# Quantum Internet

## Back before Aug. 6, 1991

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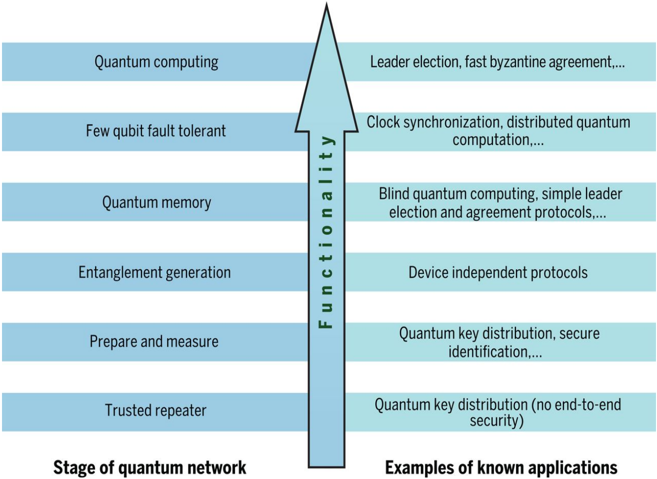
November 29, 2020

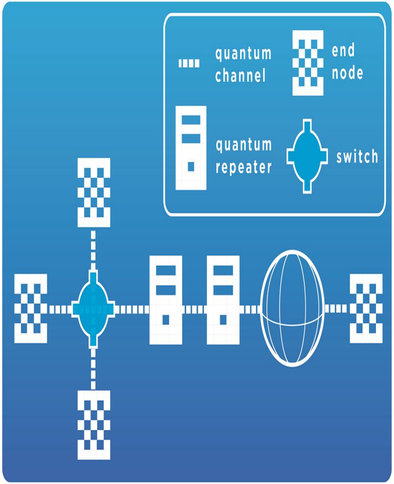
# Outline

# Applications: broadly speaking [1]



# Components:

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



# Advantage of Quantum Channel [2]

- Quantum Channel provides exponential increase in computational dimension
- $k2^n$ to $2^{kn}$ when we connect k n-bit quantum nodes
- Help to alleviate scaling and error-correlation problem
- Simulation of evolution of quantum many-body system (Remove-Chase)
- "Spin-Spin" interaction of atoms simulated by quantum channel
- Help to solve the problem of percolation

# Percolation sidenote

- I.e can the liquid flow from the top of a cube to the bottom. When the cube has a cheese (Tom and Jerry type of cheese)like internal structure but some of the paths are blocked with probability p. [1]

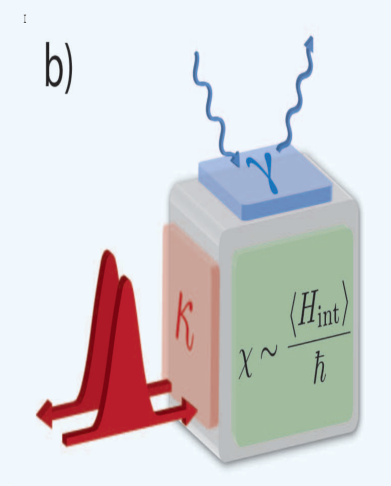
[1] Percolation Theory from Wikipedia

# Focus of this presentation: Quantum Channel

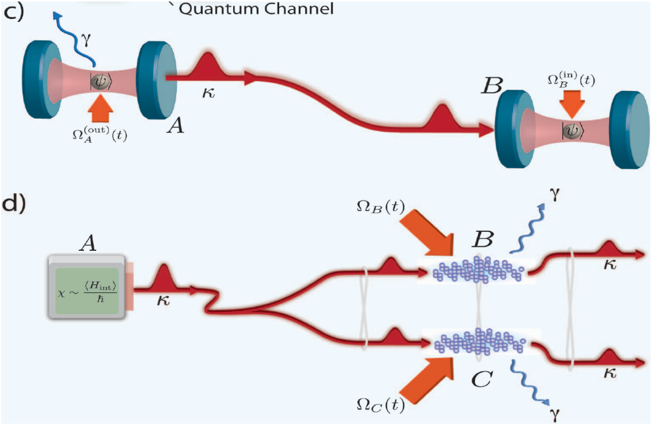
- What we transmit is light, i.e photon
- What we use to store quantum states is atom
- Coupling of single photon and atom w/ help of cavity QED
- Difficulty arises b/c photon-photon interaction cross-sections are tiny, i.e very unlikely to occur
- Quantum Information processing with atomic ensemble

# 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?
- Mistakes can be efficiently detected and fixed
- Mathematically : $\chi >> \kappa >> \gamma$



# Realization Examples [2]



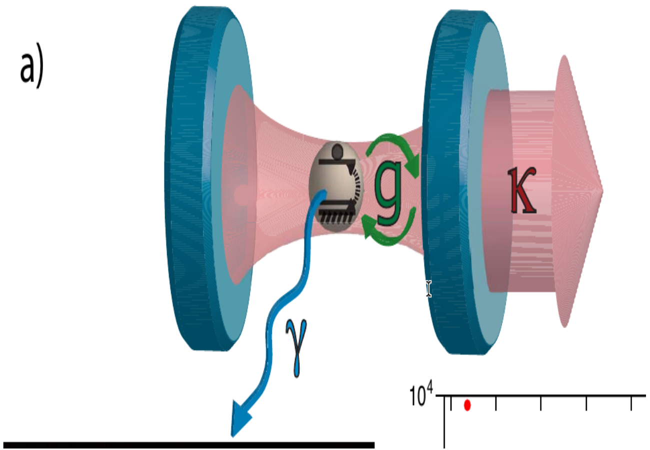

FabryPerot cavity

# 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
- $g = \sqrt{\frac{|\vec{\epsilon} \cdot \vec{\mu_0}|^2 \omega_C}{2\hbar\epsilon_0 V_m}}$
- $\gamma$: atomic decay rate to modes other than the cavity mode
- $\kappa$: 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 appreciable effect on intracavity field

[2] Mode Volume and Quality Factor

# Illustration

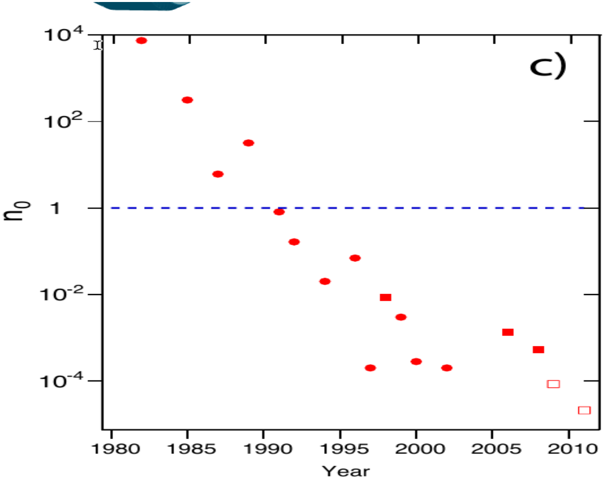


# Strong Coupling regime [2]

- Require $(N_0, n_0) << 1$
- Could achieve in microwave domain with a Rydberg atom and a high Q superconducting cavity
- In optical domain: use high-finesse optical resonator and atomic transition with large $\vec{\mu_0}$ [3]
- Better confinement of atom will also help, it reduces $V_m$

[3] Finesse

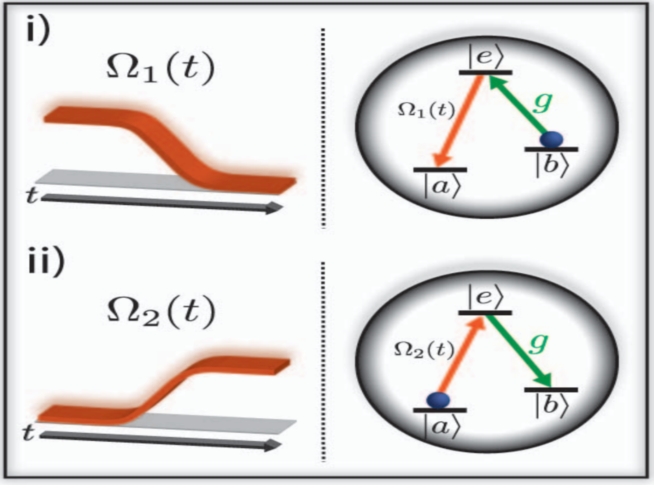
# Progress



# 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

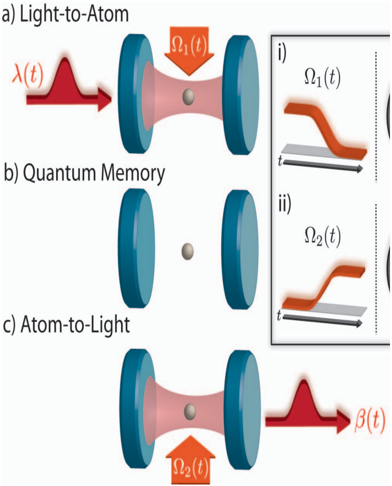


# How we do it

- 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 $\Omega(t)$ adibatically for coherent absorption and creation of photon?
- 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 atoms



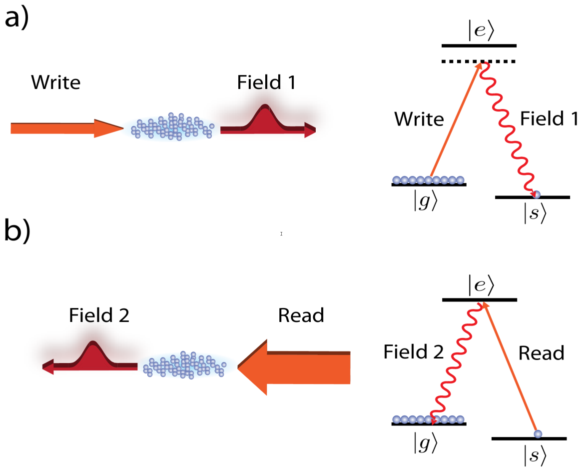
# Extend to have entanglement [2]

- Allow the control field to have different polarization over time
- May entangle the state of atom with the polarization state of a flying photon call it $p_1$
- $p_1$ is not emitted by the atom, you are just entangling it with the atom, 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?

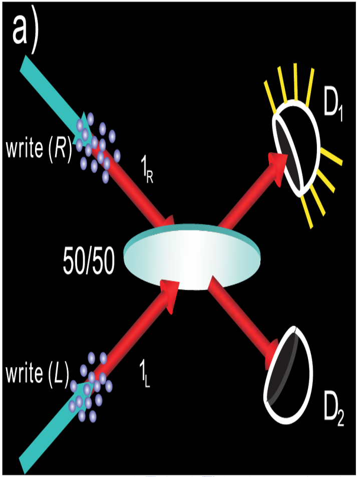
- Protocol to distribute coherence and entanglement in the discrete variable regime.
- $|\phi_{a,1}\rangle = |0_a\rangle\,|0_1\rangle + e^{i\beta}\sqrt{p}\,|1_a\rangle\,|1_1\rangle + \mathcal{O}(p)$
- $|1_a\rangle = \frac{1}{\sqrt{N_a}}\sum_{i=1}^{N_a} |g_1\rangle \ldots |s_i\rangle \ldots |g_{N_a}\rangle$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

# Illustration



# Create entangled pair of ensembles

- Combine the two ensemble 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
- Created 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.
- "Does it work for a certain algorithm" is a good criteria?

# 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

# References I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