Analysis of Physical Qubit Systems

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Abstract: We here attempt to review and summarize the general setup, advantages and shortcomings of some mainstream physical implementations of the quantum bit, Qubit. We will be outlining the qubit state implementation and preparation of it to a fiducial state. Gate operation implementations and readout methods would be taken a look at. Each implementation would be provided by advantages and disadvantages it carries with it. Ion trap, Superconducting and optical qubits are more highlighted than their counterparts as they are commercially more viable for scalable applications.

1. Introduction

"Quantum phenomenon do not occur in a Hilbert space. They occur in a laboratory"
- Ashes Peres

Qubit, the fundamental unit of quantum information is realised as a two-state device (the basis is generally taken as $|0\rangle$ and $|1\rangle$). We race towards the creation of physical quantum computers whose endeavour starts from selecting the right candidate for the qubit.

While quantum bits must be strongly inter-coupled by gates to perform quantum computation, they must at the same time be completely decoupled from external influences, except during the write, control and readout phases when information must flow freely in and out of the machine [1]. Implementation of any qubit requires to strengthen the inter-qubit coupling required for lowering gate operation time (τ_{op}) without letting parasitic environmental noise lead to decoherence of state.

DiVincenzo presents the following parameters towards the realization of quantum computation [2].

1. A scalable physical system with well characterized qubits
2. The ability to initialize state of the qubit to a simple fiducial state, such as $|0\rangle^{\otimes n}$
3. Long relevant decoherence times, much longer than the gate operation time
4. A "Universal" set of quantum gates
5. A qubit-specific measurement capability
6. The ability to interconvert stationary and flying qubits*
7. The ability faithfully to transmit flying qubits between specified locations*

Thus, we infer how essential it is to select and create an apt qubit implementation scheme to create highly accessible commercial quantum computational systems. Though research is going on in all types of qubits by academic institutions and industrial giants, we haven't figured out a

* These requirements are desired only for quantum communication purposes.

very specific scheme. Every type has its own merits and outperforms others in some aspects, but at the same time is practically challenging to tune up the factors where it ill-performs.

2. Performance Gauging Parameters

Qubits are extremely sensitive to background noise and this poses one of the most important challenges in paving the path for optimal quantum computation. The primary aim of scientists and engineers working on it is to create a near to noiseless environment for the qubit system along with efficient state measurement setup.

The following are used to justify the advantages and short-comings of a given physical setup.

- Decoherence time (τ_Q)
- Operation time (τ_{op})
- Error proneness
- Cryogenic requirements
- Scalability
- Size of the physical setup
- Quantum volume*
- Circuit Layer Operations per second (CLOPS)*

Decoherence time (τ_Q): In terms of Quantum computing performance, Decoherence time is the time taken for off-diagonal components of the density matrix to effectively vanish. In practical terms, it is the time period for which the state of the particle remains stable enough to perform operations before decoherence takes over. Decoherence can be seen as Relaxation (T1) and Dephasing (T2). Where relaxation is the tendency to return to the ground state. While dephasing is the tendency to randomize its phase visualized on the Bloch's sphere.

Operation time (τ_{op}): It is the time taken to perform a gated operation on a qubit. The number of operations thus can be calculated as [3]

$$n_{op} = \frac{\tau_Q}{\tau_{op}}$$

Error proneness: Talking about these fragile little devices, how much ever we try to protect these qubits from the noise and external interference they are prone to unwanted coupling to the environment. The goal of quantum information processing and architecture is to invent fault tolerant quantum computers. The most formidable enemy of quantum computation is the decoherence of the qubit which induces errors. Though very ingenious Quantum Error Correction (QEC) schemes have been invented, actively used and are researched, the problem of error-free quantum computation is still a challenge for engineers.

Cryogenic requirements: Thermodynamic variations in the environment is considered as noise for the very sensitive qubit. The standard requirement for stable qubit operations is $k_B T \ll \hbar\omega_{01}$, pertaining to the thermodynamic temperature of the system to be negligible in comparison to the transition energy. As the transition energy is extremely low compared to ambient room conditions, the qubit temperature needs to be taken near absolute zero in the milli-kelvin range.

* These are some industry defined modern metrics

Macroscopic cooling instruments such as dilution refrigerator are used, while individual atoms or ions are cooled using doppler, Raman sideband or resolved sideband cooling [3].

Scalability: Scalability refers to two facts. Firstly, ability to increase the number of stable qubits without letting performance per qubit decrease. Secondly, it is what a reader will first infer from the term literally mass producing and commercializing quantum computation in daily problem solving and management for commercial, Governmental and academic institutions all around the globe.

3. Types of Implementations

First, we run through the setups which will be reviewed,

1. Ion trap
    a. Optical Qubit
    b. Hyperfine Qubit
2. Superconducting
    a. Charge Qubit
    b. Flux Qubit
    c. Phase Qubit
3. Photonic
4. Quantum dots
5. NMR
6. Neutral atoms

The following are some other implementations which are less stable and wont be reviewed,

7. Topological
8. N-V centres in Diamond lattice

3.1. Ion Trap Qubit

This is one of the most widely used qubit systems for quantum computers. The ions whose state is to be manipulated are trapped in a Paul or Penning Trap (Rotating Saddle Potential created using RF frequencies). Specific ions are used for this purpose, e.g., Calcium-40, Beryllium-9, Barium-138 or Ytterbium-171. These are divalent atoms which in ionic state form univalent cations. They generally are Implemented as optical qubits or hyperfine qubits.

The Ion trap: The trapping system for ions is constructed using a standard Paul trap configuration working at radio frequency. Generally consisting of 4 plates. In it 2 opposite plates at reference potential and the other 2 with oscillating potential at rf with reference biased. Another pair of needle electrodes are used to induce harmonic confinement in z plane. The oscillating field creates a field minima in the x-y plane (a saddle point for static potentials) to trap the ion to near stationary conditions. The potential created by the rf is [3]

$$\Phi_{rf} = \frac{1}{2}(V_0 \cos \Omega_T t + U_r)\left(1 + \frac{x^2 - y^2}{R^2}\right)$$

To execute ionic manipulations, the energies should be $k_B T \ll \hbar\omega_z$. Where $\hbar\omega_z$ is the phonon. To reduces susceptibility to environmental noises the system is laser-cooled to vibrational ground state. Doppler cooling is used to cool the system down to $k_B T \approx \hbar\Gamma/2$, where Γ is the radiative width of the transition used for cooling. Further cooling is done using method called sideband cooling [3, 4]. A near perfect vacuum is aimed to be created. 2-D ion trapping chips are also used in current research settings made using photolithography techniques.

Isolation and Trapping: The corresponding atoms are resistively heated (for Ca ≈ 1070 K) and vapourised towards the trap and photo-ionized to make it univalent [5].

Optical Implementation: The state transition is done between S and D states using optical laser frequencies. The $S_{1/2}$ ground state is taken as |0⟩ and the $D_{5/2}$ state is set as |1⟩. Th P state decays into S or D state probabilistically. S-D transition is electric-dipole forbidden through selections rule (allowed under electric-quadrupole), while S-P transition is electric-dipole allowed.

The transitions between |0⟩ and |1⟩ state is executed using a stable laser (400 THz) with narrow line-width via quadrupole transition.

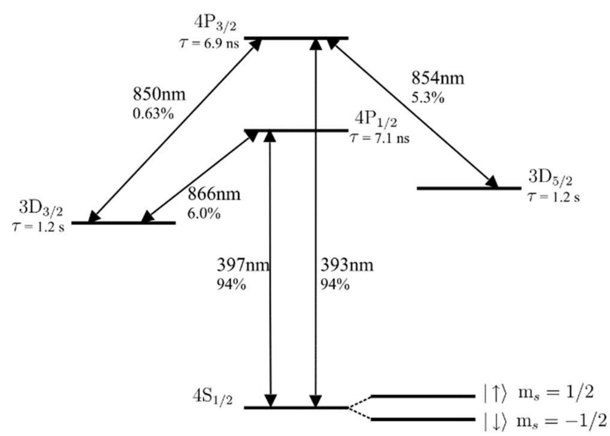

Figure 1: Lowest energy levels of the $^{40}Ca^+$ ion. A D.C. magnetic field splits up the energies of the Zeeman sub-level. Source: [6].

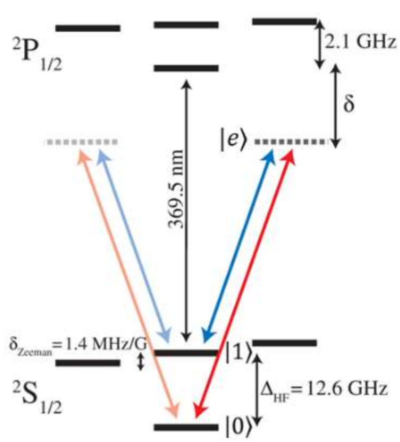

Figure 2: Energy levels in $^{171}Yb^+$ showing encoding in hyperfine energy levels. Source: [4]

Hyperfine Implementation: Non zero nuclear spin (I≠0) causes fine splitting. The state $S_{1/2}$ is split into 4I±½ different m_F states in two hyperfine manifolds [7]. Where I is the nuclear spin. The qubit states are encoded into these non-degenerate states. The state transition is achieved using Raman process via excitation to a virtual |e⟩ state.

The transitions between |0⟩ and |1⟩ state is executed using a microwave radiation corresponding to splitting energy or alternatively Raman process is carried using two lasers whose frequency difference is tuned to qubit splitting. The spins are then rotated at frequency

$$f \propto \frac{\Omega_{|0\rangle,|e\rangle}\,\Omega_{|1\rangle,|e\rangle}}{\delta}$$

Where $\Omega_{a,\ b}$ is the Rabi cycle frequency for the transition between state a to b and δ is detuning from the P state. Addressing a single qubit in a chain of qubits is difficult in the microwave method which is resolved by simulated Raman transition method [5].

Gate operations and Qubit control: To initialize the qubits to a fiducial state they are optically pumped in both methods outlined [tool box]. In optical pumping an appropriate laser drives |1⟩ state to the excited p-states (Hyperfine implementation). Any spontaneous decay from the excited state to ground states apart from $|0\rangle$ are further driven by laser. Over a period of time (∼ μs), all the spontaneous emissions result in the qubit state being initialized to $|0\rangle$.

To apply $R_x(\theta) = e^{-i\theta S_x}$ and $R_y(\theta) = e^{-i\theta S_y}$ a electromagnetic field of frequency ω_0 to turn on the Hamiltonian term [3]

$$H_I^{internal} = \frac{\hbar\Omega}{2}(S_+ e^{i\varphi} + S_- e^{-i\varphi})$$

The coupling occurs as Magnetic dipole, Two-photon Raman or Optical quadrupole coupling. Spin dependent forces can be applied to Hyperfine qubits by using differential light shift. A spatial variation in the light shift induces different forces on ions in different collective spin states. The coupling between trapped ions serving as qubits is mediated by Coulombic interaction in the form of vibrational modes of the trapped ion chain [5]. The standard Universal Gate CNOT and SWAP gates can be implemented using appropriate laser frequencies by manipulating the vibrational modes. CNOT gate requires about 50ms of gate time to be performed.

Readout: The qubit state detections is carried out using state-selection fluorescence. The photons from the readout laser resonant with a transition connecting one of the qubit states to a short-lived state are scattered. A fraction of fluorescence photons from the ion are collected (usually with an objective) on the photon-counting detector. In optical qubit system, photon is detected during $S_{1/2}$ – $P_{1/2}$ transition when the laser frequency is appropriately set. While no photon is scattered during $P_{1/2}$ – $D_{5/2}$ as this decay is not possible. Generally, counting only few percent of total fluorescent photons from the qubit is sufficient provide readout fidelities in excess of 0.99 [7, 8].

Advantages: Ion trap system have extremely long relaxation and coherence times, T1 and T2. The relaxation process which is via spontaneous decay is of several seconds in optical qubits, and several days for hyperfine qubits [5].

Extensive research is done in this implementation by academia and industry, so strong support and expertise is available to implement these systems.

Disadvantages: Trivial disadvantages occurring due to cryogenic cooling and vacuum creation possess the initial difficulty.

Gate implementation is typically slower in trapped ion qubits compared to other solid-state methods. Increasing the number of qubits also increases 2-qubit operation time. This is because coupling rate between qubit state and vibrational mode $\propto n^{-1/2}$ [5].

3.2. Superconducting Qubit

Superconducting Josephson Tunnel Junctions with capacitors is widely used by industry giants in their quantum computation architecture. A non-linear L-C circuit is created to create qubit states. Super-low temperatures are needed for maintaining superconductance and eliminate noise. Dilution refrigeration is used to bring the temperature up to millikelvin range. Mapping $|0\rangle$ to $|1\rangle$ is required, for which we have developed three major implementation schemes: Charge qubit, Flux qubit and Phase qubit. Further modifications to these are also available to optimize noise suppression and fidelity. Superconducting circuits can be described by lumped element electromagnetic circuit diagrams.

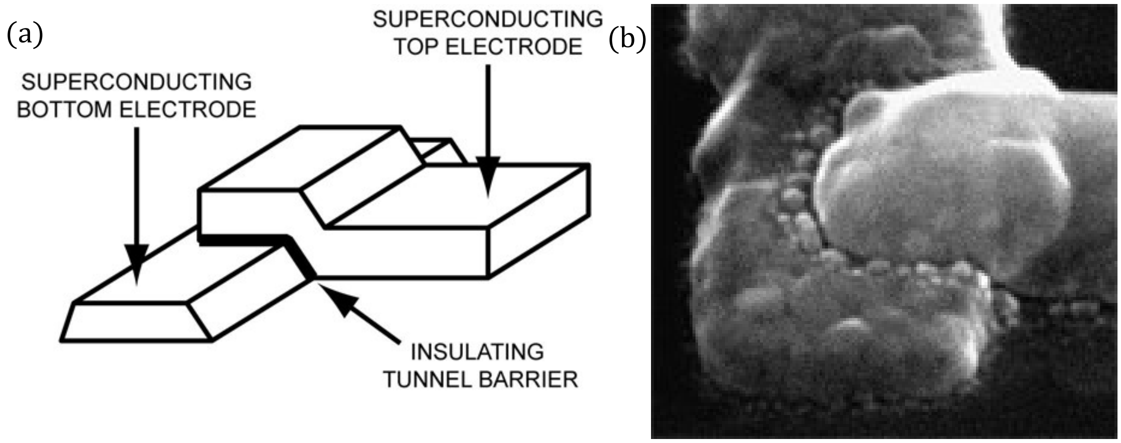

Figure 3: (a) Structure of the superconducting junction and the superconducting island with insulating Alumina barrier. (b) SEM image of an aluminium Superconducting Josephson Tunnel Junction. Source: [9]

The non-linear L-C circuit: The L-C circuit fabricated for superconducting qubit is fabricated using aluminium (and its amorphous oxide) and niobium. The junction is made using two superconducting layers of aluminium and the path for tunnelling is filled by aluminium oxide. While the superconducting island is fabricated using superconducting niobium. Aluminium is to superconducting quantum circuits what silicon is to conventional MOSFET circuits. These quantum circuits are typically made on silicon or sapphire wafers using optical or electron beam lithography ad thin film deposition [1, 10].

We find that only Josephson junction is both non-linear and non-dissipative at low temperatures. Non-linearity is required as to keep the difference in transition energy between state $|0\rangle \rightarrow |1\rangle$ and $|1\rangle \rightarrow |2\rangle$ different. In a linear Inductor the relation followed is

$$I(t) = \frac{1}{L}\Phi(t)$$

Where I(t) is the current flowing through the inductor and Φ(t) is the magnetic flux through it. While the Josephson junction behaves inductively as follows [1]

$$I(t) = I_0 \sin\left[2\pi\Phi(t)/\Phi_0\right]$$

Where $\Phi_0 = h/2e$ and the term inside the sine ($\delta = 2\pi\Phi(t)/\Phi_0$) is magnetic quantum flux called gauge-invariant phase difference across the junction. The charging energy (E_C)and the Josephson energy (E_J) is given by

$$E_C = \frac{e^2}{2C} \; and \; E_J = \frac{h^2}{4e^2 L}$$

The ratio E_J/E_Cdetermines the qubit type encoded. This ratio is

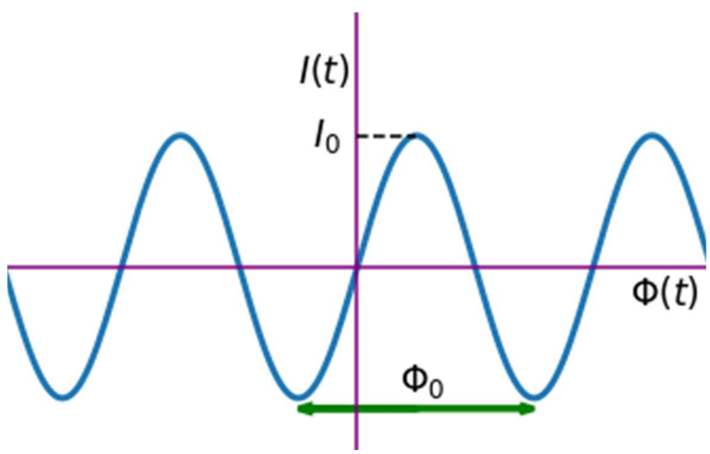

Figure 4: Profile of a Non-Linear inductor like Josephson junction. Python: 3.10.2; Matplotlib: 3.5.1

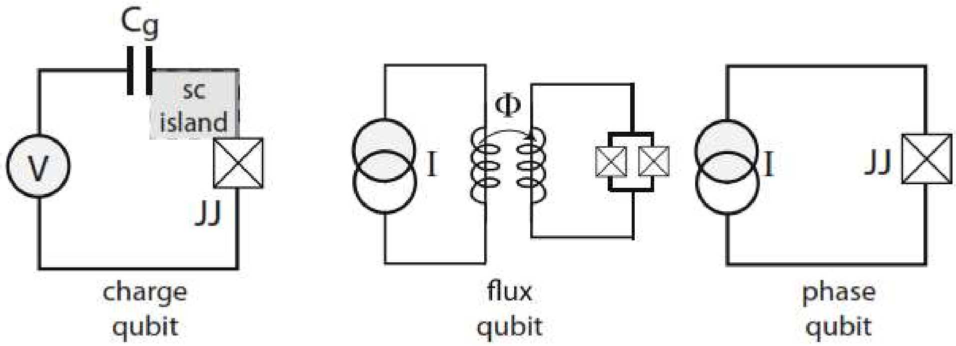

Figure 5: Schematic diagrams of three major implementations of the superconducting qubit. Where JJ denotes the Josephson Junction. Source: [12]

kept between 10 and 50 for Transmon Qubits. The qubit splitting energy is given by $E_{01} \approx \sqrt{8E_C E_J}$

Charge Qubit: Also known as Cooper-pair box. These qubits represent the operational basis state as the presence or absence of copper pairs on the superconducting capacitor island. Taking junction capacitance as C_J, gate capacitance as C_g and Josephson energy E_J, we get the Hamiltonian as

$$H = \sum_n \left[\left(\frac{2e^2}{C_g + C_J} \right) (n - n_g) |n\rangle\langle n| - \frac{1}{2} E_J (|n\rangle\langle n+1| + |n+1\rangle\langle n|) \right]$$

Where n is the number of excess Cooper pairs in the island and V_g is the gate voltage. Importantly n_g is

$$n_g = \frac{C_g V_g}{2e}$$

At low temperatures and low gate voltage we can manipulate with n=0 and n=1 giving a two-state qubit system. It operates with $E_J \ll E_C$.

Flux Qubits: The magnetic flux quanta of the circuit is used as the operational basis state for qubit control. They are based upon RF-SQUID (Radio Frequency-Superconducting Quantum Interference Device). In this device a transformer is used for control instead of a gate capacitor. The Hamiltonian for the respective is

$$H = \frac{q^2}{2C_J} + \left(\frac{\Phi_0}{2\pi} \right)^2 \frac{\phi^2}{2L} - E_J \cos\left[\phi - \Phi \frac{2\pi}{\Phi_0} \right]$$

Where q is the charge on junction capacitance $C_J$and ϕ is the superconducting wave function phase difference across the Josephson junction. It operates with $E_J > E_C$.

Phase Qubits: In these qubits the degree of freedom manipulated with is the energy levels corresponding to different quantum charge oscillation amplitudes across the Josephson tunnel junction. The charge maps to momentum, while phase maps to position corresponding to quantum harmonic oscillator. It is based upon the current biased junction.

The Hamiltonian for the respective is

$$H = \frac{2e^2}{2C_J}q^2 - I_0\frac{\Phi_0}{2\pi}\phi - E_J\cos\phi$$

It operates with $E_J \gg E_C$.

Other Qubit types like Transmon ($E_J/E_C \sim 10-50$), Fluxonium, Xmon and Quantronium, etc. are also studied in industry and academia.

Gate operations and Qubit control: Initialization of qubit you ground state is easily achievable by cooling the system sufficiently low so that it will naturally relax into $|0\rangle$. All the qubit control operations are carried via the resonator column through which electromagnetic wave with specific profiles are sent to change the state of qubit visualized by change in position of vector on the Bloch sphere. The resonator has its impedance tuned before operations and is coupled to a capacitor which acts as an intermediate stage for the signal and the artificial atom (superconducting qubit).

To perform one-qubit gates we can bias the qubit at a point with $n_g \neq 1/2$ that is not close to degeneracy point. Z gate is performed by changing $n_g$by small amount $\delta n_g$for a short time δt which imparts differential phase ϕ =$E_C\delta n_g\delta t$. X gate is performed by rapidly switching to the degeneracy point $n_g = 1/2$ waiting for time δt and then switching back. To perform two-qubit gates coupling between the qubits is done using a capacitor fabricated on the same chip very close to each other [12].

Readout: The qubit state measurement is done using a microwave frequency travelling through the readout resonator cavity coupled to the non-linear L-C qubit through a coupling capacitor. The electromagnetic wave is reflected which is then analysed to know the state on which the qubit has collapsed upon. The other way is to couple a charge trap to the qubit and use a single electron transistor (SET) to readout charge [1].

Advantages: The primary advantage of Superconducting Qubits is that they have comparatively faster gate operation time.

Furthermore, the manufacturing is based on semiconductor industry which is well mastered and established. The core circuits of charge qubits, flux qubits and phase qubits are perfectly compatible with current microelectronic processing technology. These superconducting qubits are also more scalable for industrial scales [11, 13].

Disadvantages: They have a much shorter decoherence time which could be improved a bit by introducing cavity quantum electrodynamics. The relaxation rate is also shown to be exponentially dependent on the temperature, due to qubit interaction with thermal photons. Thus, they need to be cooled to critically low temperatures in order of millikelvins for the Josephson junction to be functional and to dampen noise.

As these systems are macroscopic and are easily mass produced using standard microfabrication, there comes evident drawbacks from these mass-produced qubits. L and C can be shown as

$$L = L^{stat} + \Delta L(t)$$

$$C = C^{stat} + \Delta C(t)$$

As every fabrication batch will be slightly different there will be a slight difference in the expected and reproduced values unlike transitions in atoms which are so reproducible. The second term signifies the time-varying defects during working [1].

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3.3. Optical Qubit

Photons are Bosonic spin 1 particles that provides many degrees of freedom to be manipulated. A photon can be used as a qubit with its states encoded as probability amplitudes corresponding to its occupation of two modes of some degree of freedom of the optical field, known as dual rail encoding. Commonly utilized mode pairs are orthogonal polarizations or non- overlapping propagation paths, and recently other degrees of freedom such as transverse spatial, frequency mode, temporal mode. Transverse polarization states of a photon like horizontal or vertical, or right or left circular provide a perfect basis for computation. Setup includes mirrors, phase shifters, beamsplitters and nonlinear optical Kerr media [3].

Mirrors are used to change the photons propagation direction in space. While a phase shifter is a slab of transparent medium of length L and refractive index n. The photon's phase changes by $e^{i\, n\omega L/c_0}$, where $c_0$is the speed of light in vacuum. Beamsplitter is a partially silvered piece of glass. Nonlinear optical media such as a Kerr media is used whose index of refraction $n$is proportional to the total intensity I of th light going through it

$$n(I) = n + n_2 I$$

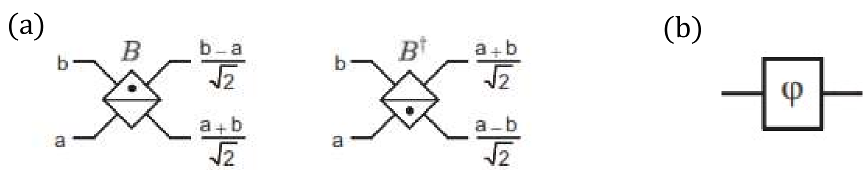

Figure 6: (a) Optical beamsplitter with two input and two output ports. The following has phase convention of π/4 for 50-50 beamsplitter. With B† as e inverse of B. (b) A standard phase shifter representation with phase shift angle of φ. Source: [3]

Deterministic photons are produced feasibility based on quantum dots which are coupled to optical cavities

Gate operations and Qubit control: Photon state initialization is done in the source itself. Polarization encoding can be converted to dual rail encoding using a beamsplitter and a phase shifter like

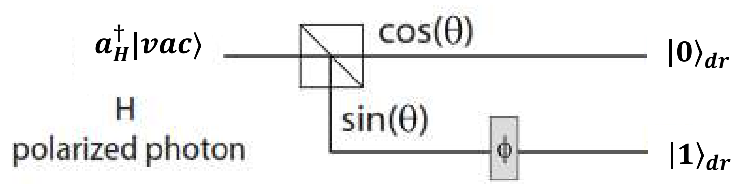

Figure 7: Conversion of polarization encoding to dual rail encoding. Source: [12]

Arbitrary unitary transformation can be applied to the photon carrying he quantum information encoded as $c_0|01\rangle + c_1|10\rangle$ in dual rail representation. Showing how a Hadamard gate can be performed on a dual rail single photon, i.e., $|01\rangle \rightarrow (|01\rangle + |10\rangle)/\sqrt{2}$ and $|01\rangle \rightarrow (|01\rangle - |10\rangle)/\sqrt{2}$ as

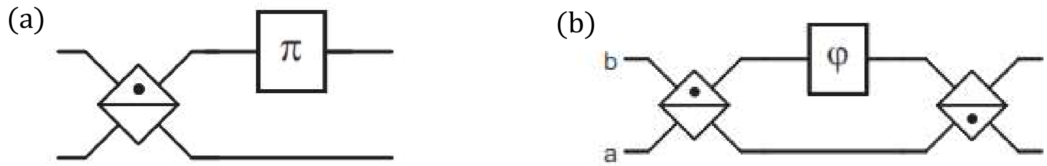

Figure 8: (a) Hadamard Gate implementation for dual rail encoded photon. (b) Circuit to compute rotation operation on dual rail states as a function of phase shift φ. Source: [3]

Two-qubit gates are applied by passing photons to be coupled through a nonlinear medium and then corresponding operations are performed.

Readout: Photon detectors are used to detect and measure the qubits. The Photon Detector (PD) used is Si avalanche photodiode (APD) operating in Geiger mode. These are relatively fast and low noise detectors. Contrary their quantum efficiency is merely up to $\eta_d \approx 65\%$. Research is going to include superconducting nanowire single-photon detectors (SNSPDs) [14].

Advantages: Photonic quantum computers work at room temperatures if superconducting detector is not used specifically. They are easily integrated into optical fibres and its based telecommunications infrastructure.

Disadvantages: The primary shortcoming of Photonic quantum computers is that the interaction of photons is quite difficult. Even sophisticated nonlinear Kerr media are very weak and don't provide cross phase modulation of π between single photon states. Therefor large ratio of cross phase modulation strength to absorption loss are difficult to realize. Secondly we don't have reliable deterministic sources of identical photons and detectors are not completely efficient as they can generate photocarriers even when no photons are incident, this phenomenon is called dark counts.

3.4. Quantum Dots

Quantum Dot: The semiconductor quantum dot is an implementation in creating an artificial atom, which is three dimensional potential well-formed inside a semiconductor to trap electron(s). The are fabricated using CMOS technology with material generally GaAs or Si, as well consisting of gate electrodes that control the energy landscape in the qubit substrate. In silicon spin qubit the information is encoded in the spin of the electron found in the quantum dot, or in the spin state of electron or nucleus of a single-dopant atom (typically group V donors like phosphorous) in the silicon substrate [12, 18].

Due to applied magnetic field and its induced Zeeman effect, the orbital for the confined electron is split into distinct spin states $|\uparrow\rangle$ and $|\downarrow\rangle$, encoding the computational basis $|0\rangle$ and $|1\rangle$. The splitting energy is given by $\gamma_e B_0$, where $\gamma_e$is the gyromagnetic ratio of the electron.

Gate operations and Qubit control: They are commonly initialized using spin-charge conversion techniques. Single qubit gates are implemented with resonant microwave field at frequency $\omega_q = 2\mu_B B_0/\hbar$. Where $B_0$is a large DC magnetic field defining the quantization axis. This slits the orbital degeneracy of the dot electron at the interface.

Two-qubit gates are implemented by raising and lowering the electrostatic barrier between the wells. When the barrier is high, tunnelling is suppressed and the qubit states don't evolve. When the barrier is lowered, tunnelling is allowed and the spins experience a Heisenberg interaction. The coupling between two qubits occurs via the intrinsic exchange interaction between them. The exchange coupling J_e is modified by tuning the above tunnel barrier. To implement CNOT, the qubit is operated in regime where J_e is smaller than the energy difference between the qubit splitting of the two electrons [12, 18].

Readout: The electron spin is measured using spin-charge conversion. Charge sensors such as quantum point contacts (QPC) and single electron transistors are located adjacent to the dot, which are then capacitively coupled. The sensors are biased appropriately. the orbital energy is then set such that the electron can preferentially tunnel to the same or nearby charge reservoir depending on its spin state. The presence or absence of electron on the dot is detected via change in current through the sensor.

Advantages: The spin-orbit coupling is weak for the electrons in silicon, resulting in long relaxation time T_1 of about several seconds to about hours (temperature < 1K and magnetic field <5T). The relaxation time is dependent upon the temperature and magnetic field.

The primary ease that these qubits bring that it is based upon existing semiconductor industry and thus is easier to develop such devices and mass fabricate.

Disadvantages: Spin qubits experience spin-flips and dephasing mediated by spin-phonon coupling, spin-orbit coupling and hyperfine coupling to nuclear spins in the host. All these reasons account for lesser number of qubits which could be entangled.

3.5. NMR Qubits

The NMR Apparatus: In NMR qubits the spin of the nuclear spin of atoms or molecules are utilized for computational basis of the system. NMR (Nuclear Magnetic Resonance) technology is used to initialize, qubit control and readout from the ensemble. They are set up in two ways as liquid or solid state, the latter being more recent. For liquid state NMR qubits pulsed NMR system is

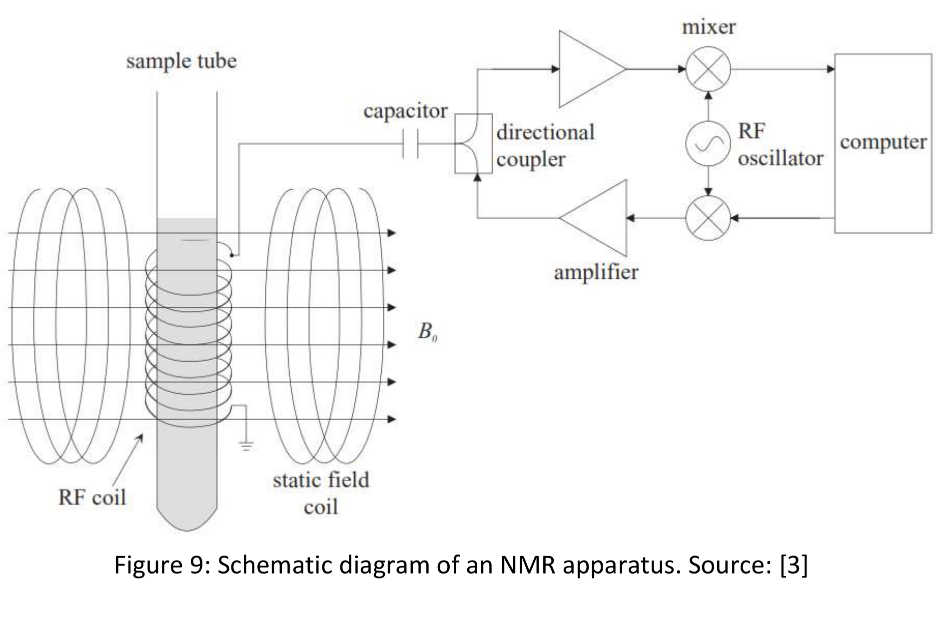

Figure 9: Schematic diagram of an NMR apparatus. Source: [3]

created. A typical molecule with Zeeman level of spin -1/2 nuclei in magnetic field like ^{13}C, ^{19}F, ^{15}N and ^{31}P are considered, which produce NMR signal at about 50 MHz when place in field of about 11.7 T. The molecules are typically dissolved in a solvent, reducing the concentration to the extent that the inter-molecular interactions become negligible, leaving a system which is ensemble of n qubits. The spectrometer is constructed from RF electronics and a large superconducting magnet, within the bore of which is held the sample in a glass tube [3, 15, 16].

Gate operations and Qubit control: A time varying magnetic field is applied, $B_0 > B_1$

$$B = B_0\hat{z} + B_1(\hat{x}\cos\omega t + \hat{y}\sin\omega t)$$

Giving the Hamiltonian as [3]

$$H = \sum_k \omega_k Z_k + \sum_{j,k} H_{j,k}^J + H^{RF} + \sum_{j,k} H_{j,k}^D + H^{env}$$

Where the first term is free precision of the spins in the ambient magnetic field, $H^D$is the magnetic dipole coupling, $H^J$is the 'J' coupling, $H^{RF}$is the effect of externally applied RF field and H^{env}describes the interaction with the environment which leads to decoherence.

One qubit gate is achieved using resonant radiofrequency fields. The power is length of the RF pulse determines the rotation angle, while the phase of the RF radiation corresponds with the rotation axis with the x-y plane. Another technique of abstract reference frames has an advantage that the Z rotation can be implemented without using any time or resources.

Two qubit gates are implemented using selective pulse techniques to excite one spin only when neighbouring spin is in one of its two eigenstates. Other techniques are also used.

Readout: As NMR is implemented as ensemble of spin systems, ensemble measurement is performed which yield expectation value rather than projective measurement. The reading is achieved by exciting the corresponding spin with an RF pulse and observing the phase of the NMR signal [15, 16, 17].

Advantages: The main point of interest is that the nucleus is naturally protected from the outside interference, i.e., spins are lined up stay stable for a long time. The second ease is that NMR technology is well developed for other applications like medical industry which makes knowledge transfer easier to operate.

Disadvantage: The primary setback NMR faces is its non-scalability. Effective pure state preparation schemes reduce signal exponentially in the number of qubits, unless the initial polarization is sufficiently high. Another issue is the implementation of pulse sequences with very large number of spins [3, 10]. A typical NMR qubit falls for decoherence by the time it takes to operate 500 gates which is well below the number required for effective error correction schemes.

3.6. Neutral Atom Qubits

Neutral atoms are used as qubits to encode basis states as two hyperfine Zeeman states of the ground electronic configuration. The energy separation is in order of few GHz. The atoms are cooled to micro-Kelvin range and then trapped in optical or magnetic potential wells. Heavy alkali elements are utilized for this purpose like Rb and Cs which have large ground state hyperfine splitting. Alkaline earth elements are also explored such as Sr and Yb which have two valence electrons which increases complexity but provides desirable narrow optical transitions that enable stronger laser cooling.

Gate operations and Qubit control: Standard optical pumping is used to initialize the qubits. The gates are implemented with microwave fields that directly couple the qubit states or with optical frequency via two-photon simulated Raman optical transition. Resonant Rabi rotations provide $R_X(\theta)$ or $R_Y(\theta)$ gates for real and imaginary Rabi frequencies. The rotation angle is $\theta = t|\Omega|$ with t as the gate time. Z gate is implemented using operator identity $Z = iYX$ [12].

The approach to implement two-qubit gates is Rydberg blockade. In this the atoms are excited to Rydberg states that have a spatial extent $r \approx a_0 n^2$ where a_0 is the Bohr radius and n is the principal quantum number. The rapid scaling of interaction strength with n provides a switchable interatomic coupling that can be turned on and off with laser pulses [19].

Readout: State measurement is done using resonant light scattering that distinguishes the quantum states. It is carried by imaging scattered light onto a sensitive detector and counting photons.

Advantages: They are easier to produce in set of large quantum registers and support massive parallelism. Like ion trap systems they have longer coherence times in order of many seconds [13].

Disadvantages: General issues of cryogenic requirements and environmental isolation is encountered. The effective gate operation duration is higher than other implementations (in order of milliseconds for collisional gates, while Rydberg gates being faster). Individual addressing is much difficult in neutral atom setup.

4. Conclusion

We observe there are various challenges to fabricate a perfect qubit. Nonetheless, we have experimented and deployed these complex systems at a low volume scale. To make quantum computation much more accessible scientists and engineers are continuously striving by devising methods which impacts the qubit structural efficiency, operating gates, readout capabilities as well as auxiliary supporting systems such as vacuum creation and cryogenic cooling technologies.

We are designing qubits to work at higher temperatures with more coupling to readout instrumentation and negligible coupling to the noisy parasitic environment. We have reviewed in brief Ion trap, Superconducting, Photonic, Quantum Dot, NMR and Neutral atom qubit systems each with its specific domain of efficiencies and shortcomings. Some more viable, scalable and industry favourite than others. The forerunners in industry namely IBM and Google use superconducting qubits, while Microsoft and Bell Labs use Topological implementation. To mention, Intel carries research upon silicon quantum dots and Ion-Q on trapped ions. We see active participation from Governmental organizations also as quantum technology is set to benefit a nation financially as well as strategically.

We hope and are actively working towards building better error correction schemes, high fidelity operation techniques, economically feasible and friendlier environments for our Qubits.

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