (color online). Scheme of the satellite QKD demonstration. Qubit pulses are sent at a 100 MHz repetition rate and are reflected back to the single photon level from the satellite, thus mimicking a QKD source in space. Synchronization was performed by using the bright SLR pulses at a repetition rate of 10 Hz.

Phys. Rev. Lett. **115**, 040502 (2015)
義大利團隊, qubit error ratio 4.6%

世界第一個量子通訊衛星 (中國), viable for 300s

(中央社台北18日電) 2017/06/18 13:52

陸首顆量子衛星墨子號 可全球秘密通訊



Phys. Rev. Lett. **120**,
030501(2018)

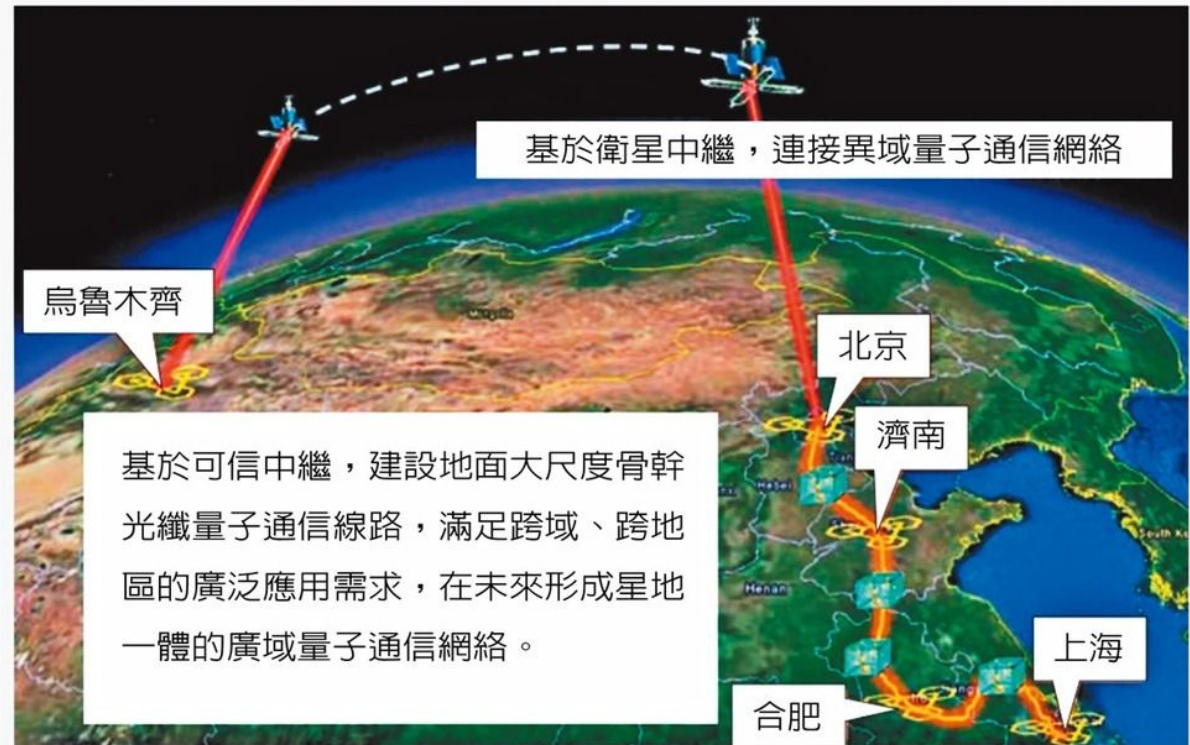
量子保密通信 京滬幹線開通

全長逾2000公里的量子保密通信骨幹網絡「京滬幹線」2017/09/29 開通，是世界首條量子保密通信幹線。中科院院長白春禮昨日到「京滬幹線」北京控制中心，用量子加密視頻會議系統與合肥、濟南、上海、新疆南山等地的科研人員對話，並通過「墨子號」量子衛星與奧地利地面站的衛星量子通信，與奧地利科學院院長塞林格(Anton Zeilinger)作了世界首次洲際量子保密視頻通話。交通銀行、工商銀行、阿里徵信已開始使用此幹線加密實時交易和數據傳輸。

量子通信是迄今唯一被嚴格證明無條件的安全通信方式，可以有效解決信息安全問題。「中國量子通信技術已經走在了世界前列，並持續保持著其優勢地位。我們的量子保密通信技術比國外領先了4-5年。」潘建偉說。

京滬幹線

示意圖



量子通訊發展概況

世界首個商用量子通信專網濟南測試成功



世界首個大型商用量子通信專網於**2017年7月**在濟南完成第一階段黨政機關量子通信專網測試，與周邊數百平方公里的，近200個終端進行保密通信。它是目前世界上規模最大、功能最全的城域量子通信網路，業務可涵蓋政務、**金融**、政法、科研、教育等五大領域，能為用戶提供基於量子加密的電話、傳真、文件和文本通信業務。

Source: MOST_量子科技研究與發展規劃案報告(管希聖)

世界各國量子通訊網進行近況

UK

QKD network integrated with commercial communication

Austria

QKD network of 8 nodes demonstrated

China

2,000 km QKD network between Shanghai and Beijing is underway



USA

Installing QKD network

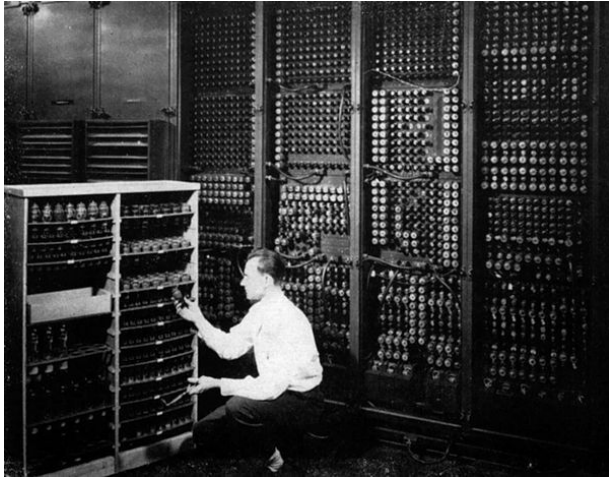
Japan

QKD network to transmit sensitive Genome data

世界各國的投入、台灣的發展與機會

量子技術の展望

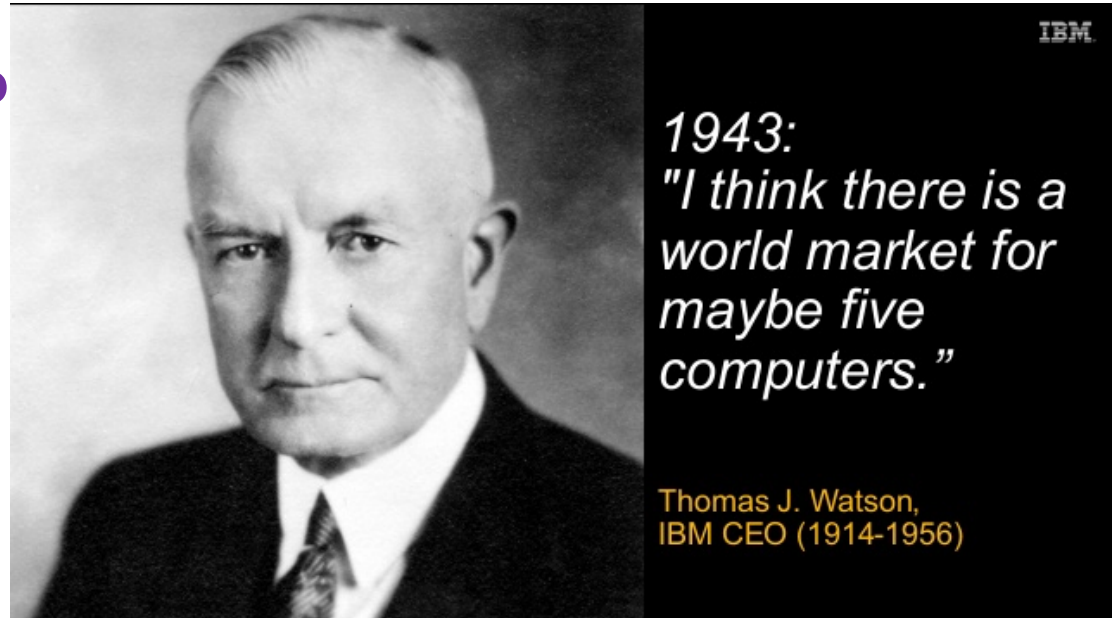
Eniac 1943



Quantum Technolo



Recall



量子科技發展評估



Status

Near-term applications that are beyond the capability of classical computers

50 -100 qubits

1000

1000-10,000

1000,000...

Noisy Intermediate quantum computing regime 、 quantum simulation 、 optimization

Intermediate scale & rate quantum communication

Probably 5-10 years

Universal Quantum computing

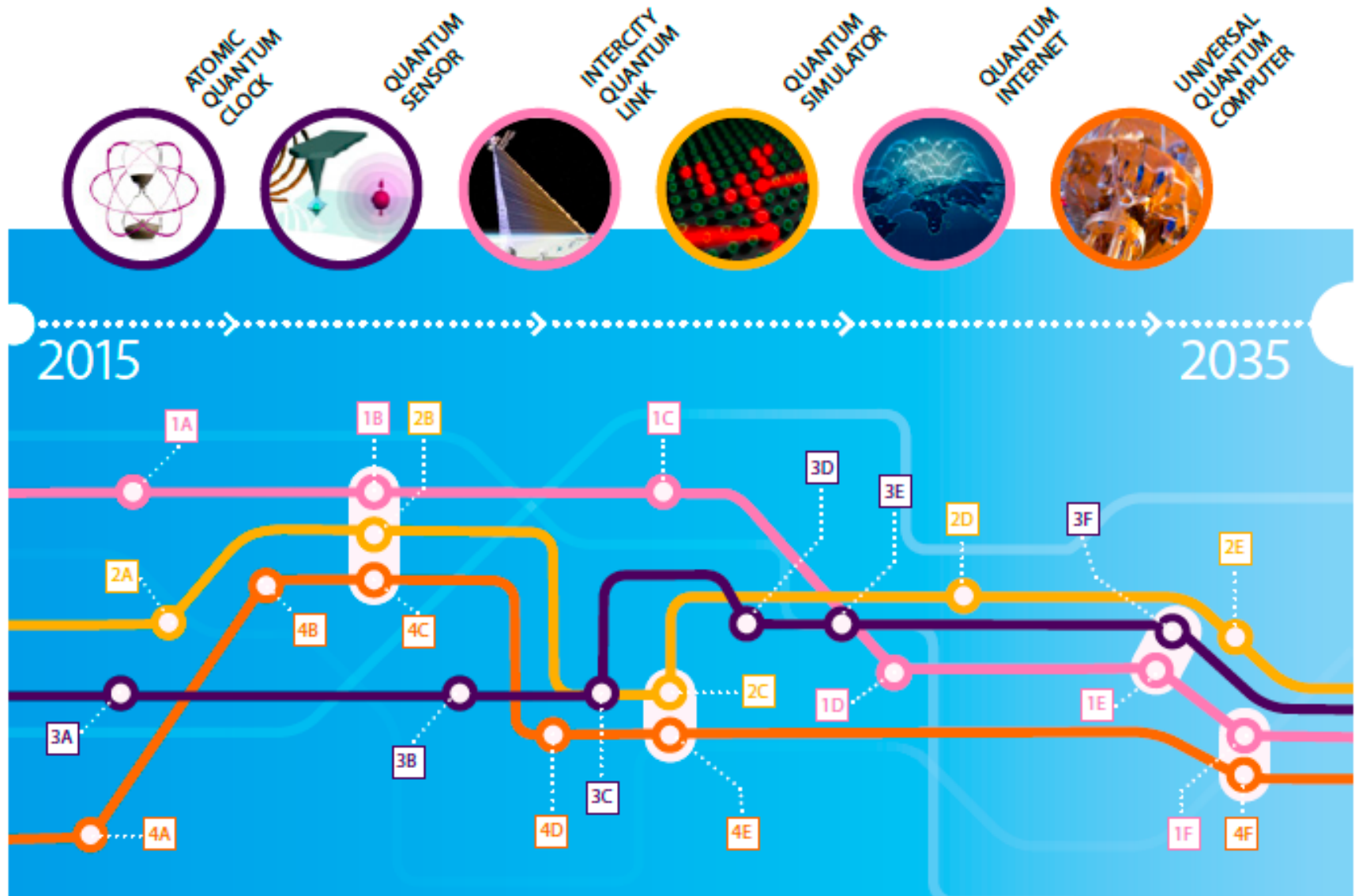


200km

1000km

global quantum network

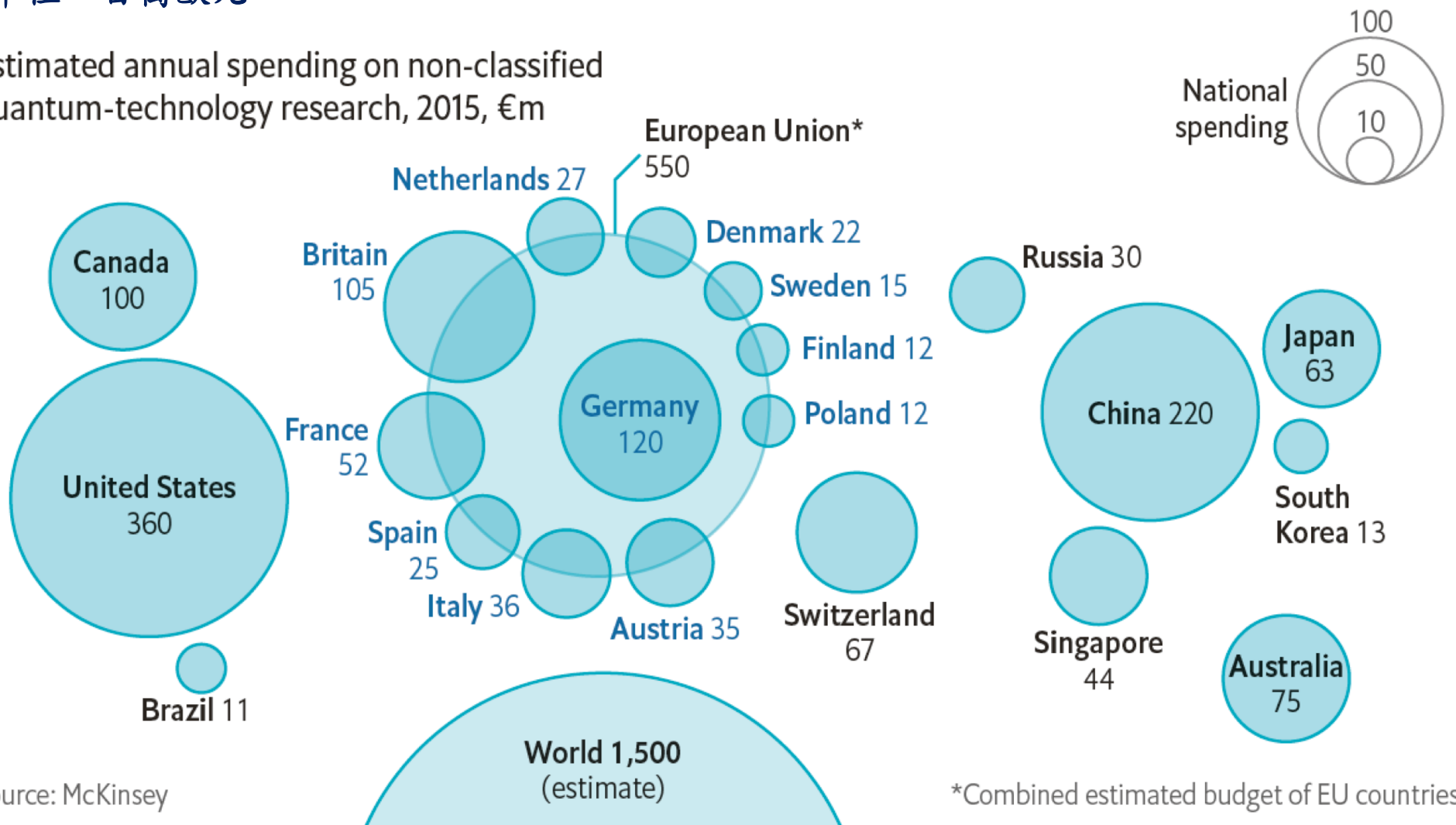
Quantum Technologies Timeline



2015世界各國量子科技(非機密)之投入

單位：百萬歐元

Estimated annual spending on non-classified quantum-technology research, 2015, €m



2015世界各國量子科技的專利數

Patent applications to 2015, in:

Quantum computing



Quantum cryptography

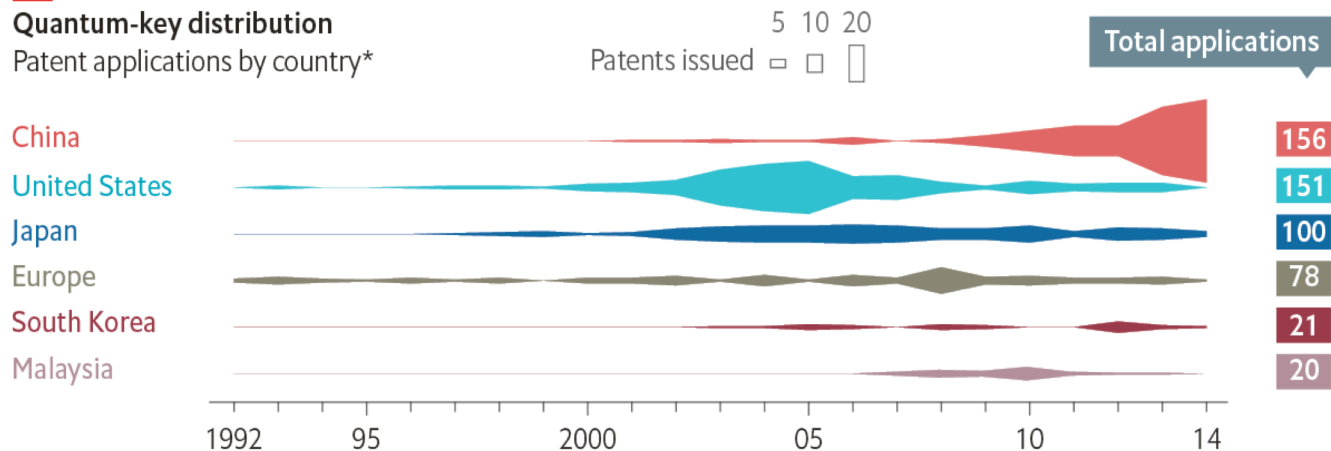


Quantum sensors



Quantum-key distribution

Patent applications by country*



Sources: UK Intellectual Property Office; European Commission

*By location of corporate headquarters

世界各國量子科技投入與發展概況

- 基於量子科技的巨大潛在價值，歐美各國都在積極整合各方面研究力量和資源，展開協同研究。
- 歐洲地區已有超過20個國家投入量子資訊與量子科技的研究，並分別提出了相關的大型計畫。歐盟委員會於2016年5月發表了量子宣言(Quantum Manifesto)，號召歐洲國家共同發起一項預算高達十億歐元的量子科技旗艦計畫。已獲得許多歐洲產業、研究機構以及科學家們的支持，此旗艦計畫於2018年啟動。在宣言中表明了第二次量子革命正在世界各地展開，各國皆期望藉此行動在科學、工業和社會等方面能取得革命性的進步，這項計畫的目的在使歐洲於這場技術革命中能夠保持領先地位。

世界各國量子科技投入與發展概況

- **美國**於2000年即把量子電腦的發展列為國家科技戰略目標之一。2009年白宮國家科技委員會提出聯邦量子資訊科學展望白皮書。**美國國家科學基金會(NSF)**於2016年就將量子科技應用定位其未來發展與投資的五個主軸之一。
- **英國**政府成立了量子科技戰略顧問委員會擬定了國家量子技術戰略，於2013年**投入2.7億英鎊成立英國國家量子科技計畫**，幫助量子行業在英國紮根。又於**2015年提出英國國家量子科技策略並承諾將投入1,500萬英鎊於量子科技人力資源培育**，預備為未來的勞動力提供高級技能，以實現量子科技能為英國帶來利益。
- **加拿大**資助量子計算基礎研究至2015年已累積投入超過 **2,500 萬加元**，除了相關的量子技術方面的研究外，更以建造通用型量子電腦為主要目標。**滑鐵爐大學於 2002 年成立了量子計算研究所 (IQC)**，該研究所同時在加拿大政府與民間企業資助下不斷擴大規模，為加拿大指標性的量子相關技術研究機構**(15年約5億加幣;約119億台幣)**。
- **澳洲**剛核准的新一期7年計畫(2017-2023)資助經費為**3,370萬澳幣**資助ARC Centre of Excellence for Quantum Computation and Communication Technology，以及資助資助經費為**3,190萬澳幣** ARC Centre of Excellence for Engineered Quantum Systems新一期7年計畫(2017-2023)，**參與的研究機構配合款為994萬澳幣(總經費約為新台幣10億747萬元)**。

世界各國量子科技投入與發展概況

- **日本**2000 年日本科學技術振興機構（JST）在《先進技術探索研究計畫》中，設定了為期5年的量子計算與資訊研究項目。**日本文部科學省**決定從2018年開始，在10年中投入**300億日元(約80億台幣)**用於製造量子電腦。
- **新加坡**政府於2007年斥資**1億5000萬新元(約33.56億台幣)**資助新加坡國立大學成立當時世界最大的量子科技中心 (Center for Quantum Technology). 此為東南亞第一個量子資訊科學研究中心，並以成為此領域的領導者為目標積極發展相關研究。
- 中國在2015年習近平總書記在關於“**十三五**”規劃建議的說明中明確指出，要在**量子通信等領域部署體現國家戰略意圖的重大科技專案**。2016年中國國務院發布《國家創新驅動發展戰略綱要》點出十大產業技術體系創新，其中在發展引領產業變革的顛覆性技術方面，提出大陸**應要積極開發量子資訊等技術**。2016年8月發射世界首顆量子通訊實驗衛星墨子號，並計畫在2030年建成全球化的量子通訊網路；並在2017年宣佈未來5年計劃投入**1,000億元**在合肥打造量子信息國家實驗室園區。



House Passes \$1.275B National Quantum Initiative

By John Russell

September 17, 2018

Last Thursday the U.S. House of Representatives passed the National Quantum Initiative Act (NQIA

(<https://www.congress.gov/bill/115th-congress/house-bill/6227/text>)) intended to accelerate quantum computing

physicsworld

QUANTUM NEWS

US invests \$249m in quantum information science as White House unveils strategic overview

28 Sep 2018 Hamish Johnston

AdChoices 

Leading Solution Providers



(<https://tci.taborcommunications.com/sponsor-adaptive>)

業界的投入

Google

intel

IBM

NEC

Honeywell

Microsoft

LOCKHEED MARTIN

BOEING

NO BARRIERS
WARRIORS

Raytheon

AIRBUS
GROUP

Alibaba Group
阿里巴巴集团

NVIDIA

SIEMENS

hp

NOKIA Bell Labs

AMGEN

Atos

IBM teams up with Samsung,
JPMorgan to develop quantum
computing

startups

D-Wave
The Quantum Computing Company™



IONQ

rigetti

1QBit

CQC

CAMBRIDGE
QUANTUM
COMPUTING
LIMITED

我國的因應與規劃

成立評估小組進行評估計畫



國立台灣大學物理系教授 管希聖 (E-mail: goan@phys.ntu.edu.tw)

國立成功大學物理系教授 陳岳男 (E-mail: yuehnan@mail.ncku.edu.tw)

國立清華大學光電工程研究所教授 李瑞光 (E-mail: rkleee@ee.nthu.edu.tw)

中研院原子與分子科學研究所副研究員 陳應誠 (E-mail: chenyc@pub.iams.sinica.edu.tw)

科技部 開會通知單

開會事由：量子科技研究與發展會議

主持人：陳部長良基

出席者：許次長有進;廖司長婉君;台大物理管希聖教授;清大光電李瑞光教授;成大物理陳岳男教授;中研院原分所陳應誠副研究員;雪梨大學謝明修教授

科技部：透過教育部深耕計畫中心，選擇加碼**前瞻量子科技研究中心**

科技部拚量子電腦 年砸7千萬輔導團隊研發

發稿時間：2018/04/10 11:48 最新更新：2018/04/10 11:48 字級： A- A+

(中央社記者朱則瑋台北10日電) 量子電腦是未來重要科技技術，科技部推動量子電腦專案計畫，每年新台幣7000萬元經費，約3至5年時間，結合台灣半導體產業，輔導團隊研發量子電腦技術，並培育相關人才。

Quantum Technology Centers/Projects in Taiwan

~ 140 Million NTD (~ 3 Million Euro)/Year, including NTHU Center for Quantum Technology, IBM-NTU Quantum Computer Hub, and three large-scale Quantum Information and Technology Projects.

Quantum Technology Centers /projects

AMO platform

Silicon-based platform

Superconductor/topological platform

Theory platform

Quantum communication

- Quantum memory
- Quantum repeater
- Quantum key distribution
- Single photon source

Quantum simulation/metrology

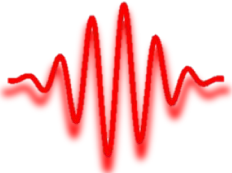
- Squeezed light /Continuous variable qubit
- Precision measurement
- Ultra cold atom simulator
- Silicon photonics

Quantum Materials

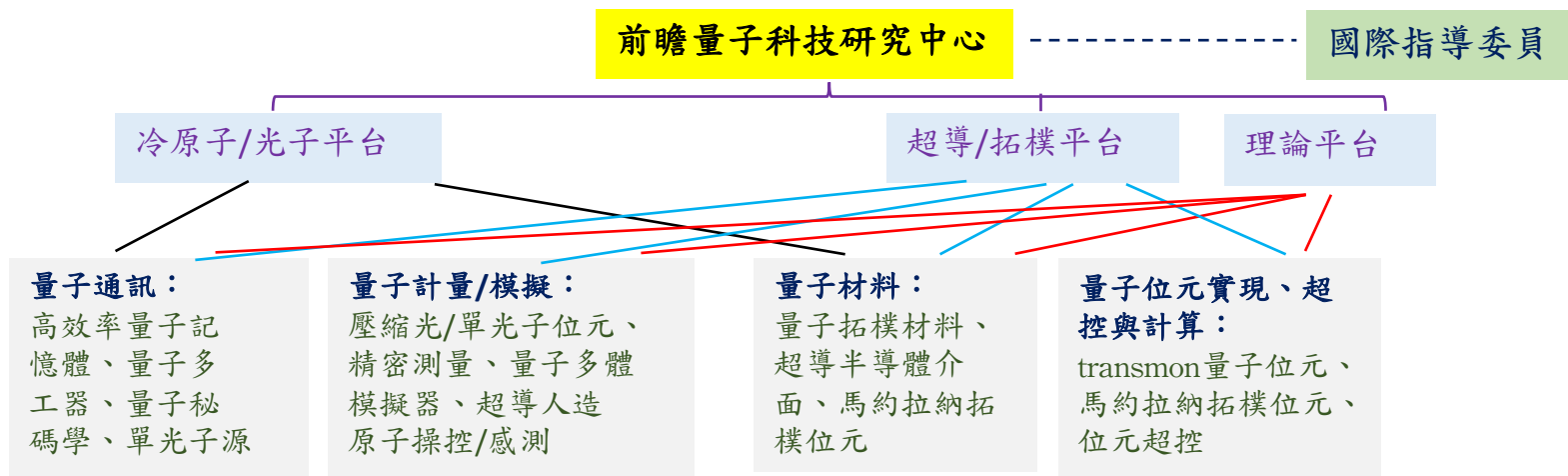
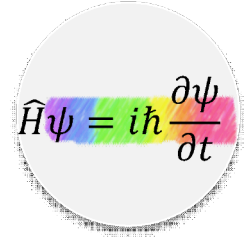
- Quantum topological materials
- Majorana fermion based qubit
- Superconducting/silicon hybrid system

Qubit realization manipulation and computation

- Transmon qubit
- Majorana qubit realization and manipulation
- Silicon-based qubit



前瞻量子科技研究中心 (Center for Quantum Technology)

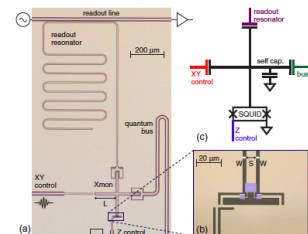


整合國內主要從事量子技術的研究人員：中研院、台大、交大、清華、成大等50人團隊

Focused subjects

- 多個超導量子位元的製作與量子計算之實現
- 建立量子通訊網路及測試量子密鑰協議的平台
- 實現連續變數(continuous variable)型的量子訊息
- 實現馬約拉納費米子(Majorana fermion)的量子位元

+ 培育量子技術人才



發展量子通訊網路

* 建立校園短距離(清大-交大-量測中心)點對點量子通訊測試平台

--以光纖網路、通訊波段($\sim 1.55\mu\text{m}$)實現
與測試密鑰分發

* 發展量子中繼器關鍵技術：

-- 發展量子記憶體以冷原子氣體或固態材料
為基礎，達成儲存效率90%

* 量子多工器：光量子態之互相轉換效率達世界第一。

* 發展量子通訊所需的高效能單光子源(窄頻單模、高亮度)：亮度達到一秒鐘產生接近一百萬顆($10^6/\text{s}$)的單光子，以提高量子密鑰的輸送效率。線寬達到100千赫(kHz)以下，以可提昇量子通訊的糾纏態製造率。

結合上述單光子源，發展以光纖為骨幹的遠距離(200km)量子通訊。

可能參與合作的對象：中華電信、中科院....

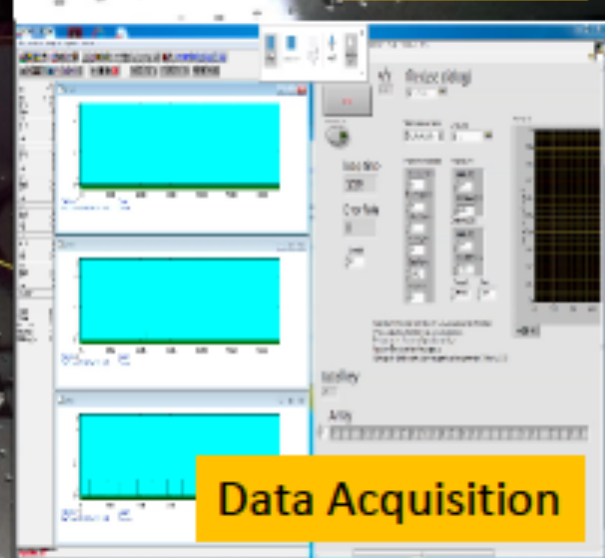
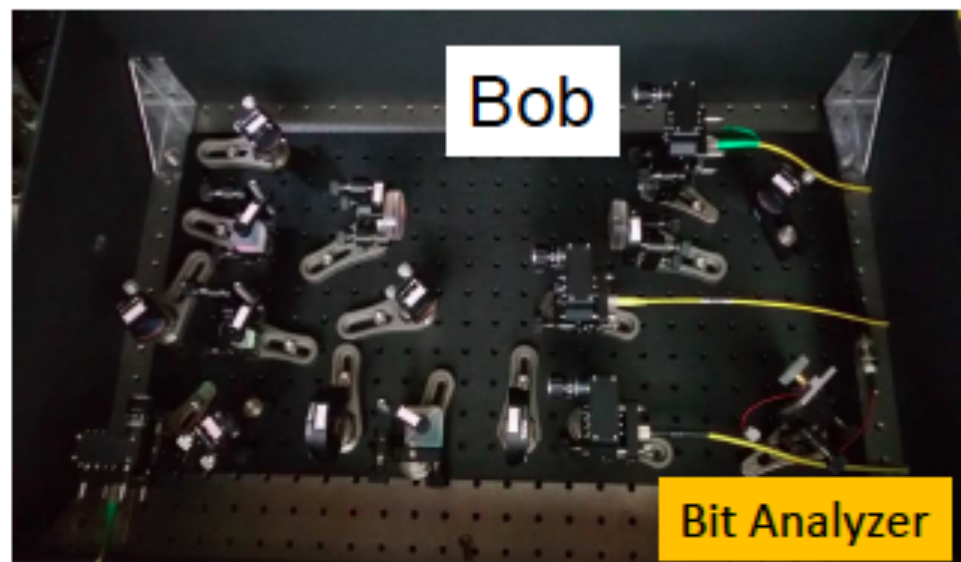
Quantum Key Distribution (QKD) Network



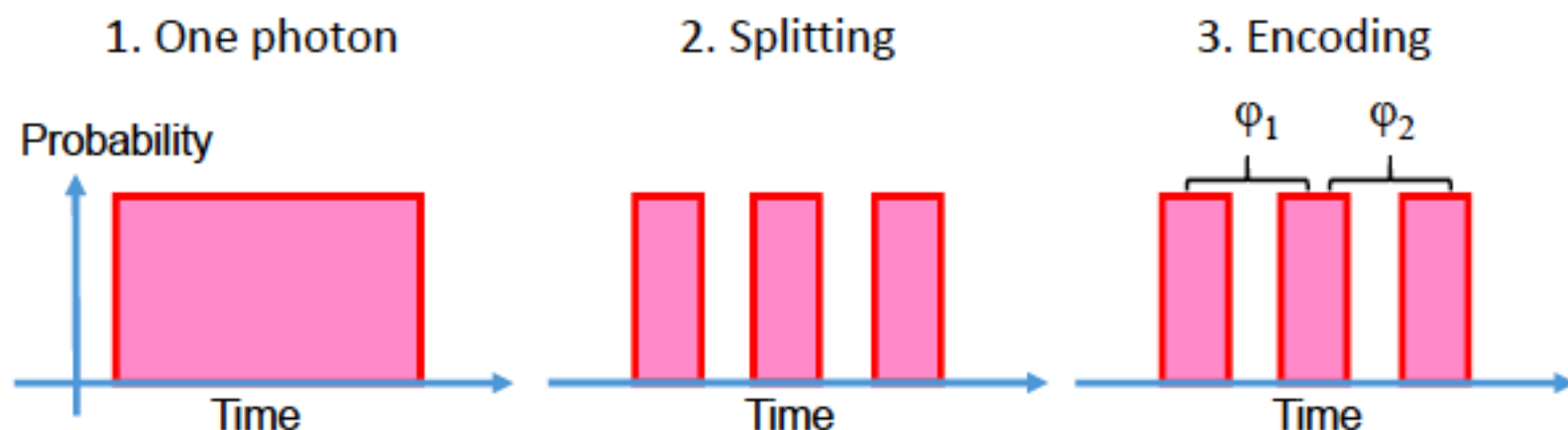
Quantum Key Distribution (QKD) Network



Status of Our QKD System



Bit Generator (Alice)

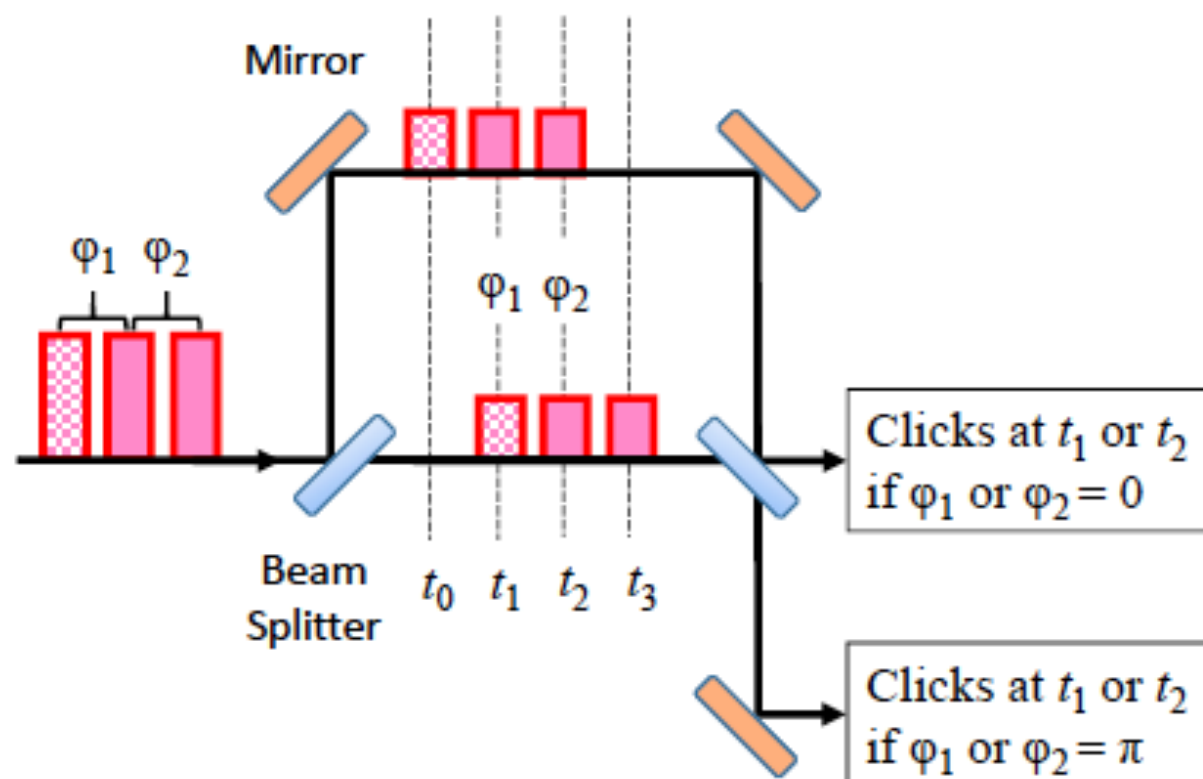


(ϕ_1, ϕ_2) are randomly picked from phases 0 and π , corresponding to bits 0 and 1, so that the single photon is in one of the non-orthogonal states

$$|\psi\rangle = \frac{1}{\sqrt{3}} (|1\rangle_a |0\rangle_b |0\rangle_c \pm |0\rangle_a |1\rangle_b |0\rangle_c \pm |0\rangle_a |0\rangle_b |1\rangle_c)$$

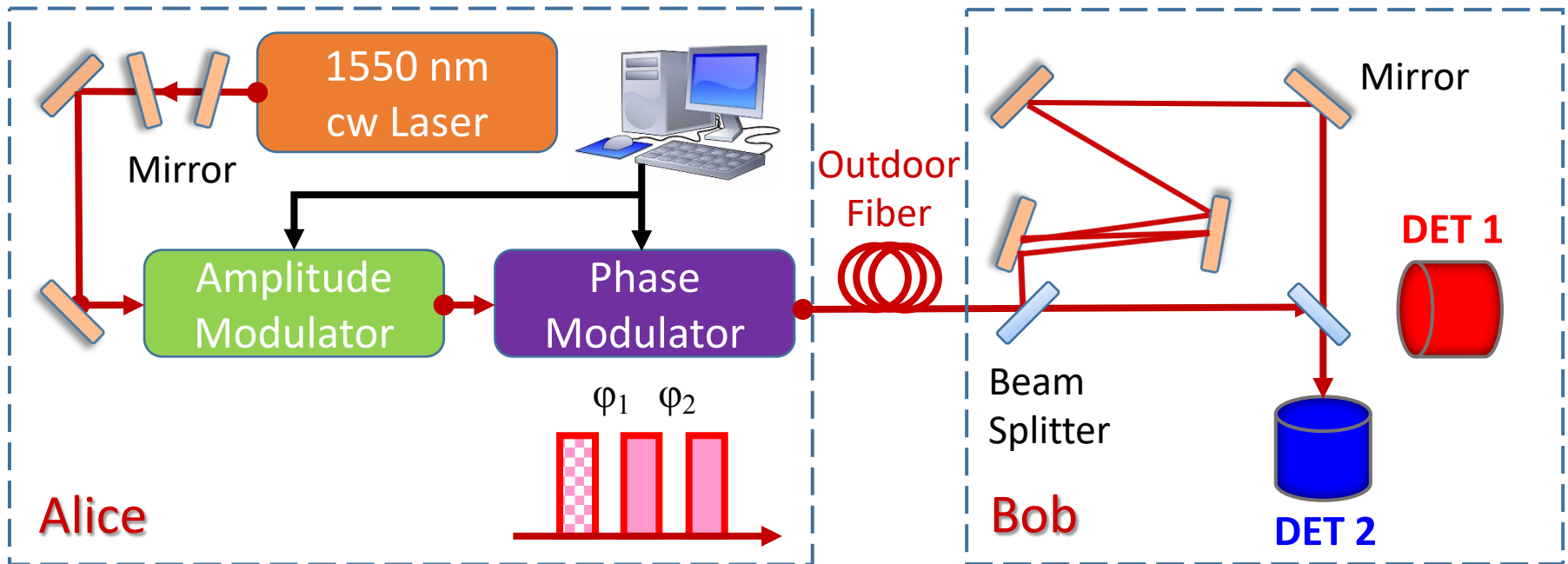
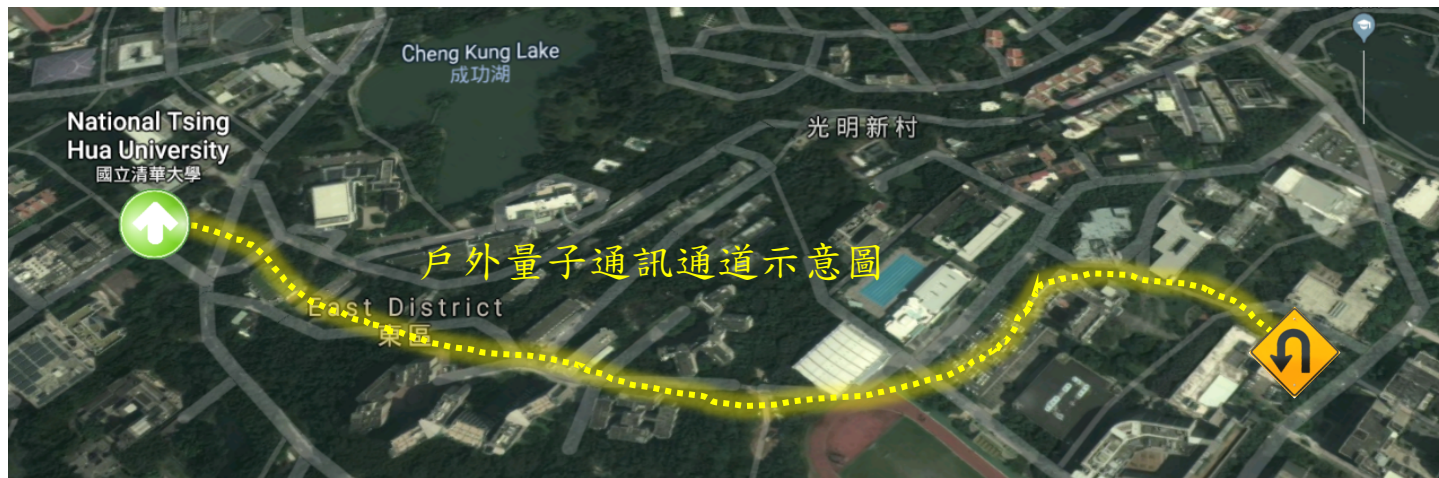
and cannot be identified by a single measurement.

Bit Analyzer (Bob)



Field Test of Quantum Key Distribution

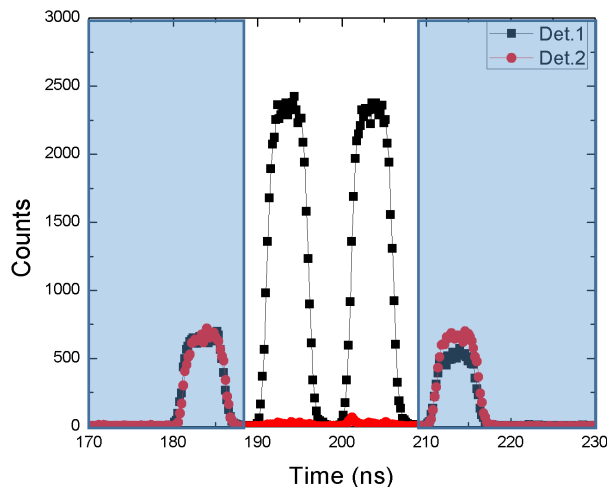
褚志崧副教授、高永成、黃聖軒、吳至翔、張進宣



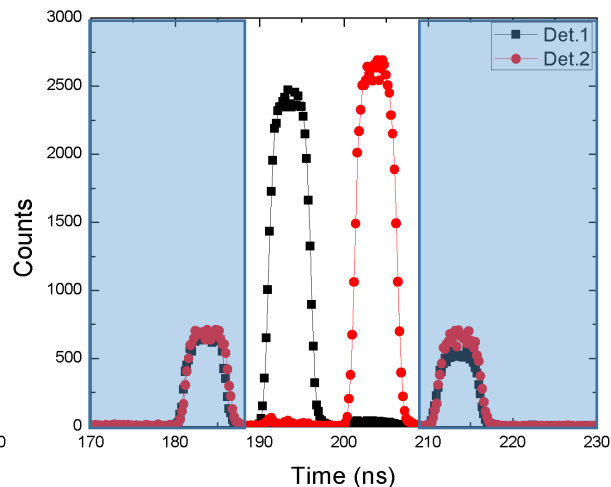
Field Test of Quantum Key Distribution

褚志崧副教授、高永成、黃聖軒、吳至翔、張進宣

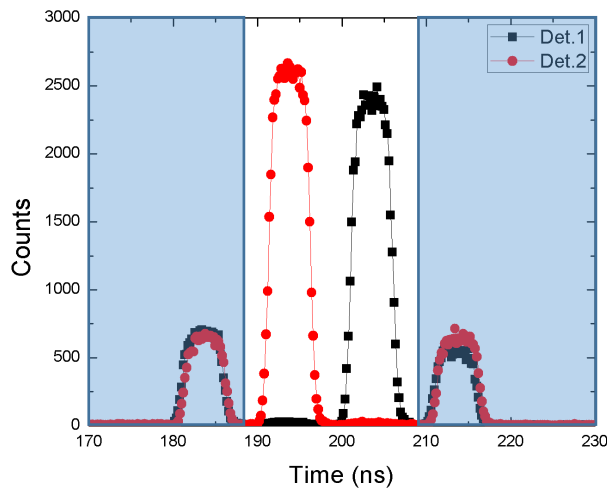
Alice's Bits: (0,0)



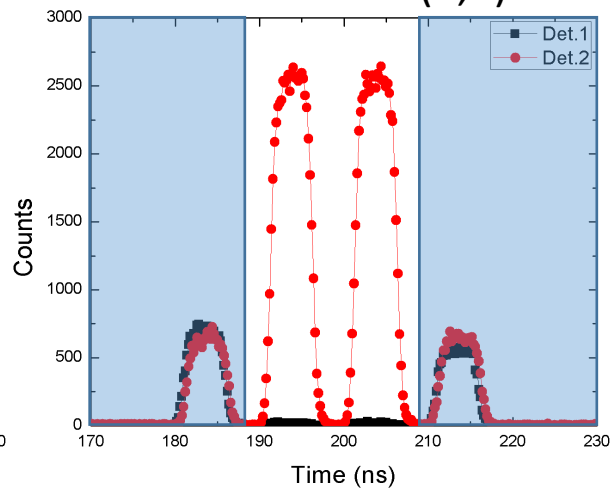
Alice's Bits: (0,1)



Alice's Bits: (1,0)



Alice's Bits: (1,1)



Fiber Length: 3.44 km

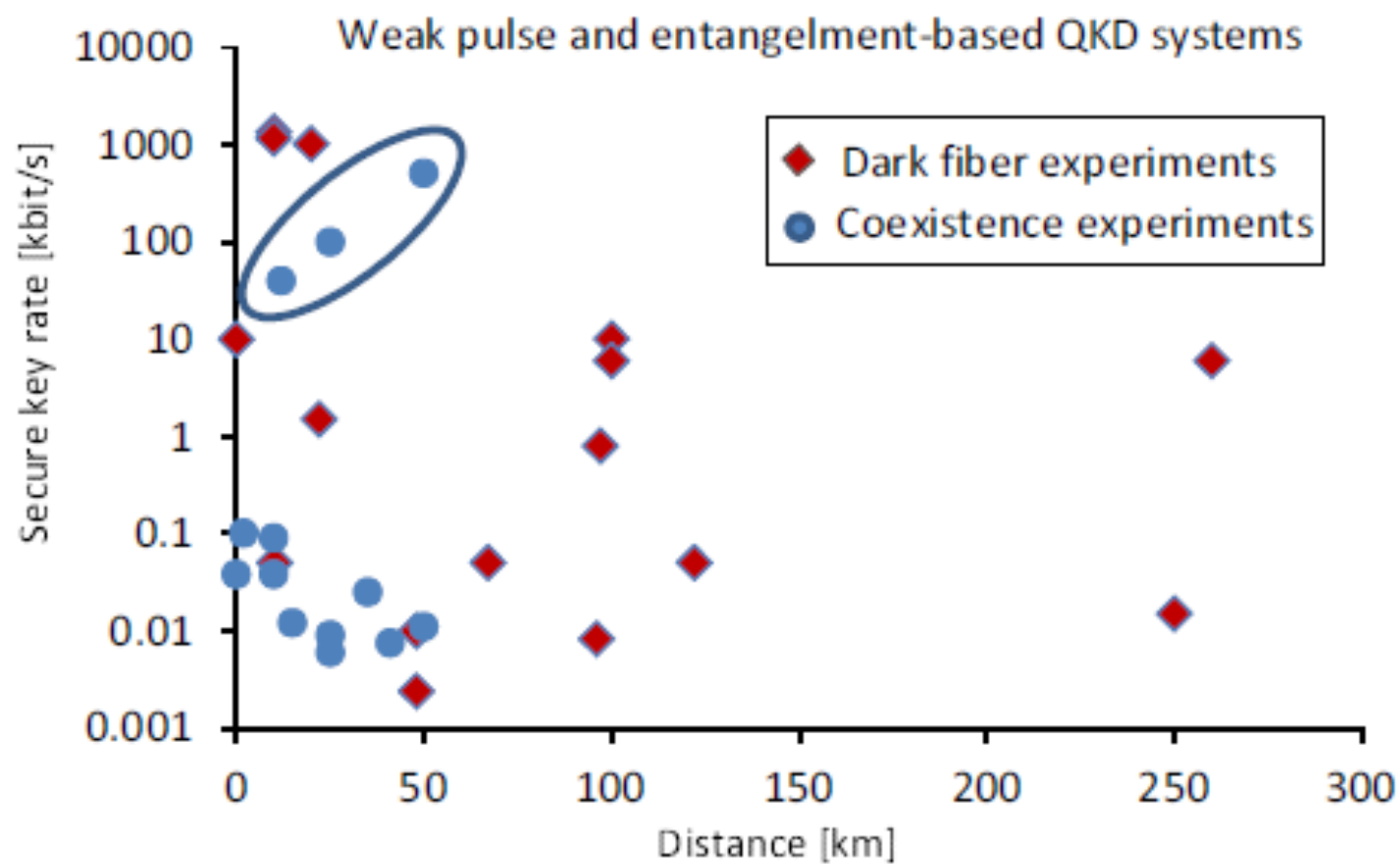
Source: 1550 nm attenuated laser pulses (average photon number = 0.1)

QKD Protocol: Differential-phase-shift QKD

Raw Key Rate: ~ 100 kbit/s

Bit Error Rate: ~ 2.5 %

Detectors' efficiency: 10 %



$$\hat{H}\psi = i\hbar \frac{\partial \psi}{\partial t}$$

量子計量與模擬

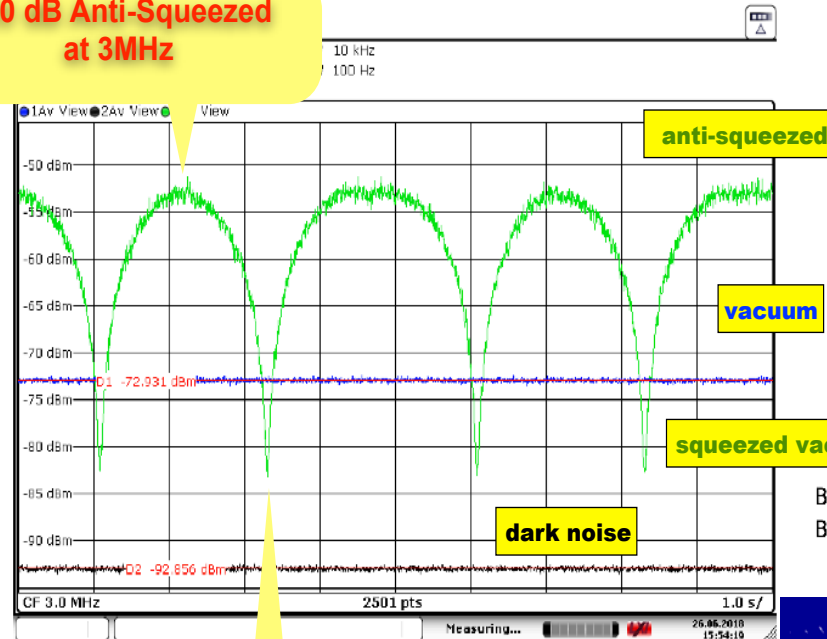
連續變數量子位元

Squeeze light :

OPO 532nm incident power: 96mW
MC output(LO beam)= 14.5mW

specialy ordered InGaAs Photodiodes
Laser Components GmbH $\phi=500\mu\text{m}$ QE $\geq$ 99%

**+20 dB Anti-Squeezed
at 3MHz**



Clearance= 20dB

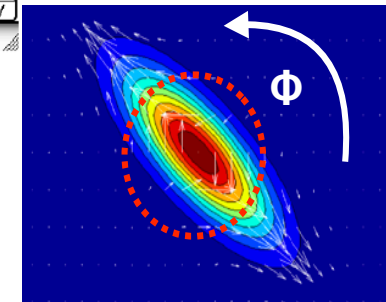
Zero Span mode at 3MHz
RBW=10kHz
VBW=100Hz

Blue Line: 14.5mW Vacuum noise
Black Line: Dark noise

**-10 dB Squeezed vacuum
at 3MHz**

Squeezing angle, Φ

Date: June 26th, 2018



量子電腦：

CES 2018: Intel's 49-Qubit Chip Shoots for Quantum Supremacy

By Jeremy Hsu (/author/jeremy-hsu)
Posted 9 Jan 2018 | 0:00 GMT

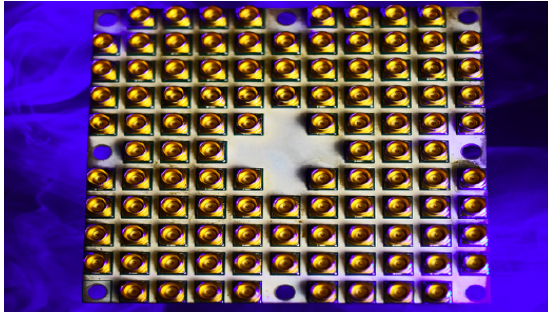


Photo: Intel
Intel's new 49-qubit superconducting quantum test chip is named Tangle Lake.

IBM Raises the Bar with a 50-Qubit Quantum Computer

by Will Knight November 10, 2017



New Scientist Live Limited VIP tickets remaining - Book now

DAILY NEWS 22 June 2017, updated 26 June 2017

Google on track for quantum computer breakthrough by end of 2017

=> 超導(Al/Si or Al/Sapphire Al_2O_3)

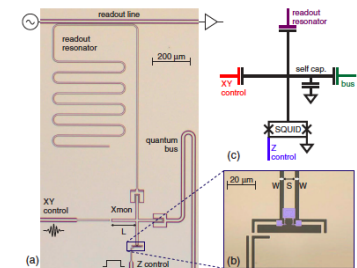
➡ 發展以超導為基礎的量子位元

- * 建立 Transmon/Xmon 元件(Al/Si)為基礎的量子位元
由2個以上少量子位元的製作與高保真度1至3個量子位元邏輯閘開始，
掌握多位元製作的訣竅

-- 標準晶片製程+微波技術與半導體製程相容，
微米等級、均勻性要求高

- * 以量子模擬物理系統為主要研究方向

- * 掌握技術後，尋找業界參與大尺度製程



Thank you for your attention!