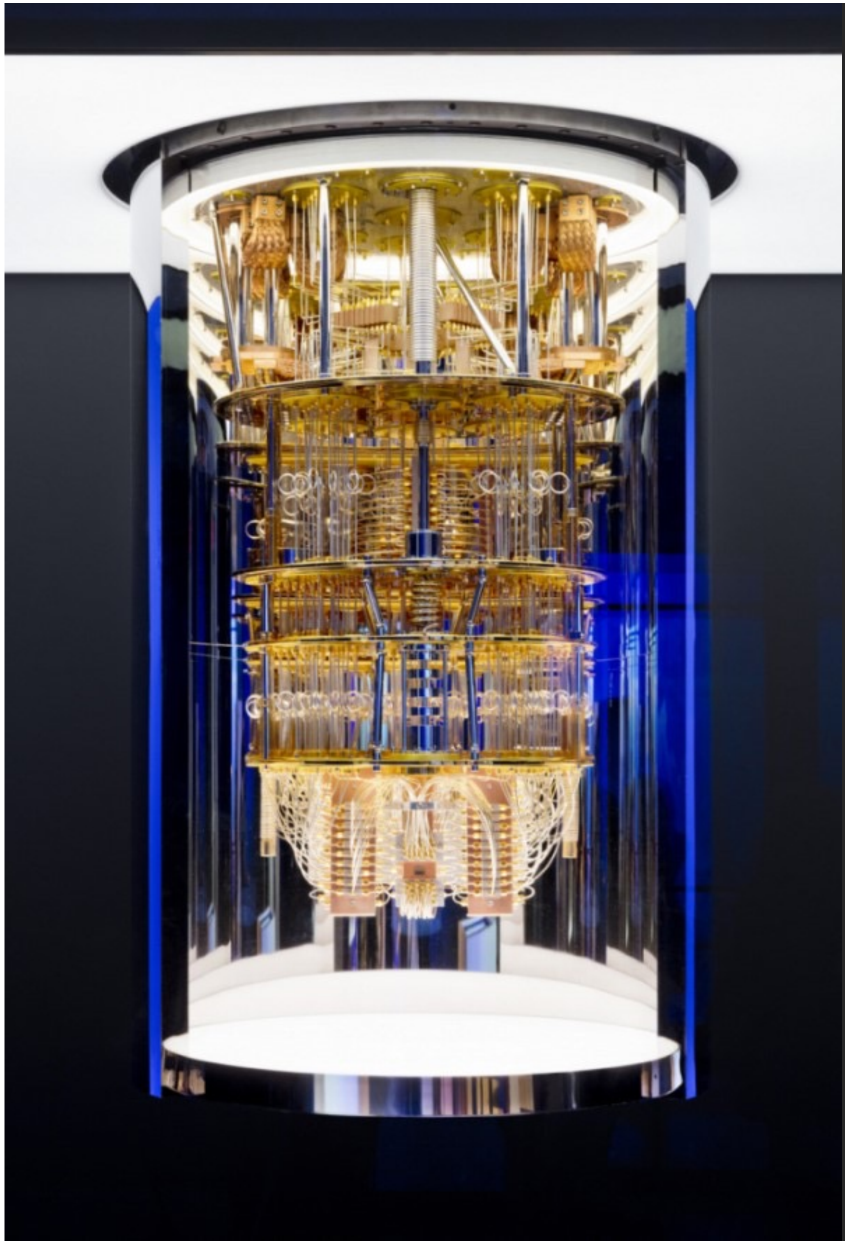

Lecture 7: Realization of Quantum Computing

COMP3366
Quantum algorithms & computing architecture

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Objectives:

- **[O1] Concepts:** DiVincenzo's criteria. Physical systems for implementing QC.

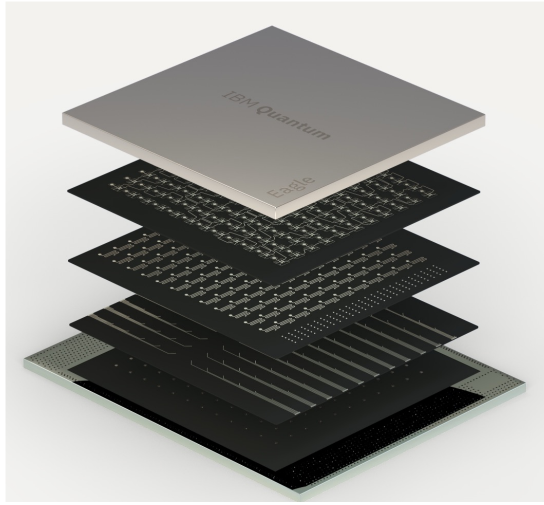
  (Working principle/Advantages/Disadvantages of NMR and superconducting QCs.)

- **[O2] Problem solving:** Understand the working principle of temporal labeling*.

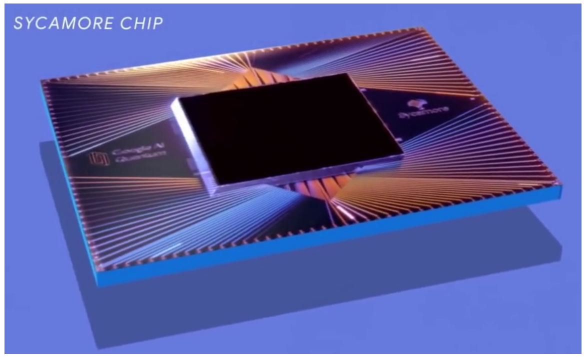
How are different quantum computers built?

What are the pros & cons of each implementation?

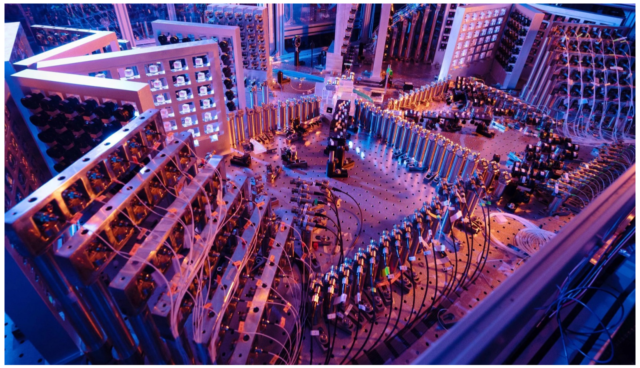
(Annealers) D-Wave systems, first commercially available quantum computational devices.



(Superconduct) IBM Eagle '21, 127-qubit



(Superconduct) Google Sycamore,
54 square grid lattice transmon qubits
First to claim "<u>quantum supremacy</u>"



(Optical) USTC Jiuzhang (九章) 2.0,
144 mode photonic circuit

(NMR) Table-top quantum computer:
Spin Q Gemini(mini)

See https://en.wikipedia.org/wiki/List_of_quantum_processors

Part I:
Guiding principles for quantum computer engineers

DiVincenzo's criteria

- Question: What criteria should a physical system satisfy to become a platform for quantum computing?
- Criteria for quantum information processing:

scalable → 可扩展到多 qubit
w~ → 可被控制

Computing (DiVincenzo)

1. A scalable physical system with well-characterized qubits
2. Ability to initialize the qubits. → $|0\rangle$ on
3. Long (de)coherence time. 相干时间

Memory

- **足够长的相干时间（long coherence time）**
  - 量子比特会因与环境相互作用而失去量子特性（退相干，decoherence）。
  - 相干时间必须远长于执行单个量子门操作所需的时间，否则计算会在完成前就“崩溃”。

4. Universal set of quantum gates.
5. Measurement of qubits and read-out of quantum information.

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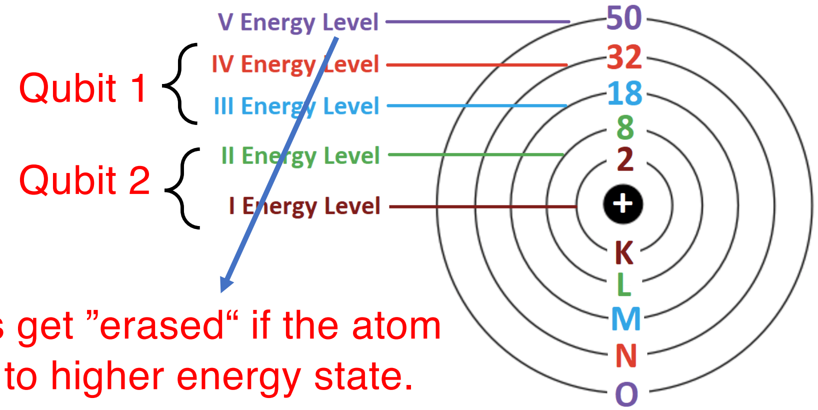
6. Interconvert stationary and flying qubits.
7. Transmission of qubits over long distances.

Communication

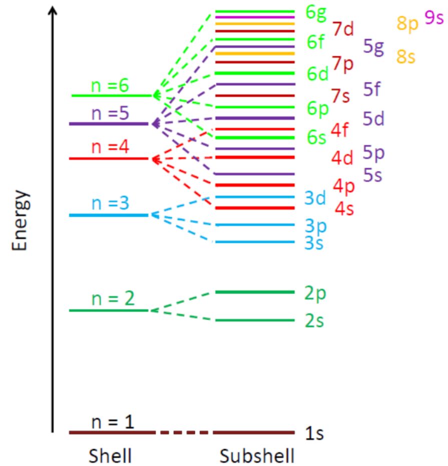
Well-characterized qubits

- The two states $|0\rangle$ and $|1\rangle$ should be perfectly distinguishable.
- What are good qubits?
  - Well-defined states: e.g., spin up and spin down of a spin-1/2 particle
  - Isolation: a qubit accumulates error when disturbed.
    A qubit must be isolated as much as possible from its surroundings.

Note: Qubits are not particles; they are usually states of particles. We could define more than one qubit in an atom.



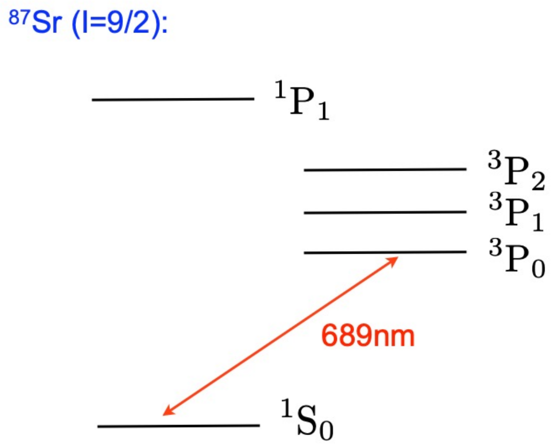
Qubits get ”erased“ if the atom gets to higher energy state.



Good & bad qubits

- Good examples:
  - Spin up and down of a spin-1/2 particle (electrons, nuclei atoms/ions …) ✅
  - Two-level atoms: Ground state + one well-characterized (i.e., we know the receipt to prepare it) energy level ✅

- Bad examples:
  - Energy levels of an atom that are not “gapped enough” ❌
    (the excited states $(^3P_0)$, $(^3P_1)$ would not be a good qubit because the state may be accidentally transferred to $(^3P_2)$)
  - Positions of a particle ❌ (continuous; may not be distinguishable due to noise)
  - Harmonic oscillators (HOs) with equally spaced energy levels. ❌
    (see the next slide)

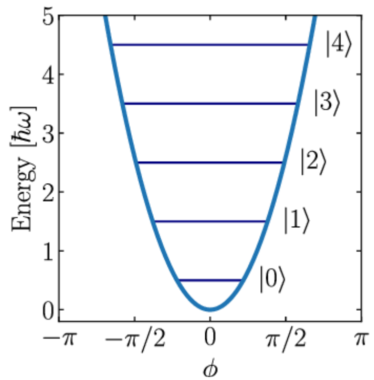


The ground state $(^1S_0)$ and the excited state $(^3P_0)$ of an Sr atom forms a good qubit.

Engineering qubits

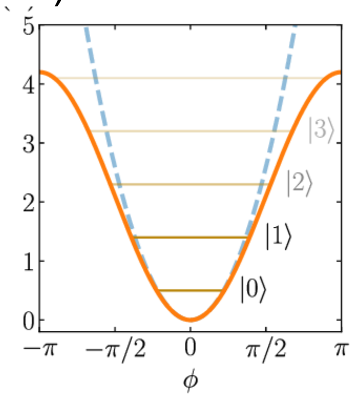
- Quantum systems that are initially flawed as a qubit can be modified and engineered into good qubits.
- For example:
  - Harmonic oscillators (HOs) are quantum systems with with equally spaced energy levels.
  - A pulse for X gate ($|0\rangle \rightarrow |1\rangle$) may (accidentally) transfer $|1\rangle$ to $|2\rangle$, ”erasing” the qubit. ❌
  - There is a way to perturb HOs, creating small differences between the energy levels.
  - This would prevent the erasure error. ✅ (super-conducting qubits; see later)

Quantum systems are very picky on ”food”. They only consume pulses with energy (equivalently, frequency) that exactly equal to the energy gap ω_{ij} between their current energy ω_i and the energy of the target state ω_j. We can use this feature to engineer quantum gates (see alter).



HOs:

$\omega_{23} = \omega_{12} = \omega_{01}$

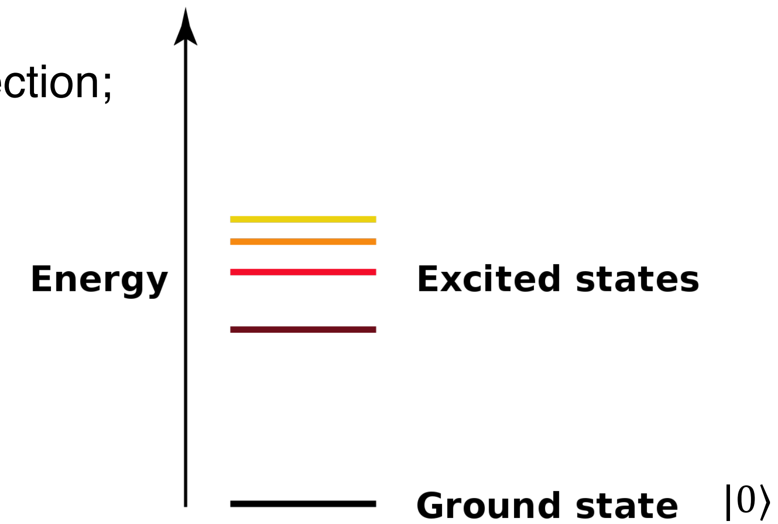


Perturbed HOs:

$\omega_{23} \neq \omega_{12} \neq \omega_{01}$

Initialization

- When starting, a quantum computer must have qubits initialized to $|000\ldots\rangle$.
- Ability to faithfully prepare $|0\rangle$ is required!
  - The preparation of $|0\rangle$ must be inexpensive and effective.
  - Approaches:
    cooling (when $|0\rangle$ is the lowest energy state of a system; that's why we usually define $|0\rangle$ to have the lowest energy),
    projection (via measurement and post-selection; see later for the case of NMR QCs)
    …



Lifetime of a qubit

- A qubit's merit decays gradually due to unavoidable disturbances.
- Two important merits of a qubit:

1. The longitudinal relaxation time T_1: 能量丢失
   Time it takes for excited states (e.g., $|1\rangle$) to drop to the ground state $|0\rangle$.
2. The transverse relaxation time T_2: 失去量子特性
   Lifetime of superpositions (the time it takes for $(|0\rangle + |1\rangle)/\sqrt{2}$ to decay to the probabilistic mixture of $|0\rangle$ and $|1\rangle$)

Usually, $T_2 \leq 2T_1$

- T_2 is usually shorter and more important.
- Question:
  Two quantum computers that use different physical systems.
  One has $T_2 = 1s$, and the other has $T_2 = 0.00001s$.
  Which one is better?
- Insufficient information … It depends on how fast are the quantum gates!

Decoherence times T_1 and T_2

- What is decoherence
  (or quantum noise/errors)? 衰变
  - The effect that a quantum state decays into a mixture of states.
  - Decay of quantum states into classical behavior
  - Why? Because quantum states interact with its surroundings!
- Appropriate length of a quantum circuit:
  - Long enough for conducting quantum computing.
  - Short enough to maintain quantum characterization.

在 longitudinal relative tim T_1 内完成操作

System	decoherence time τ_Q	operation time τ_{op}	max operation num. $n_{op} = \lambda^{-1}$
Nuclear spin	$10^{-2} - 10^{8}$	$10^{-3} - 10^{-6}$	$10^{5} - 10^{14}$
Electron spin	10^{-3}	10^{-7}	10^{4}
Ion trap (In^+)	10^{-1}	10^{-14}	10^{13}
Electron – Au	10^{-8}	10^{-14}	10^{6}
Electron – GaAs	10^{-10}	10^{-13}	10^{3}
Quantum dot	10^{-6}	10^{-9}	10^{3}
Optical cavity	10^{-5}	10^{-14}	10^{9}
Microwave cavity	10^{0}	10^{-4}	10^{4}

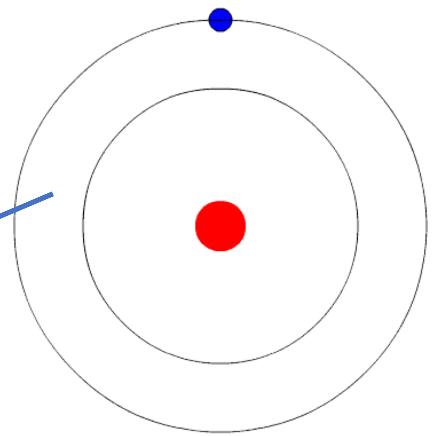
We want to do as many logical operations as possible before the qubits decohere.

Quantum gates

短脉冲

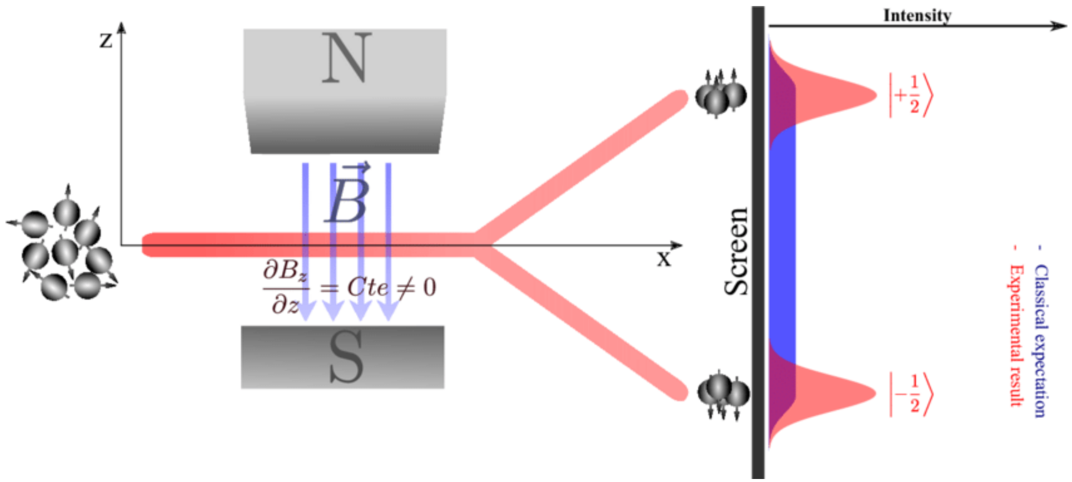
- Usually, short pulses (electromagnetic fields) are used for implementing quantum gates. Different gates = pulses with different energies (frequencies) and durations.
- Single-qubit: the frequency of the pulses = energy gap between $|0\rangle$ and $|1\rangle$
- Contradicting objectives:
  - To keep the qubits from decaying, we need to isolate them.
  - To perform quantum computations, we need to interact with them.
- That's one major reason why QC is hard to implement!

For example:
A Y-rotation $e^{iY\theta/2}$ can be implemented as a pulse of frequency = ω_1 (energy of $|1\rangle$) - ω_0 (energy of $|0\rangle$) with duration $\propto \theta$



Measurements

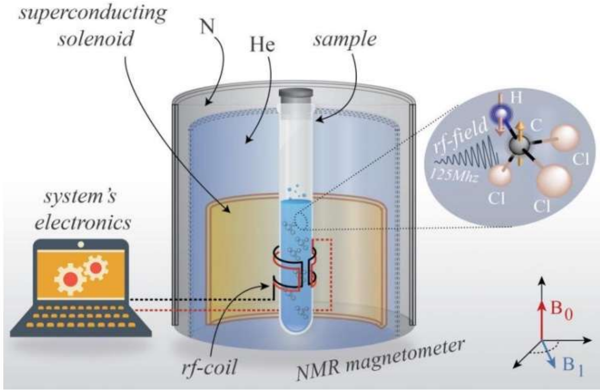
- For good qubits, $|0\rangle$ and $|1\rangle$ are perfectly distinguishable.
  Example: Stern-Gerlach experiment (measurement in the computational basis)
  spin $\left|+\frac{1}{2}\right\rangle = |0\rangle$ and $\left|-\frac{1}{2}\right\rangle = |1\rangle$; the state passes through a magnetic field and goes up (down) if the state is in $\left|+\frac{1}{2}\right\rangle$ ($\left|-\frac{1}{2}\right\rangle$).



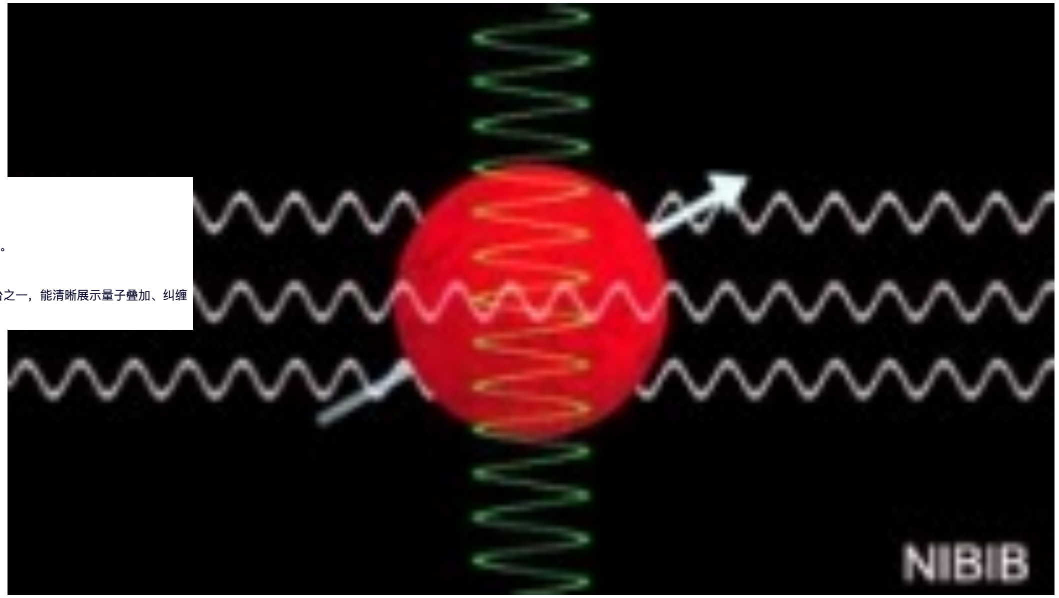
- To gain enough data, we usually measure many copies of a qubit rather than a single qubit!

Part II:
NMR quantum computer

NMR (Nuclear magnetic resonance)



- Idea:
  - Same physical principle as MRI. → 核磁共振
  - Use the nuclear spin of atoms in a molecules as qubits. → 微术
  - Perform operations via applying radio-frequency pulses.
  - Acts on millions of identical molecules at the same time.
- Pros:
  - Based on mature technologies of MRI.
  - Ideal for demonstration of QC.



✅ **优点（Pros）：**

- **技术成熟：**
  基于已广泛应用于医学和化学的 MRI 和 NMR 技术，仪器设备和控制方法非常成熟。
- **非常适合演示量子计算原理：**
  在早期量子计算实验中（如实现 Shor 算法分解 15 = 3×5），NMR 是最成功的平台之一，能清晰展示量子叠加、纠缠和算法流程。

- Cons:
  - Poor scalability.
    (due to state preparation; see later.)

❌ **缺点（Cons）：**

- **可扩展性差（Poor scalability）：**
  这是最致命的问题。虽然可以用 2~7 个核自旋实现小规模量子计算，但**无法有效扩展到几十或上百个量子比特。**

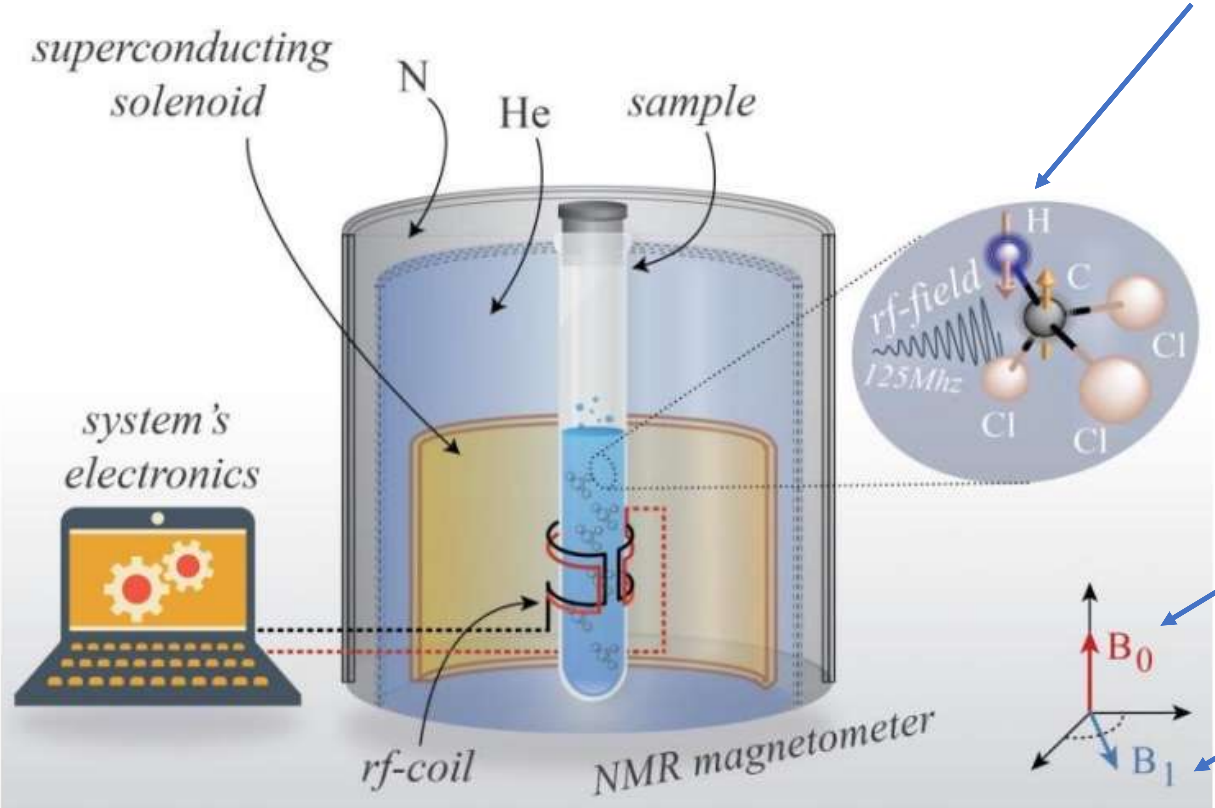
🔍 **为什么难以扩展？关键在于“初态制备”（state preparation）：**

- 在标准量子计算中，我们需要将系统初始化为一个**纯态**（pure state），比如 |000…0⟩。
- 但在 NMR 中，由于分子处于**室温热平衡态**，其初始状态是一个**高度混合的热态**（接近完全随机），信噪比极低。
- 虽然可以通过“伪纯态”（pseudo-pure state）等技巧模拟纯态行为，但这种方法的信号强度随量子比特数**指数级衰减。**
  - 例如：10 个 qubit 的信号可能只有 1 个 qubit 的百万分之一，几乎无法探测。

因此，**当 qubit 数量增加时，信号太弱，无法可靠读出结果**，导致 NMR 不适合构建大规模量子计算机。

NMR working principle

Quantum states = “directions” of the nuclei spin



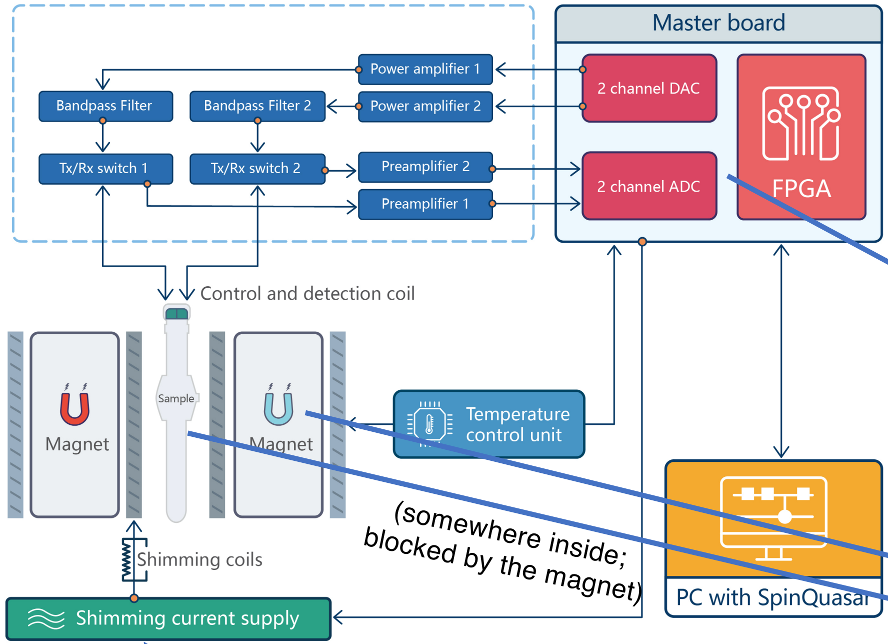
Static field: strong homogeneous field for alignment of the molecule spins

RF pulses (fast magnetic pulses) = quantum gates

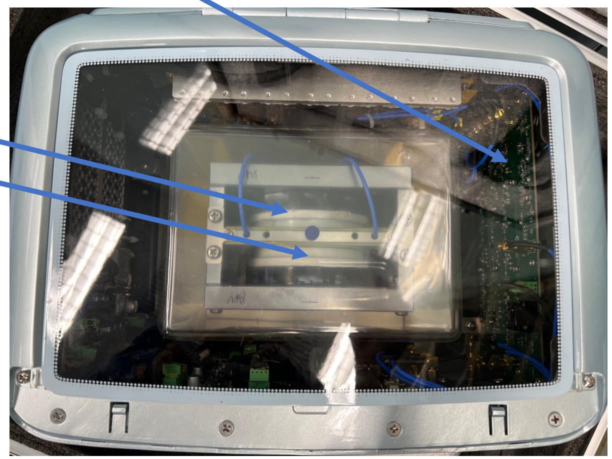
Specs of our "Gemini" NMR QC

Functions:

- 2-qubit quantum computation.
- Demonstration of Grover.
- Demonstration of QFT.
- Demonstration of D-J algorithm …



Molecule =
Dimethylphosphite ($(CH_3O)_2PH$)
Qubit 1: ^1H Qubit 2: ^{31}P
Decoherence time: $T_2 \sim 0.3s$.
Thermalization time: $T_1 \sim 4s$.
Single-qubit gate time: $\sim 10^{-5}s$
CNOT gate time: $\sim 10^{-3}s$



Superconducting coil replaced by
normal coils + a shimming field:
✅ cost 1M → 5k USD
❌ worse homogenity

Qubits in NMR

自旋状态 原子核 单分子

- In NMR, qubits are spin states of different nuclei in a single molecule.
- Within one molecule, it is possible to find several systems, each being a proton (^1H; other possible nuclei include ^{13}C, ^{19}F, ^{15}N, ^{31}P) with spin $\frac{1}{2}$.
- Spin $\frac{1}{2}$ system is the simplest among all: 2 eigenstates "up" and "down".
- Applying a static external magnetic field B_0 gives them different energies.
- We can define a qubit $|0\rangle$ as the ground state (lower energy; spin in the same direction as B_0) and $|1\rangle$ the excited state (higher energy; spin in the opposite direction of B_0), for each system.
  The energy gap is called $\omega_0\hbar$.

$|0\rangle \rightarrow$ 与 B_0 同向 $\rightarrow$ 基态，低能态

$|1\rangle \rightarrow$ 与 B_0 反向 $\rightarrow$ 激发态，高~

Gates in NMR

射频脉冲

- In NMR, gates are RF (radio frequency) pulses whose strengths ($= B\cos\omega t$) are oscillating with a frequency ω.
- They are much weaker than the static field ($B \ll B_0$), so the nuclei are almost unaffected by them unless $\omega \approx \omega_0$.
- When $\omega \approx \omega_0$, the RF pulses resonant with the spins and flips their directions → quantum gates.
- Different qubits in an NMR have different values of ω_0, so their gates will not affect each other.

Measurements in NMR

- When the RF pulses are gone, the nuclei spins automatically go back from the final states to the ground states.
  In the meantime, it releases energy as electro-magnetic pulses.

  线圈
- Coils can be used to detect these pulses.
  Different pulses are released for different final states.
  Just like how MRI tells apart different human tissues.
- This realizes a measurement in the computational basis!
- NMR as an ensemble quantum computer:
  The signal of a single molecule is too weak.
  We need billions of them to generate a detectable signal.
  Therefore, an NMR quantum computer is actually an ensemble of billions of identical quantum computers (i.e., one molecule is one quantum computer).

Imperfect initialization in NMR*

- (Imperfect initialization): A major drawback of NMR is that the initial state of NMR computers is imperfect.

- This is characteristic of NMR, since the reason is that NMR runs at room temperature whereas most other systems run at very low temperature.

- Luckily, there is a smart trick to deal with it.
  On the other hand, this trick does not work when we have many qubits.
  This eventually leads to the poor scalability of NMR quantum computers.
- Let us check it out together!

An ensemble of quantum states*

- The NMR quantum computer's initial state is subject to noise.
- The effect of noise can be characterized using the notion of an ensemble of quantum states.
- Consider, for instance, a two-qubit NMR quantum computer.
  Ideally, we want to initialize it to $|00\rangle$.
- The effect of noise/inaccuracy:
  Due to noise, the initial state is a probabilistic mixture of everything:
  With probability $q(x)$, it is in the state $|x\rangle$, for $x = 00,01,10,11$.
- We denote the realistic state of the NMR computer by a two-qubit ensemble:

$$\{q(x), |x\rangle\}_{x=00,01,10,11}.$$

Can be determined via noise-level estimation and calibration.

Statistics of an ensemble*

- Consider, for instance, an initial two-qubit ensemble:
$$\{q(x), |x\rangle\}_{x=00,01,10,11}.$$
- After any computation U, the ensemble becomes:
$$S = \{q(x), U|x\rangle\}_{x=00,01,10,11}.$$
That is, U is applied on each "classical branch".
- For any basis $\{|\phi_y\rangle\}$, we have a generalized version of the Born rule $P(y) = |\langle\psi|\phi_y\rangle|^2$:

(Generalised Born rule)
Probability of getting y wrt. S is given as
$$P(y)_S = \sum_x q(x)\left|\langle\phi_y|U|x\rangle\right|^2.$$

If we directly use noisy initial state for computation* …

- An NMR QC has noisy initial state as an initial two-qubit ensemble:
$$\{q(x), |x\rangle\}_{x=00,01,10,11}.$$
- After any computation U, the ensemble becomes:
$$S = \{q(x), U|x\rangle\}_{x=00,01,10,11}.$$
- If we measure in $\{|\phi_y\rangle\}$, instead of the ideal noiseless output $P(y) = \left|\langle\phi_y|U|00\rangle\right|^2$, we get:
$$P(y)_S = q(00)P(y) + q(01)\left|\langle\phi_y|U|01\rangle\right|^2 + q(10)\left|\langle\phi_y|U|10\rangle\right|^2 + q(11)\left|\langle\phi_y|U|11\rangle\right|^2$$

Ideal, noiseless output

Unknown noise terms (because we don't know what would be the output if we apply U to $|01\rangle, |10\rangle, |11\rangle$)

Temporal labeling of NMR*

- Now, if an NMR computer is initialized in the two-qubit ensemble S, and $\{|\phi_y\rangle\}$ is any two-qubit basis, say $|\phi_y\rangle = |B_y\rangle$.
- (Temporal labeling) Before the desired computation U, we do, with equal probability 1/3:
  1. Nothing (the identity gate $I \otimes I$).
  2. The unitary $P \coloneqq CNOT_{2,1}CNOT_{1,2}$. 循环
  3. The unitary $P^\dagger$. or P^2

> Exercise:
> Show that $P|00\rangle = |00\rangle$, $P|11\rangle = |10\rangle$, $P|10\rangle = |01\rangle$, $P|01\rangle = |11\rangle$.

- P and $P^\dagger$ leaves $|00\rangle$ invariant, while permuting $|10\rangle, |01\rangle, |11\rangle$.
- Question: What is the new initial ensemble after the above step?
- The new ensemble is

$$\left\{q(00), |00\rangle; \underbrace{\frac{1-q(00)}{3}, |01\rangle; \frac{1-q(00)}{3}, |10\rangle; \frac{1-q(00)}{3}, |11\rangle}_{\text{Equal probability}}\right\}$$

Temporal labeling of NMR*

- After computation U the new ensemble is

$$S' \coloneqq \left\{q(00), U|00\rangle; \frac{1-q(00)}{3}, U|01\rangle; \frac{1-q(00)}{3}, U|10\rangle; \frac{1-q(00)}{3}, U|11\rangle\right\}$$

- Question: What is $P(y)$ wrt. S' for any measurement basis $\{|\phi_y\rangle\}$?
- We denote $P(y)$ wrt. S' (S) as $P(y)_S(P(y)_{S'})$:

$$P(y)_{S'} = q(00)\left|\langle\phi_y|U|00\rangle\right|^2 + \frac{1-q(00)}{3}\left(\left|\langle\phi_y|U|01\rangle\right|^2 + \left|\langle\phi_y|U|10\rangle\right|^2 + \left|\langle\phi_y|U|11\rangle\right|^2\right)$$

$$= \frac{4q(00)-1}{3}\left|\langle\phi_y|U|00\rangle\right|^2 + \frac{1-q(00)}{3}\left(\left|\langle\phi_y|\psi_1\rangle\right|^2 + \left|\langle\phi_y|\psi_2\rangle\right|^2 + \left|\langle\phi_y|\psi_3\rangle\right|^2 + \left|\langle\phi_y|\psi_4\rangle\right|^2\right)$$

with $|\psi_x\rangle \coloneqq U|x\rangle$ for $x = 00,01,10,11$.

- What are $|\psi_x\rangle$? We don't know; but we know $\{|\psi_x\rangle\}$ is an ONB for two qubits!

$\rightarrow \left|\langle\phi_y|\psi_1\rangle\right|^2 + \left|\langle\phi_y|\psi_2\rangle\right|^2 + \left|\langle\phi_y|\psi_3\rangle\right|^2 + \left|\langle\phi_y|\psi_4\rangle\right|^2 = \langle\phi_y|\phi_y\rangle = 1!$

Exercise:
Show that if $\{|x\rangle\}$ is a basis and U is a unitary, $\{U|x\rangle\}$ must be a basis

Temporal labeling of NMR*

A known bias (determined via estimation of noise level).

$= P(y)$ (the idea output when the state preparation has no error

- Conclusion:

$$P(y)_{S'} = \frac{4q(00)-1}{3}\left|\langle \phi_y | U | 00 \rangle\right|^2 + \frac{1-q(00)}{3}$$

- We can obtain the ideal output probability as $P(y) = \frac{p(y)_{S'} - \frac{1-q(00)}{3}}{\frac{4q(00)-1}{3}}$.

当 qubit 越多时，约为0

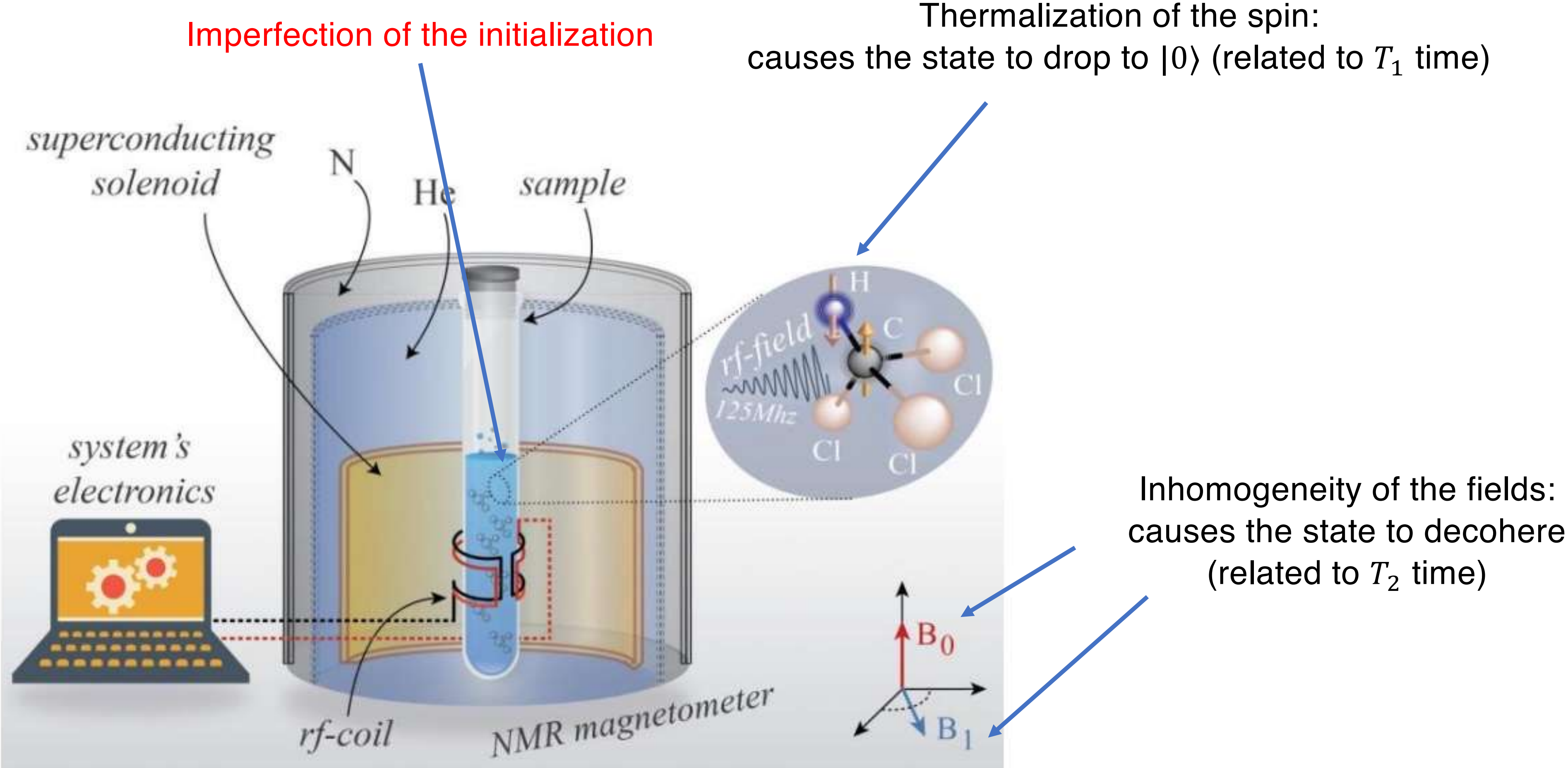
- Here $\{|\phi_y\rangle\}$ can be any basis of measurement.
  The probability $P(y)$ after temporal labeling is essentially the same as starting in a noiseless state $|00\rangle$ and do the computation, just a bit "less sharp" with a constant $\frac{4P(00)-1}{3} < 1$ and shifted by a known constant!

Using the trick of temporal labeling, we can mitigate the effect of noise in the initialization of NMR quantum computers.

Scalability of NMR*

- Temporal labeling gets rid of noise but returns a signal whose sharpness relies on $q(00 \dots 0)$ -– the probability that the initial ensemble is in $|00 \dots 0\rangle$.
- When there are many qubits, this probability could be very small.
- Indeed, it is fair to assume every ensemble has the same $q(0)$, then for n ensembles $q(00 \dots 0) = q(0)^n$ decays exponentially with n.
- In addition, qubits are states with distinct energy gaps within one molecule in the NMR framework. To build a larger computer, we need to find a larger molecule that fits the criteria.
- Conclusion: NMR QC does not have good scalability.

Other noises in an NMR



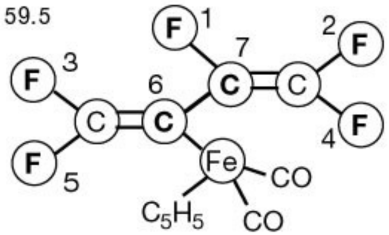
First demonstration of Shor on NMR QC (2001)

Experimental realization of Shor's quantum factoring algorithm using nuclear magnetic resonance

Lieven M. K. Vandersypen*†, Matthias Steffen*†, Gregory Breyta*, Costantino S. Yannoni*, Mark H. Sherwood* & Isaac L. Chuang*†

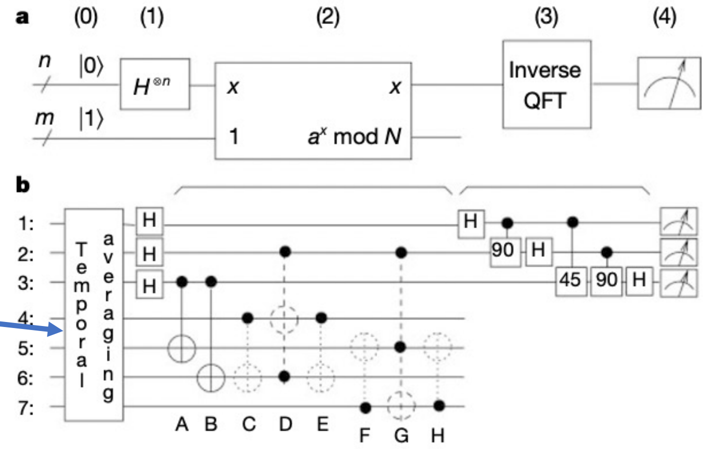
** IBM Almaden Research Center, San Jose, California 95120, USA*
† Solid State and Photonics Laboratory, Stanford University, Stanford, California 94305-4075, USA

i	$\omega_i/2\pi$	$T_{1,i}$	$T_{2,i}$	J_{7i}	J_{6i}	J_{5i}	J_{4i}	J_{3i}	J_{2i}
1	−22052.0	5.0	1.3	−221.0	37.7	6.6	−114.3	14.5	25.16
2	489.5	13.7	1.8	18.6	−3.9	2.5	79.9	3.9	
3	25088.3	3.0	2.5	1.0	−13.5	41.6	12.9		
4	−4918.7	10.0	1.7	54.1	−5.7	2.1			
5	15186.6	2.8	1.8	19.4	59.5				
6	−4519.1	45.4	2.0	68.9					
7	4244.3	31.6	2.0						



The molecule used for the demonstration, which hosts 7 qubits (F and C nucelli).

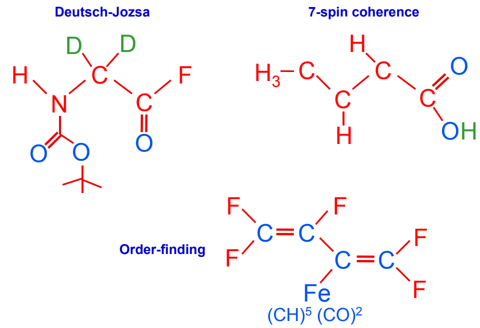
Temporal ordering (averaging)



Order finding circuit for factorizing $N = 15$

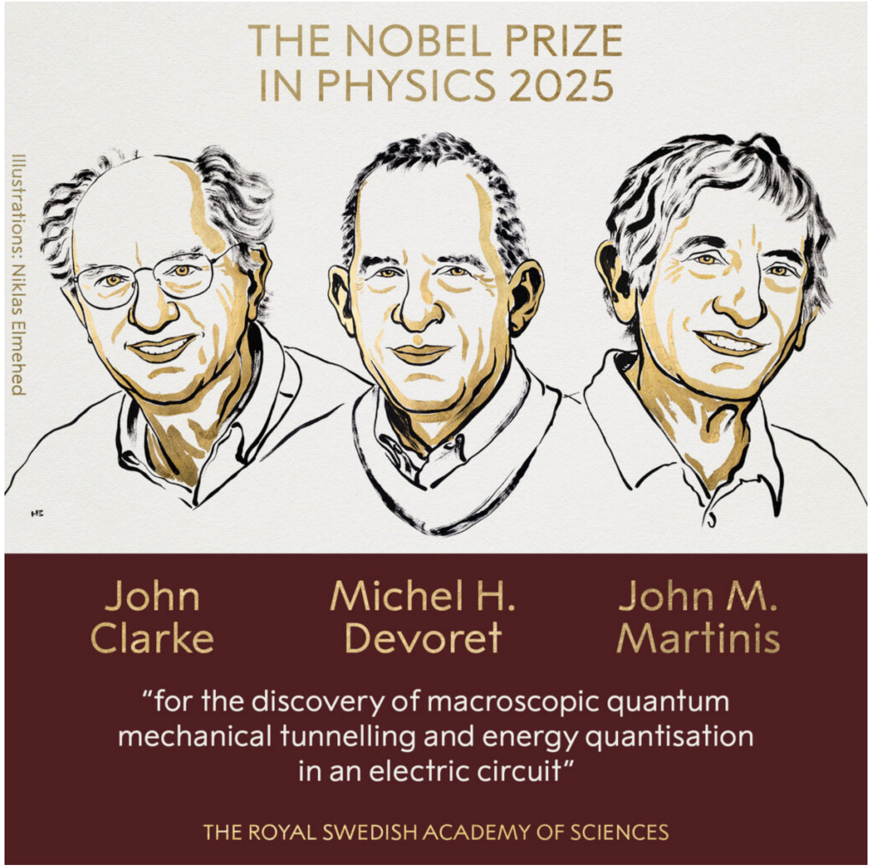
Pros and Cons of NMR

- Pros:
  - Lower cost.
  - Relatively mature:
    MRI has been there for years. The techniques are all very mature.
- Cons:
  - Poor scalability:
    To build a larger quantum computer,
    we need to find larger molecules with more protons.
  - Signal losses due to state preparation noise.

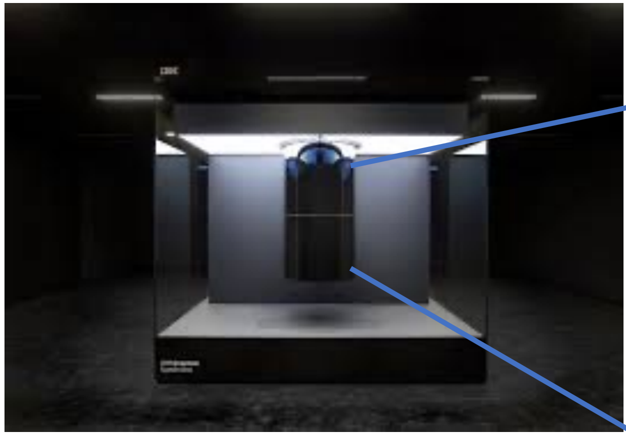


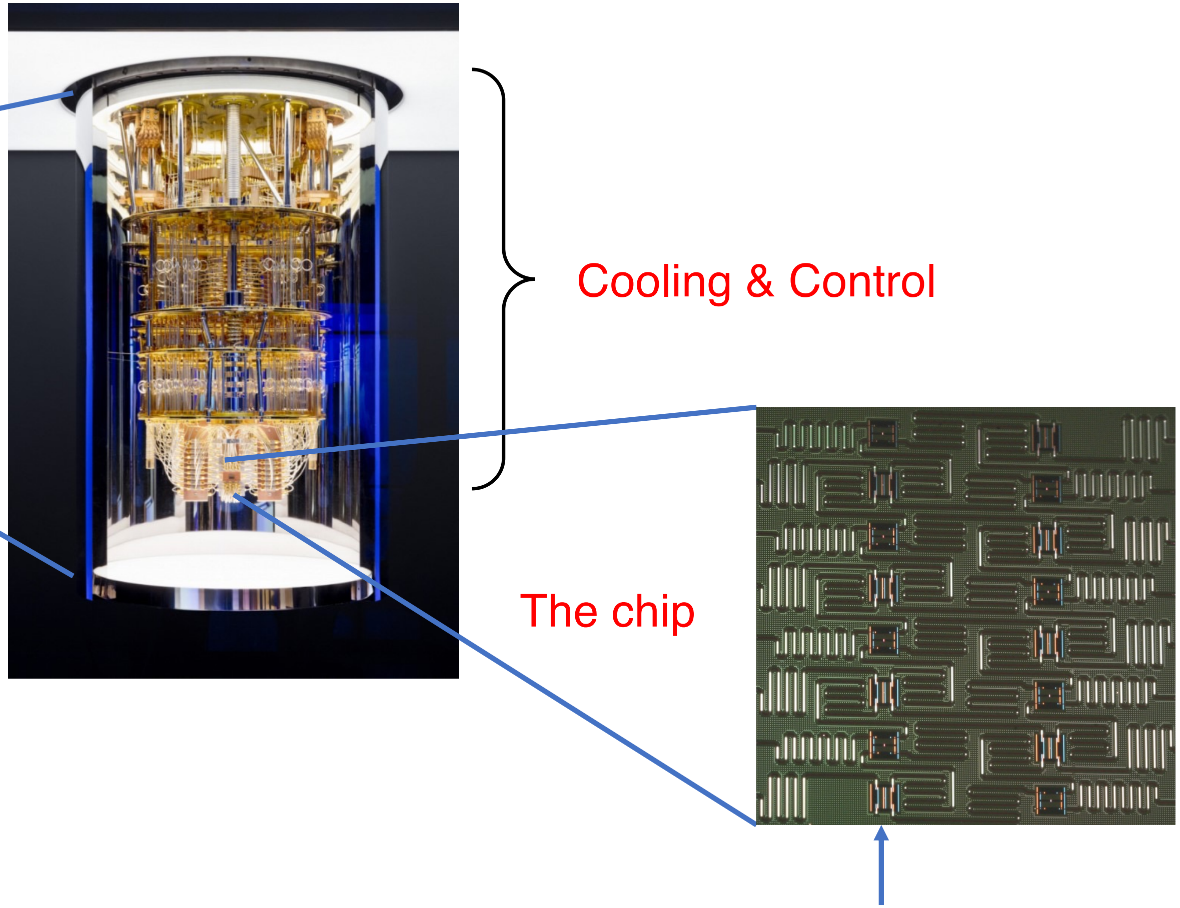
- NMR are very good for demonstrating quantum computations in the near term but it has poor scalability.
- In the far future, it is likely that we will use other systems. See next part.

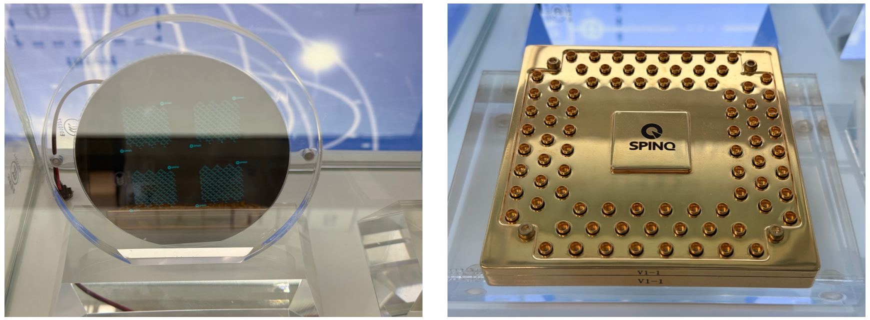
Part III: Super-conducting quantum computers (brief overview)



Unveiling a quantum computer



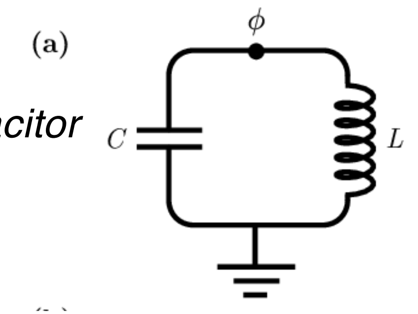




A superconducting chip and its shell (by Spin Q)

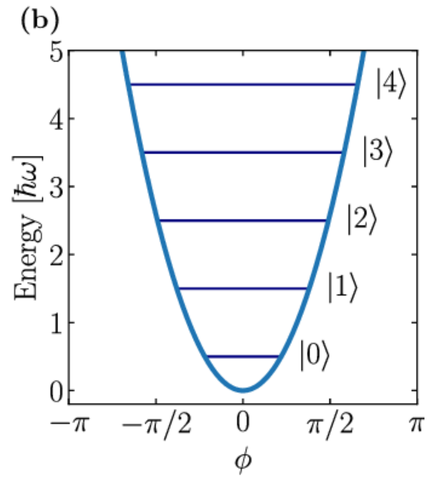
Superconducting LC circuit as a qubit

capacitor



inductor

Energy $E = \frac{\Phi^2}{2L} + \frac{Q^2}{2C}$



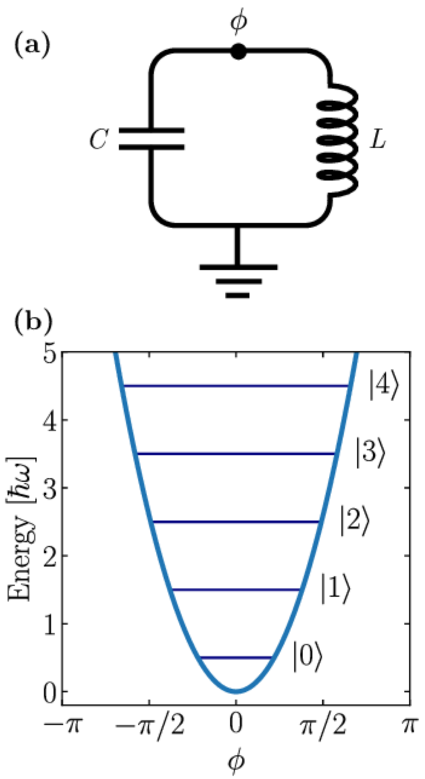
= a harmonic oscillator
("a microscopic spring")

- In a superconducting LC circuit, there is no resistance ("friction"), and its current oscillators forever.
- A superconducting LC circuit is a quantum system but not a qubit.
- It is a harmonic oscillator with infinite dimensions! Each eigenstate corresponds to a unique energy level.
- The energy gaps are equal.
- Its energy can be increased by driving it with microwave whose frequency corresponds to the energy gap.

有无穷多个等间距的能级

$|0\rangle \quad |1\rangle \quad |2\rangle \quad \cdots$

Superconducting LC circuit as a qubit

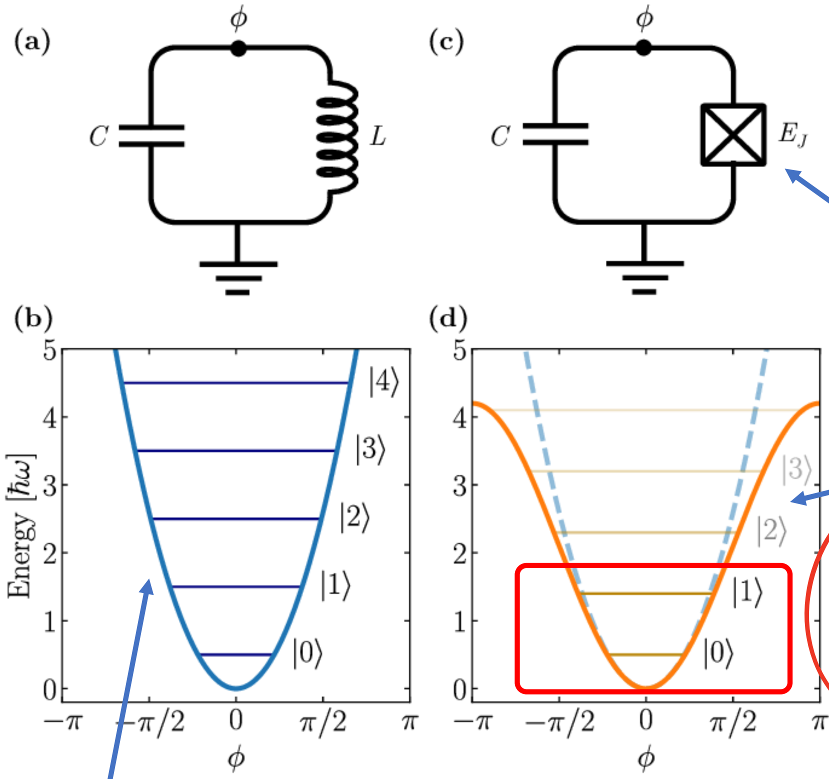


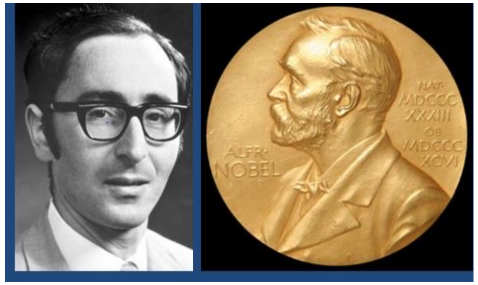
Energy $E = \frac{\Phi^2}{2L} + \frac{Q^2}{2C}$

= a harmonic oscillator
("a microscopic spring")

- An attempt to use a superconducting LC circuit as a qubit.
- From $|0\rangle$ to $|1\rangle$:
  We can increase its energy by driving it with microwave (whose frequency corresponds to the energy gap).
- However, this might "overcook" the state. As the gaps are the same, we may end up doing $|0\rangle \rightarrow |1\rangle \rightarrow |2\rangle \rightarrow \cdots$

From a harmonic oscillator to a qubit





Replacing the inductor by
a Josephson's junction

Anharmonic energy
Energy gaps are not equal

$\omega_{12} \neq \omega_{01}$

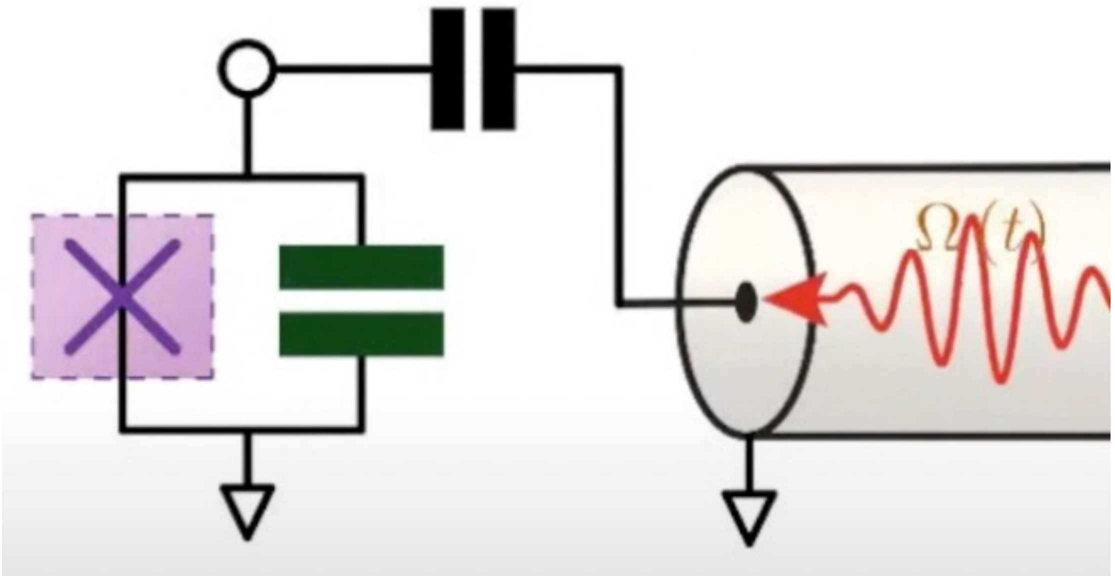
$\Delta E_{01} = \hbar\omega_{01}$

Energy gaps are equal

$\omega_{23} = \omega_{12} = \omega_{01}$

- No overcooking:
  As the gaps are not the same, the resonator with frequency $= \omega_{01}$ will only do $|0\rangle \rightarrow |1\rangle$.
- Therefore $|0\rangle, |1\rangle$ becomes a qubit isolated from higher energy levels!

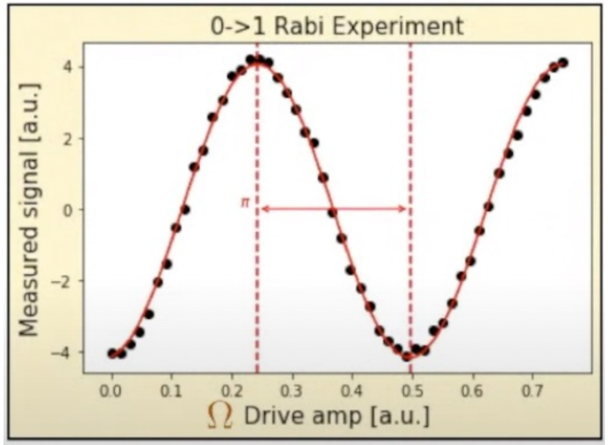
Superconducting qubit operations



qubit

Input-output line
(control and readout)

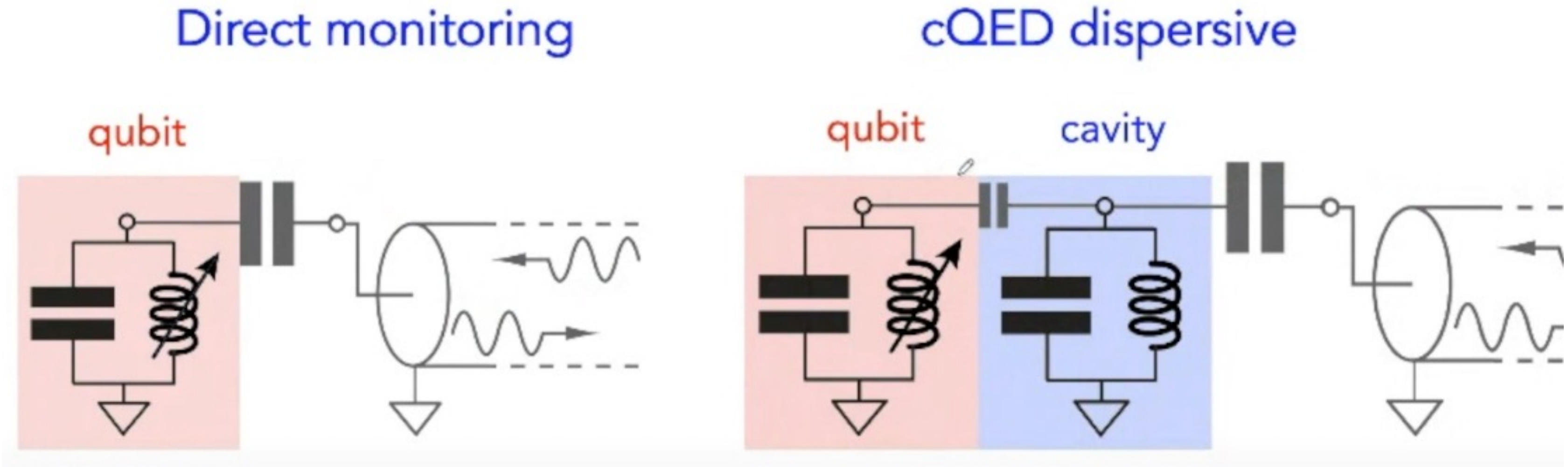
- Qubit can be controlled by connecting it to a resonate (in & out line) and driving it with suitable microwave.



A control wave driven $|0\rangle \rightarrow |1\rangle$
(X gate)

Pic. credit: Zlatko Minev

Superconducting qubit readouts



qubit LC circuit Input-output line

- Coupling the qubit first to an LC circuit can reduce the noise compared to direct monitoring.

Pic. credit: Zlatko Minev

Performance of superconducting qubits

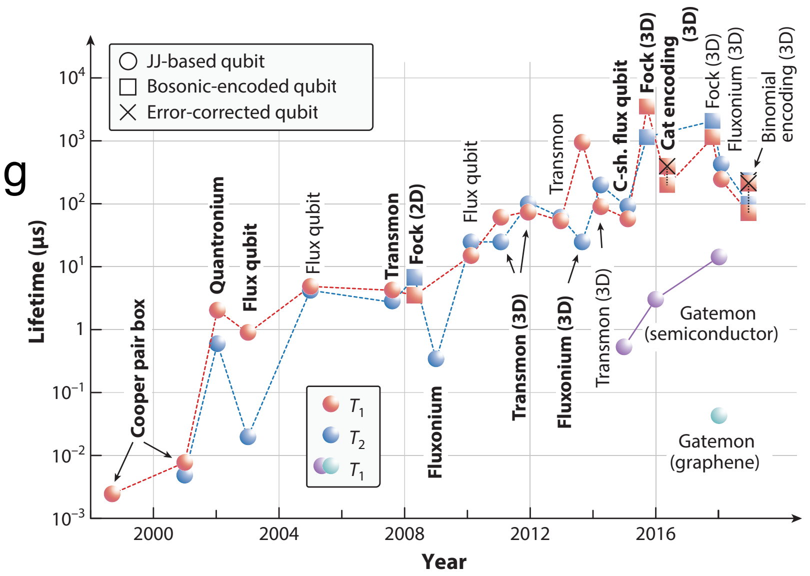
- Main source of noise:
  - (qubit errors) e.g., imperfection in Josephson junctions and the resonator.
  - (gate errors) e.g., crosstalk induced by imperfect coupling
- Lifetime:

$$T_1, T_2 \sim 0.5ms$$

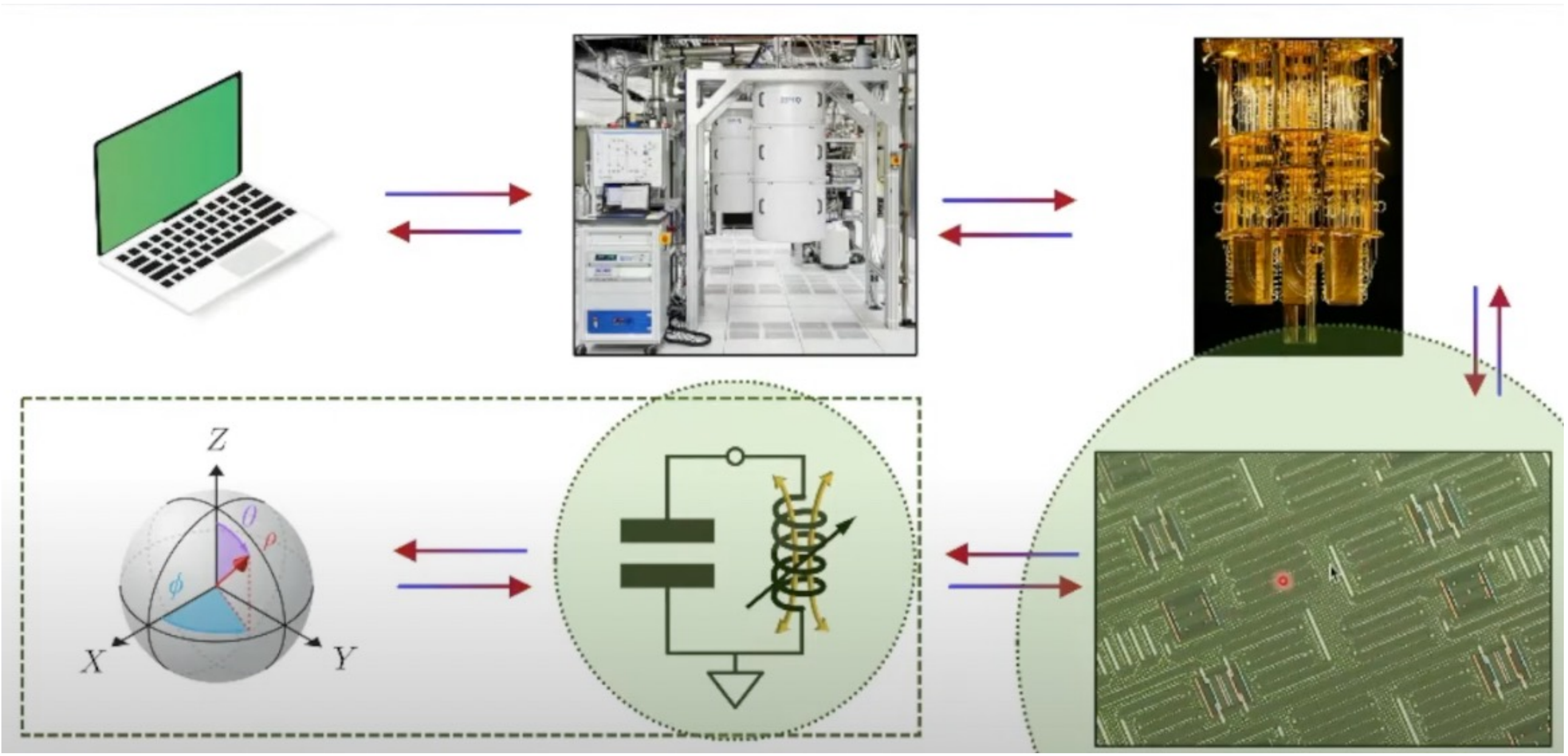
- Gate time:

$$10^{-7}s$$

- In theory, we could do up to 10^6 gates in a qubit's lifetime! But for now much fewer, because the gate error is dominating.
- Scalability: much better than NMR; its structure (qubits on a chip) is similar as classical CPUs.



Cloud quantum computing



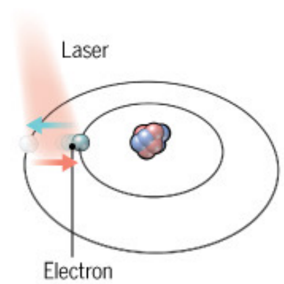
Pic. credit: Zlatko Minev

Pros and Cons of superconducting qubits

- Pros:
  - Utilizes the mature semiconductor industry.
    (Qubits are arranged in a similar way as classical DRAMs.)
  - Fast (gate operation).
  - Scalable.
- Cons:
  - Must stay cool.
  - Short lifetime.
- Who is working on it?

Other physical systems for quantum computing

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.

Longevity (seconds) **>1000**

Logic success rate **99.9%**

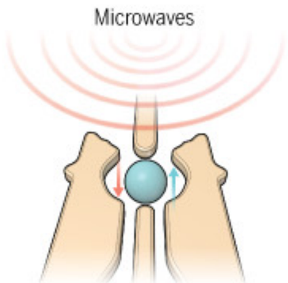
Number entangled **14**

Company support
ionQ

Pros
Very stable. Highest achieved gate fidelities.

Cons
Slow operation. Many lasers are need

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.

Longevity (seconds) **0.03**

Logic success rate **~99%**

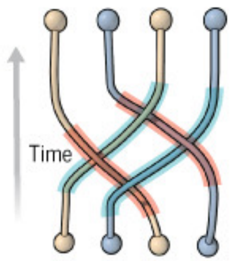
Number entangled **2**

Company support
Intel

Pros
Stable. Build on existing semiconduct industry.

Cons
Only a few entangled. Must be kept cc

Topological qubits



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

Longevity (seconds) **N/A**

Logic success rate **N/A**

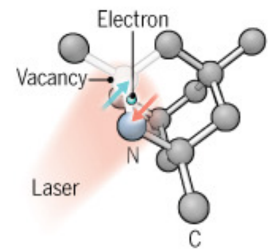
Number entangled **N/A**

Company support
Microsoft, Bell Labs

Pros
Greatly reduce errors.

Cons
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.

Longevity (seconds) **10**

Logic success rate **99.2%**

Number entangled **6**

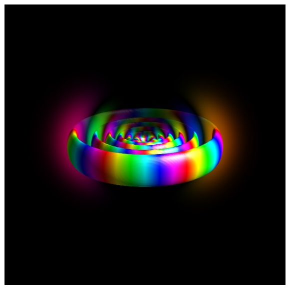
Company support
Quantum Diamond Technologies

Pros
Can operate at room temperature.

Cons
Difficult to entangle.

Source: Science

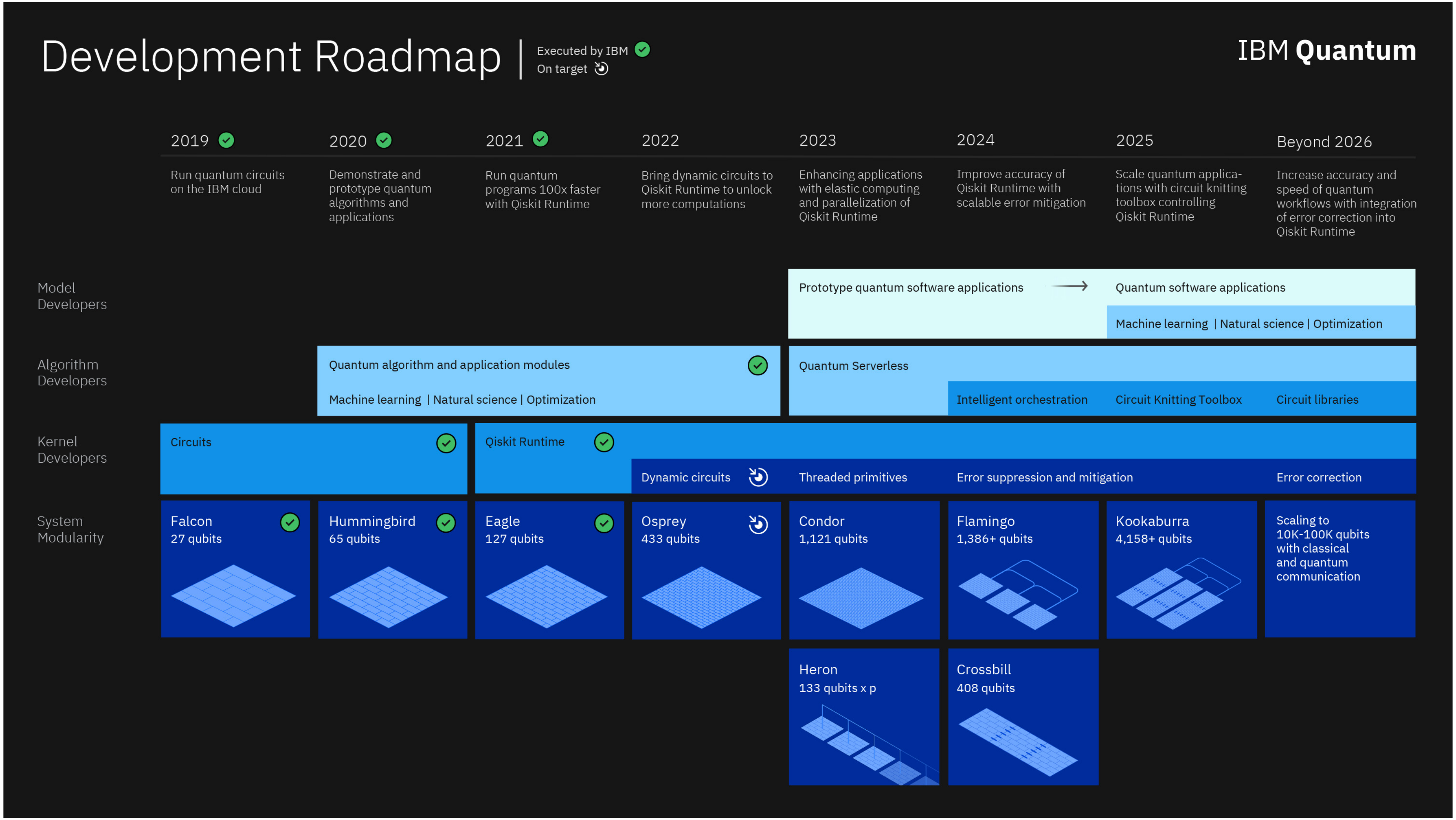
Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.



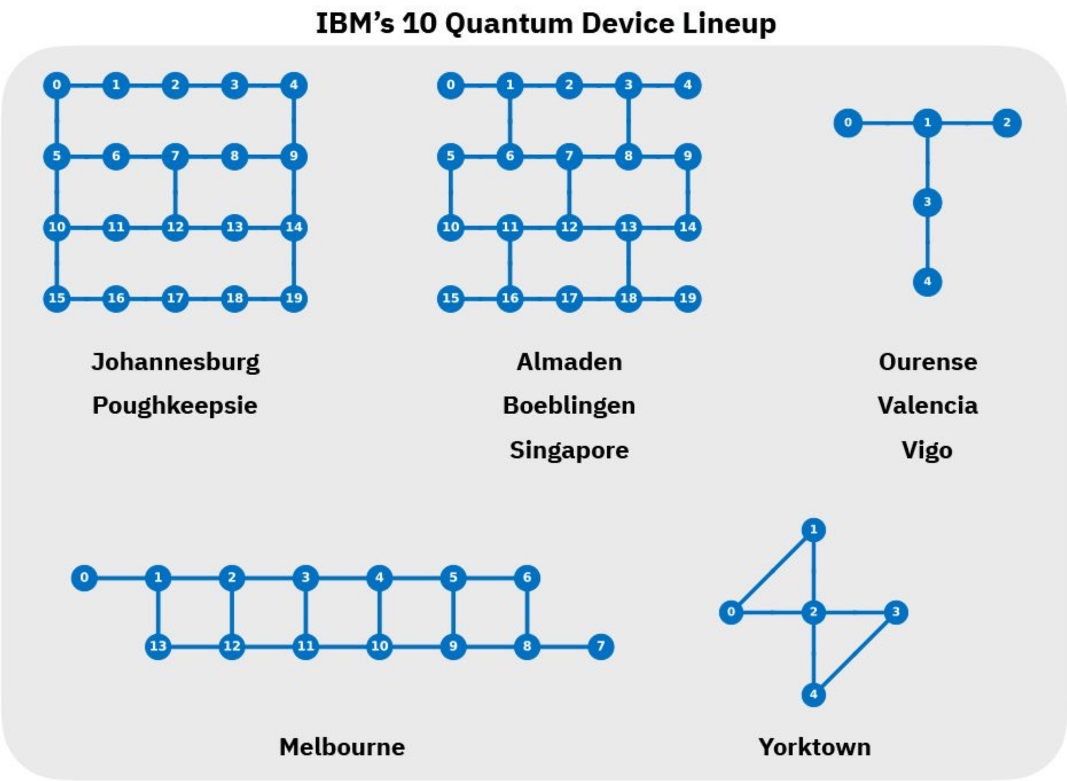
+ Rydberg atoms … more to emerge!

State of the art

Super-conducting QC. IBM's roadmap as an example.

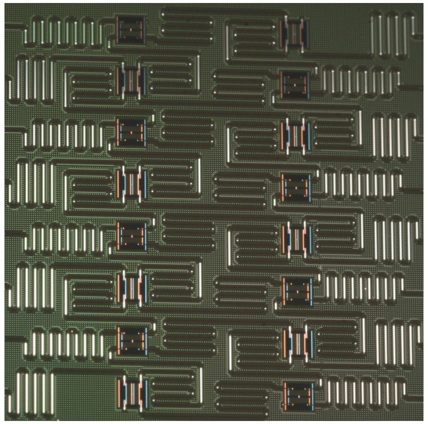


Connectivity of qubits



Connectivity of qubits in IBM's QCs. Connected pairs of qubits (vertices) are linked by an edge.

In the circuit model, we can perform CNOT over any two qubits.



Qubits in a real QC are fixed on a board. Only some of the qubits are connected, namely that we can directly implement two-qubit gates over them.

Exercise:
How do we implement a two-qubit gate over two disconnected qubits?

Summary

- DiVincenzo's criteria for quantum computing.
- Exemplary systems: NMR and super-conducting qubits.
- An ensemble of quantum states; temporal relabeling for NMR (and the reason for its poor scalability)
- State of the art; physical connectivity of qubits.

Homework

- Review the lecture slides; you may find the review questions in the next slides helpful.

  Try the exercises in the slides and discuss with your classmates.

- Attempt Q1-2 in Assignment 3.

- Optional: Read p277-283,324-343 of *Quantum Computation and Quantum Information* by Nielsen and Chuang.

Review questions

- What are DiVincenzo's criteria?

可扩展 . . .

- What does it mean that a qubit gets erased?

退相干

- What is the biggest disadvantage of NMR and why?

不可扩展

- What is the "qubit" for a super-conducting qubit?
- Name a few systems for implementing qubits and QC.