Quantum Internet

Back before Aug. 6, 1991

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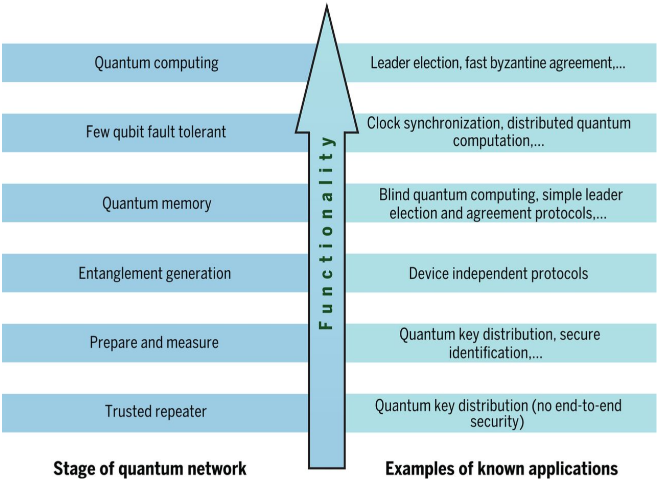
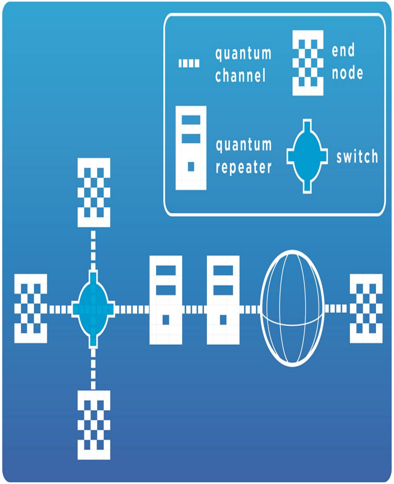
Outline

Applications: Broadly Speaking [1]



Components:

- Quantum Node
- Quantum Channel
- Quantum Repeater (WiFi Extender)
- Switch



Advantages of a Quantum Channel [2]

- A Quantum Channel provides an exponential increase in computational dimension
  - $k2^n$ to 2^{kn} when we connect k n-bit quantum nodes
- Helps to alleviate scaling and error-correlation problems
  - Simulation of evolution of quantum many-body systems
  - "Spin-Spin" interaction of atoms simulated by a quantum channel
  - Percolation problem

Percolation sidenote

- I.e., can the liquid flow from the top of a cube to the bottom? When the cube has a Swiss cheese like internal structure but some of the paths are blocked with probability p[1].

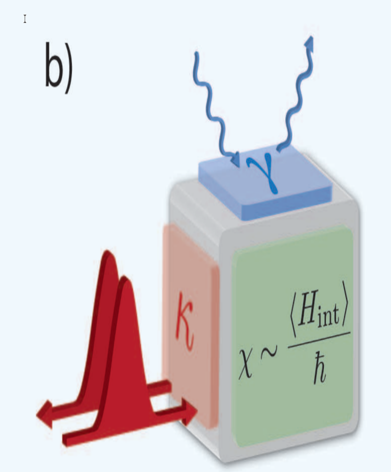
[1] Percolation Theory from Wikipedia

Focus of This Presentation: Quantum Channels

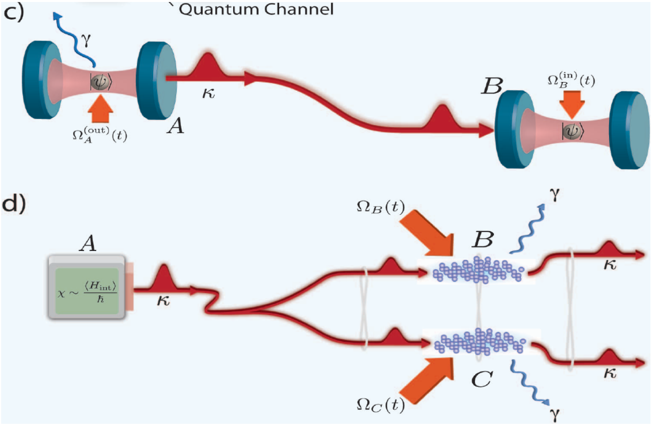
- Transmission of photons
- Use of atoms to store quantum states
- Coupling of a single photon and an atom w/ help of cavity QED (Quantum Electrodynamics)
- Photon-photon interaction cross-sections are tiny, i.e., very unlikely to occur
- Quantum Information processing with atomic ensembles

Requirements for Physical Realization [2]

- Interaction between light and matter should be easily tunable
- Done through an interaction Hamiltonian $< H_{int}(t) > \approx \hbar\chi(t)$
- Physical processes that controls $\chi(t)$ need to be robust in the face of imperfections (by adibatic transfer)
- Mistakes can be efficiently detected and fixed (with quantum error correction)



Example [2]



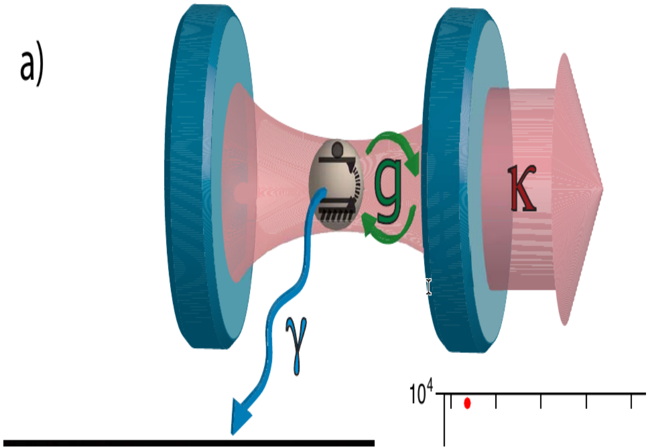
Fabry-Perot cavity

Terms[2] [2]

- V_m: mode volume, approximately the volume of resonator, defines spatial confinement. Debated definition
- Quality factor: roughly defines how long the light lives in the cavity
- $\vec{\epsilon}$: polarization vector
- $\vec{\mu_0}$: transition dipole moment: how strong does the atom feel a EM wave with certain polarization?
- $g = \sqrt{\frac{|\vec{\epsilon}\cdot\vec{\mu_0}|^2\omega_C}{2\hbar\epsilon_0 V_m}}$
- γ: atomic decay rate to modes other than the cavity mode
- κ: decay rate of cavity mode
- $n_0 \approx \gamma^2/g^2$: photons required to saturate the intracavity atom
- $N_0 \approx \kappa\gamma/g^2$: number of atoms required to have an appreciable effect on intracavity field

[2] Mode Volume and Quality Factor

Illustration

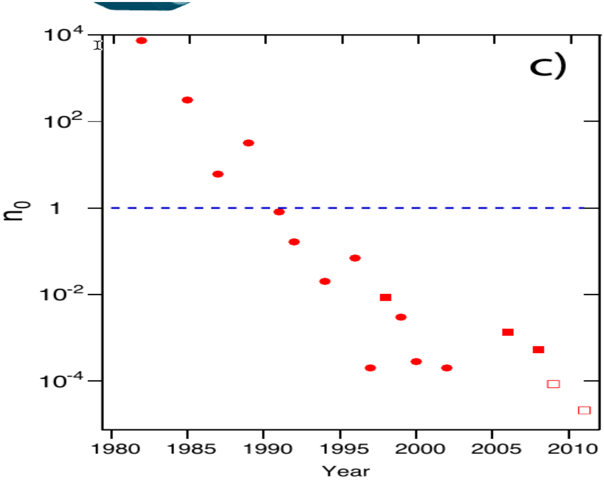


Strong Coupling Regime [2]

- Requires $(N_0, n_0) << 1$
- Could be achieved in the microwave domain with a Rydberg atom and a high Q superconducting cavity
- In the optical domain: uses a high-finesse optical resonator, and atomic transitions with large $\vec{\mu_0}$ [3]
- Better confinement of the atoms will also help by reducing V_m

[3] Finesse

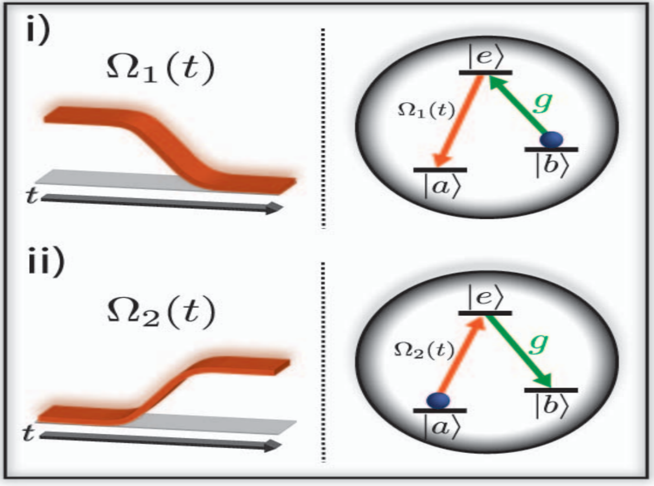
Progress



How We Send Bits Classically

- OK, it's a diagress, watch yourself if interested
- Basically explains why we want a single photon to be sent
- Classically, we send a bunch of them to represent a classical bit
- Video, watch it!

Illustration

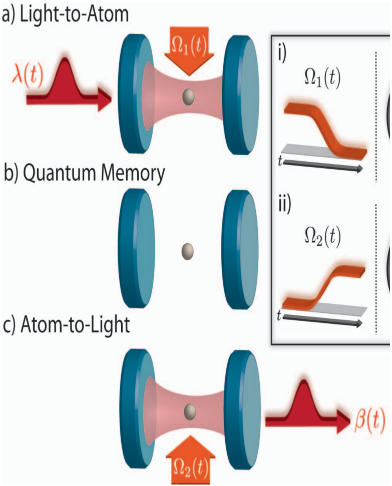


How We Do It

- Mathematically $|a\rangle|0\rangle \leftrightarrow |b\rangle|1\rangle$
- Notation is $|\psi_{atom}\rangle|\phi_{Fock}\rangle$
- Dark State $|D\rangle = cos\theta|a\rangle|0\rangle + sin\theta|b\rangle|1\rangle$
- $cos\theta = [1 + \frac{\Omega(t)^2}{g^2}]^{-1/2}$
- Need to modify $\Omega(t)$ adiabatically, to coherently map the atomic state to the photon's state (and vice versa)
- Intermediate transition $|b\rangle \rightarrow |e\rangle$ stongly coupled to a mode of optical cavity of energy $\hbar g$

Importance

- Could serve as Quantum Memory
- Optical field as a superposition of 0 and 1 Fock state sent through fiber
- Use the control field $\Omega(t)$ to store the superposition information into the atoms



Extended Entanglement [2]

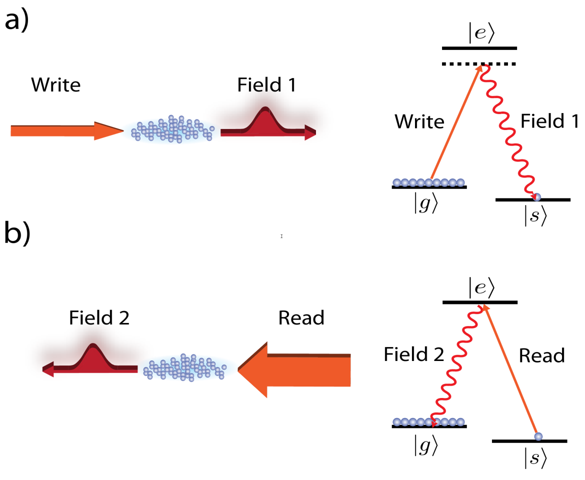
- Allows the control field to have different polarization over time
- May entangle the state of atom with the polarization state of a flying photon, p_1
- p_1 is not emitted by the atom, just entangling it with the atom. However, could have came from the emission process of another atom, thus having the state info of that atom.
- Apply another control field to disentangle the atom with p_1 and emit another photon p_2 which is in turn entangled with p_1

% - No pics :(, the source file does not allow access, darn

What Is It?

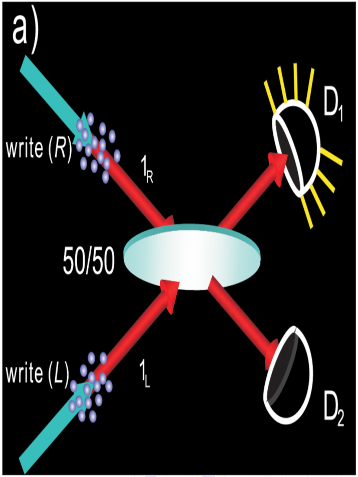
- Protocol to distribute coherence and entanglement in the discrete variable regime.
- $|\phi_{a,1}\rangle = |0_a\rangle |0_1\rangle + e^{i\beta}\sqrt{p}\,|1_a\rangle |1_1\rangle + \mathcal{O}(p)$
- $|1_a\rangle = \frac{1}{\sqrt{N_a}} \sum_{i=1}^{N_a} |g_1\rangle \ldots |s_i\rangle \ldots |g_{N_a}\rangle$
- Note: the sharing of this 'spin up' property gives entanglement amongst all N_a qubits

Illustration



Create an Entangled Pair of Ensembles

- Combine the two ensembles of entangled atoms
- $|\Psi_{L,R}\rangle = \frac{1}{\sqrt{2}}[|0_a\rangle_L |1_a\rangle_R \pm e^{i\eta_1} |1_a\rangle_L |0_a\rangle_R]$
- Resilient to important sources of imperfections and loses in propagation and detection
- Creation of entanglement through measurement



Extending Entanglement for Quantum Networks

- Network of quantum nodes need not and should not be bipartite.
- How to create entanglement among N quantum nodes?
- How do we verify and quantify and entanglement between N parties?
- Is "does it work for a certain algorithm" a good criterium?

Outlooks

- New developments in how to make quantum channels and other parts more robust

Challenges

- Quantification of entanglement between many entities
- Concurrence, negativity, and entropy of entanglement

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