Quantum Computing With Addressable Optical Lattices: Error characterization, correction & optimization

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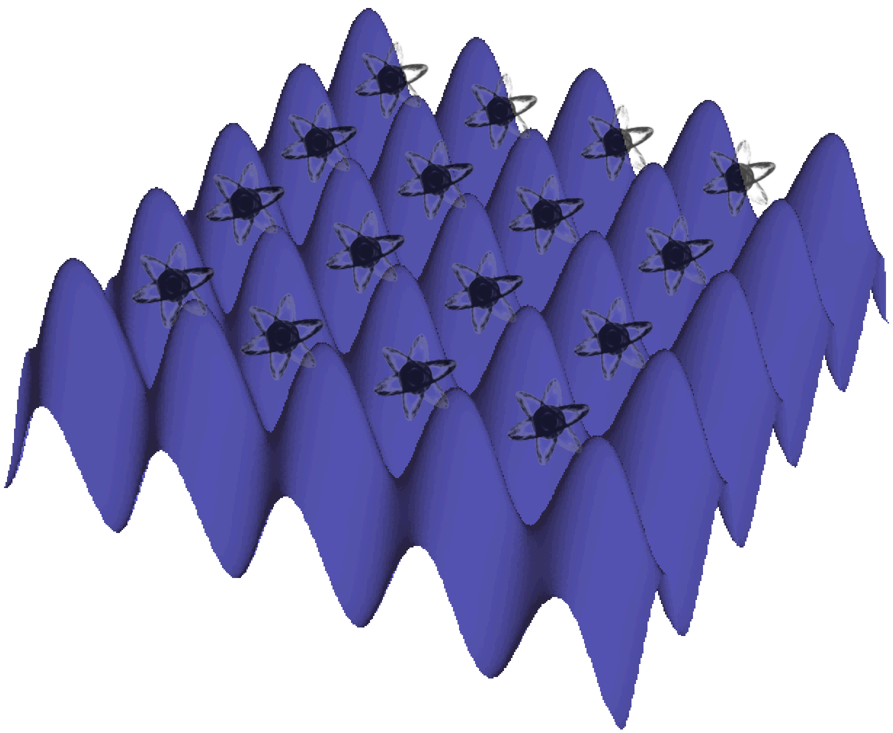
Overview

- Create an "optical lattice" standing wave potential using two interfering laser beams per spatial dimension
- Initialize the lattice by putting one ^{133}Cs atom in each lattice site
- Perform single qubit gates by "addressing" individual sites with a focused laser, then use μ-wave pulse
- Do two-qubit CPHASE gate by exciting neighbouring atoms to Rydberg states, and using dipole-dipole coupling



Atoms in a 2-D optical lattice

Why addressable optical lattices?

(This is not David DiVincenzo)

Good balance between isolation from environment and control

Satisfies the DiVincenzo criteria for quantum computing

- ◆ Reasonably scalable (> 10^3 qubits)
- ◆ Initialization
- ◆ Long coherence times
- ◆ Universal gates
- ◆ Single qubit measurements

The Road Ahead

where we’ve been

- Large lattice spacing (CO_2 laser) with Cs atoms
- Imaging of individual lattice sites
- Site-specific operations using addressing laser
- Single qubit gates, qubit readout with Cs

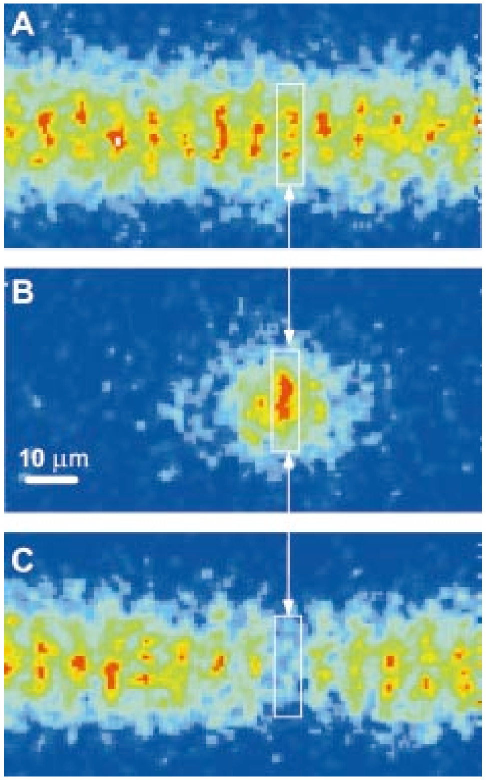
where we’re going

- Creating perfectly filled addressable lattice
- Two qubit Rydberg dipole-dipole gate

Experimental demonstration: Single site addressability

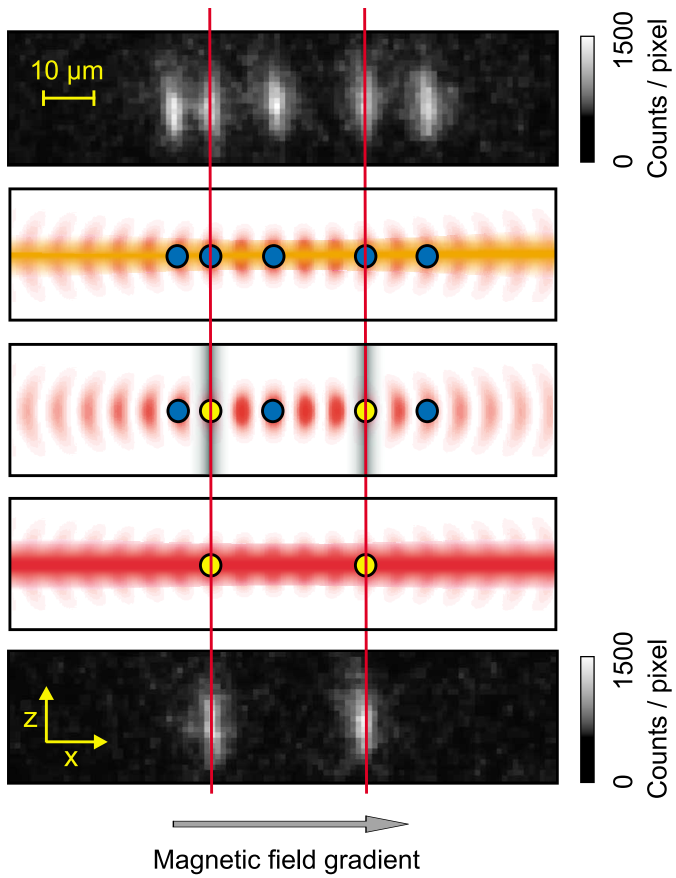
Scheunemann *et al* (PRA **62** 051801) make a 1D optical lattice with bunches of Cs atoms, and demonstrate the following:

- Large lattice spacing (~ 5 μm) optical lattice with Cs
- Single site imaging
- Single site operations (e.g. addressability)



Groups of Cs atoms trapped in a 1-D lattice potential
Image from PRA **62** 051801

Experimental demonstration: Single qubit gates

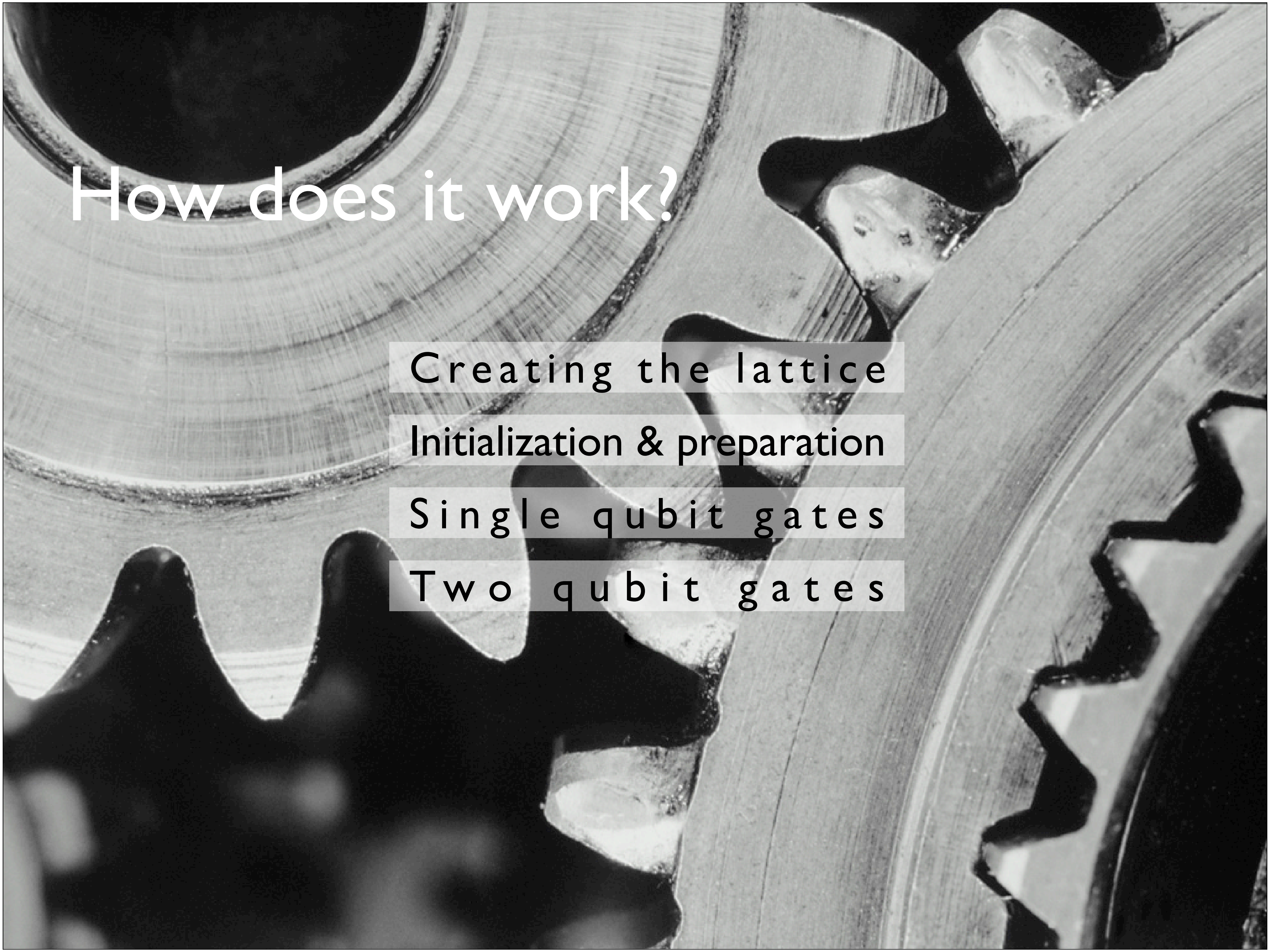


Cesium atoms trapped in a 1-D lattice potential

Image from PRL **93** 150501

Schrader *et al* (PRL **93** 150501) make a 1D optical lattice with a string of Cs atoms, and demonstrate several key requirements for quantum computation:

- Single qubit state flip (using magnetic field for addressing)
- Qubit readout
- Initialization
- Long storage times (25 s)

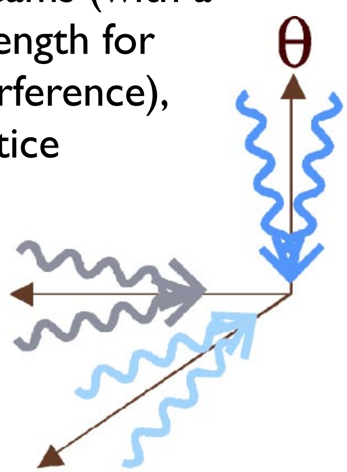

How does it work?
Creating the lattice
Initialization & preparation
Single qubit gates
Two qubit gates

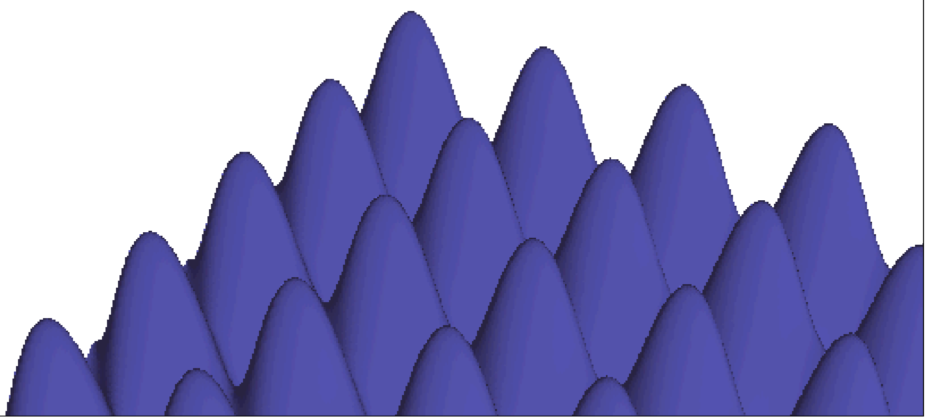
Creating the lattice

- Can use a CO_2 laser (λ = 10.6 μm) to produce a lattice with spacing *a* = 5.3 μm
- Or, can use a blue-detuned laser (e.g. λ < 852 nm) with an angle θ between beams to give a lattice of spacing $a = \lambda / (2 \sin [\theta / 2])$
- Using three pairs of beams (with a slightly different wavelength for each pair to avoid interference), create a 3D optical lattice

Bonus! 50% more numbers and equations!

200 mW beams at 800 nm could produce a 20 x 20 x 20 lattice with *a* = 5 μm, trap depths of 170 μK and very low (~ 10^{-4} Hz) photon scattering rates.



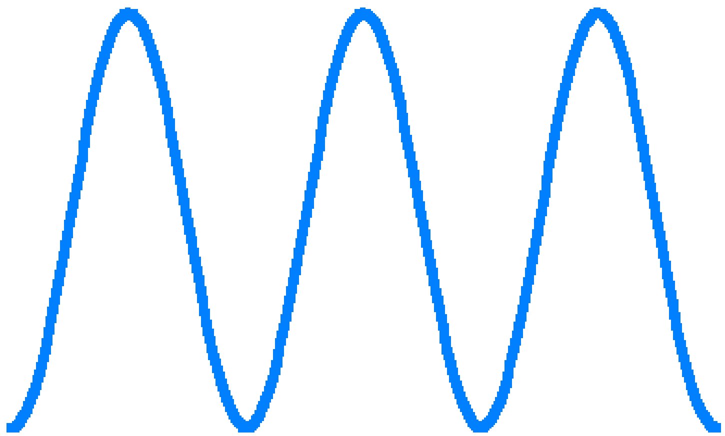


Initialization & preparation (1)

- Load lattice from a MOT (magneto-optic trap), leaving several atoms in each lattice site
- Laser cool atoms, which causes atoms to be lost in pairs via photon-assisted collisions (PRL **82** 2262, Nature **411** 1024)
  - After a few ms, half the sites have one atom, the other half have no atoms
- Image the lattice plane-by-plane with high numerical aperture lens while cooling in optical molasses
- Cool to vibrational ground state using 3D Raman sideband cooling (PRL **84** 439)
- Need to compact the lattice—rearrange atoms to create a smaller, perfectly-filled lattice

Initialization & preparation (2)

- How do we selectively move atoms from site to site?
  - "Tag" atoms to be moved
  - Shift lattice potential to right for tagged atoms, to left for untagged atoms
  - Untag all atoms
  - Restore lattice potential
- Can tag atoms very fast, so we can effectively move an arbitrary number of atoms (in the same direction) in parallel

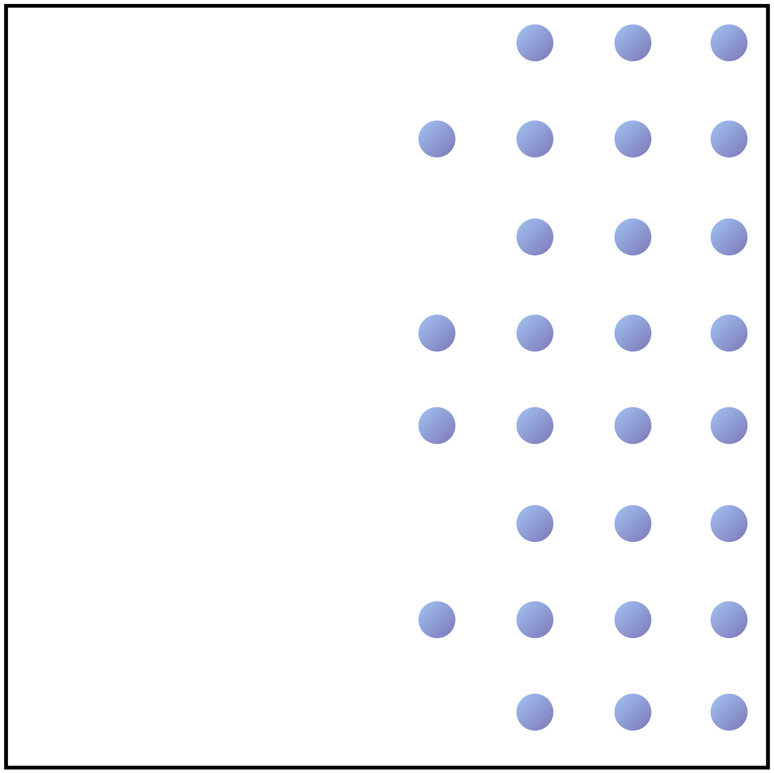


Blue is potential for untagged atoms, green is potential for tagged atoms

$$U(x) \propto 2\cos(\theta)\cos\left(\frac{2\pi x}{a}\right) + \frac{m_F}{F}\sin(\theta)\sin\left(\frac{2\pi x}{a}\right)$$

The (1D) lattice potential

Initialization & preparation (3)



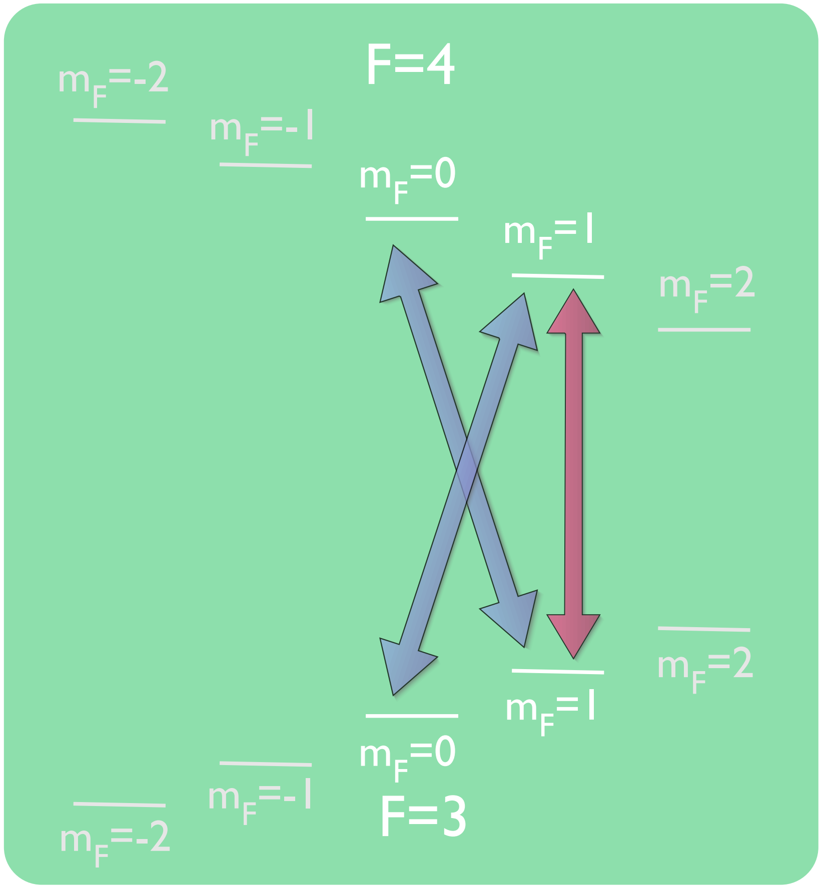
- Compact lattice via a divide-and-conquer algorithm:
  - I. Partition in half
  - II. Balance the two halves
  - III. For each half, apply (I)
  - IV. When all rows are balanced, compact rows to right
- For a d-dimensional lattice of n^d atoms, takes $O(n)$ steps (each step takes 10^{-2} to 10^{-3} s)
- Can re-image and repeat if first iteration does not yield perfect lattice

Single qubit gates (1)

How do we perform a gate on a single qubit without disturbing neighbouring atoms?

Single qubit gates (2)

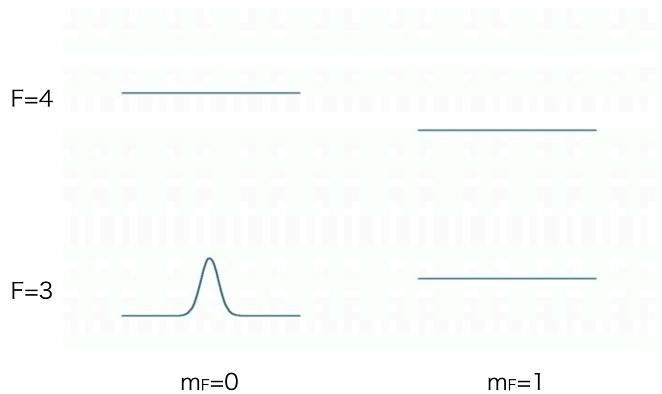
- Use focused addressing beam at "magic wavelength" (~880 nm) to shift $m_F \neq 0$ levels at target site while leaving $m_F=0$ levels & atoms untouched
- Use a microwave pulse to flip the atom's state from $m_F=0$ qubit state to $m_F=1$ temporary state,
- Use another pulse to flip between temporary states
- A final pulse flips back to a $m_F=0$ qubit state



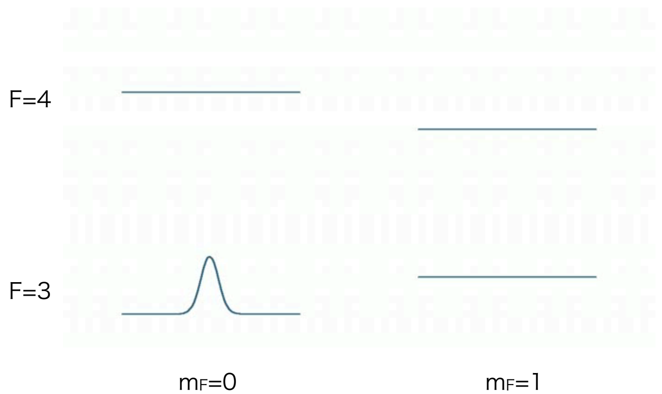
Single qubit gates (3)

- Target atom sees large AC Stark Shift of $m_F=1$ levels, whereas neighbouring atom sees little or no Stark shift
- Microwave pulse is on-resonant for target atom, driving transition
- Neighbour atom experiences small, fast off-resonant Rabi cycles
- Can in principle achieve high gate fidelity (~0.99999) for fast gates (~ 10 - 100 μs)

Target atom



Neighbour (non-target) atom



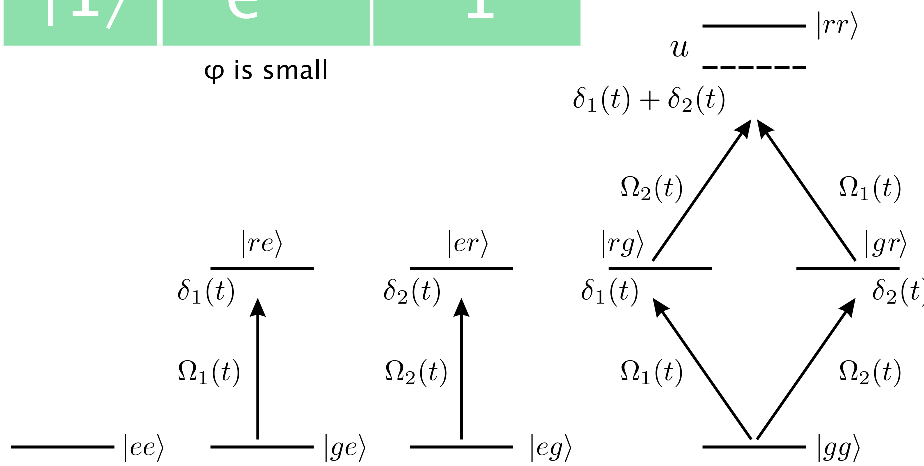
Two qubit gates (1)

- A controlled-phase (CPHASE) gate together with local operations is universal for quantum computation
- To implement CPHASE,
  - Apply a π pulse to the first atom to bring it to a Rydberg state
  - Apply a 2π pulse to the second atom
  - Apply another π pulse to the first atom
- Get a relative phase change, as shown in the table

Phase as a function of input

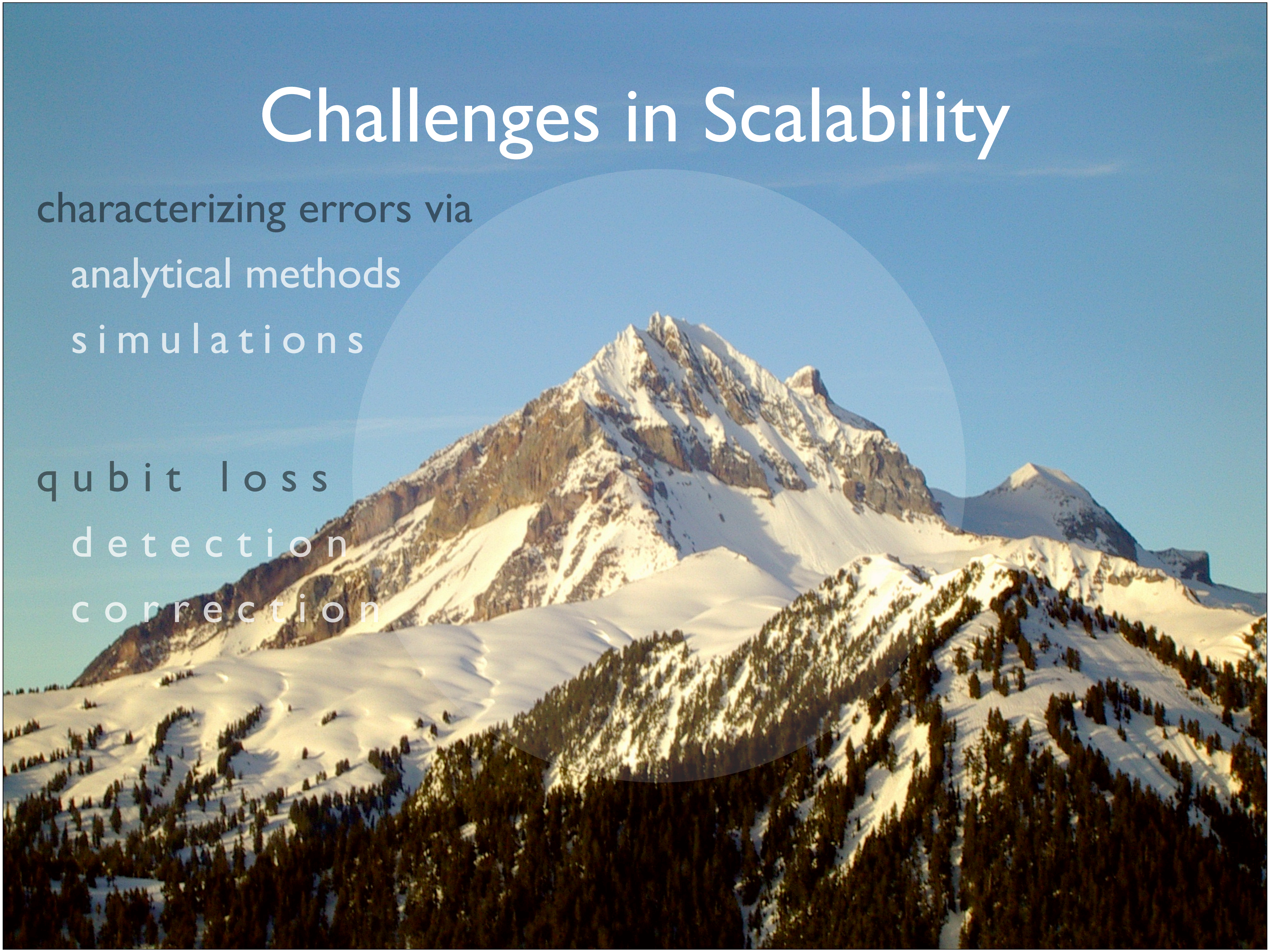
	$\vert 0\rangle$	$\vert 1\rangle$
$\vert 0\rangle$	$e^{i(\pi-\varphi)}$	$e^{i\pi}$
$\vert 1\rangle$	$e^{i\pi}$	1

φ is small



Schematics for each of four possible gate inputs

Graphic from Jaksch *et al.* 2000. PRL **85** 2208.


Challenges in Scalability
characterizing errors via
analytical methods
simulations
qubit loss
detection
correction

Characterizing Errors (I)

- Some sources of error:
  - Single qubit gates
  - Two qubit gates (quant-ph/0502051, PRA **67** 040303)
  - Qubit loss
  - Spontaneous emission / scattered photons
- Can describe some errors via analytical techniques
- Use **qsims** to perfom numerical simulations of gates to characterize errors and perform optimization

Characterizing Errors (2)

- An analytical example: undesirable off-resonant transitions in single qubit gates
  - Even though they are detuned by ~1 MHz, non-target atoms have a very small probability of undergoing an off-resonant transition when a single qubit gate is applied to other atoms
  - Probability is described by $P_{|0\rangle \leftrightarrow |1\rangle} \simeq \frac{\Omega^2}{\Omega^2 + \Delta^2} \sin^2 \left(\sqrt{\Omega^2 + \Delta^2} \frac{T}{2} \right)$
  - We can minimize this by appropriate choice of the gate time, *T*, but are limited by our pulse timing resolution, δ_T, and obtain

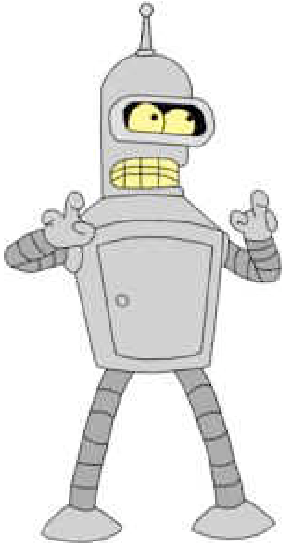
$$P_{|0\rangle \leftrightarrow |1\rangle} \simeq \left(\frac{\pi}{2} \frac{\delta_T}{T} \right)^2$$

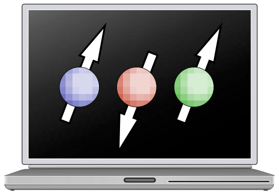
- If we have a lattice of n^3 atoms, but can only do *n* single qubit gates simultaneously, this will ultimately limit scalability (although limit will be large)

qsims: Quantum Simulation Software

Special advertising supplement

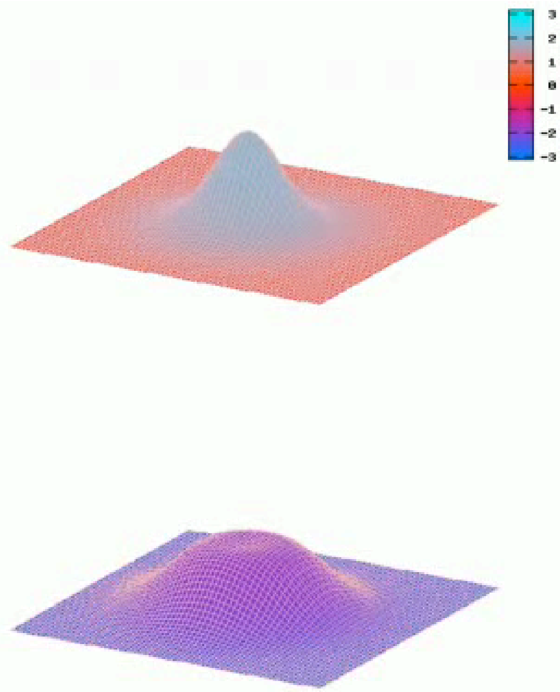
- We need a way to simulate and study quantum gates with high precision—a Quantum Simulation Software (qsims) package
- qsims is free, GPL'd, software developed by T. R. Beals
- qsims can simulate a wide range of Hamiltonians, and allows for nearly arbitrary time dependence
- http://sf.net/projects/qsims/





qsims (2)

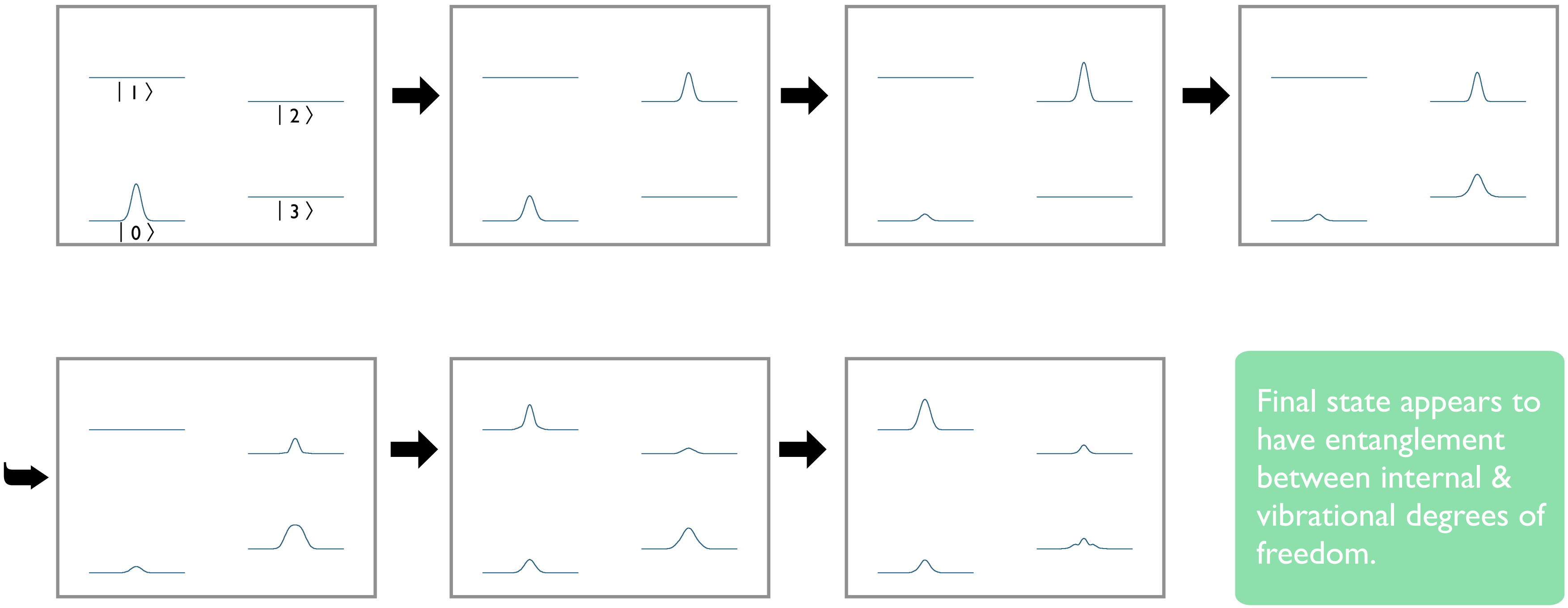
- qsims uses a discretized grid to represent the spatial wavefunction of an atom, with one grid for each internal state
- Momentum portion of Hamiltonian is calculated using R. Kosloff's pseudospectral (a.k.a. Fourier grid) method
- Time propagation is accomplished with a Chebychev polynomial expansion of the Schrodinger propagator



Chebychev polynomials: $T_0 = 1,\ T_1 = x,\ T_2 = -1 + 2x^2,\ T_3 = -3x + 4x^3 \ldots$

$$T_{n+1}(x) = 2xT_n(x) - T_{n-1}$$

Simulation: bad single qubit gate



Final state appears to have entanglement between internal & vibrational degrees of freedom.

- Can do numerical optimization of gate parameters
- Study effects that are analytically intractable

Trap depth = 100 μK, stark shift = 0.2 MHz, coupling = 6.579 kHz, gate time = 0.11 ms, beam waist = 0.6 μm. **Fidelity = 0.8676.**

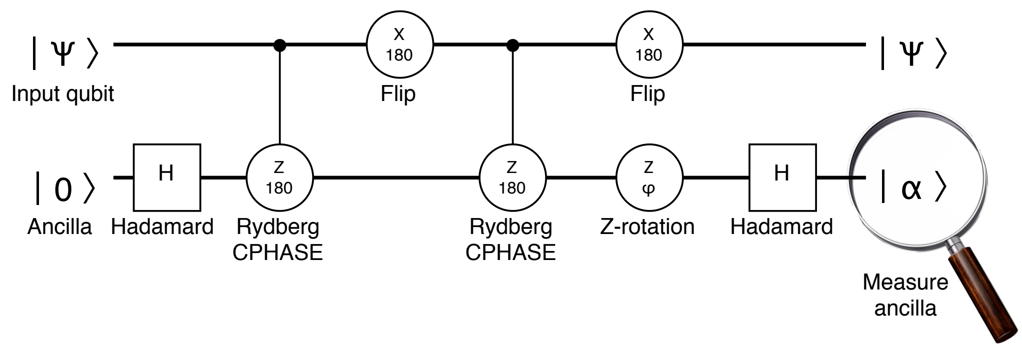
Qubit loss detection & correction

- Need to be able to perform Quantum Non-Demolition (QND) measurements
- QND determines presence of an atom without disturbing its state
- When atom loss is detected, replace lost atoms with spares using "optical tweezers"
- Perform standard error correction to restore state

Qubit loss detection (I)

- In the Rydberg CPHASE gate, a missing control qubit acts as $|1\rangle$
- Use this to perform qubit loss (or leakage) error detection without disturbing qubit state

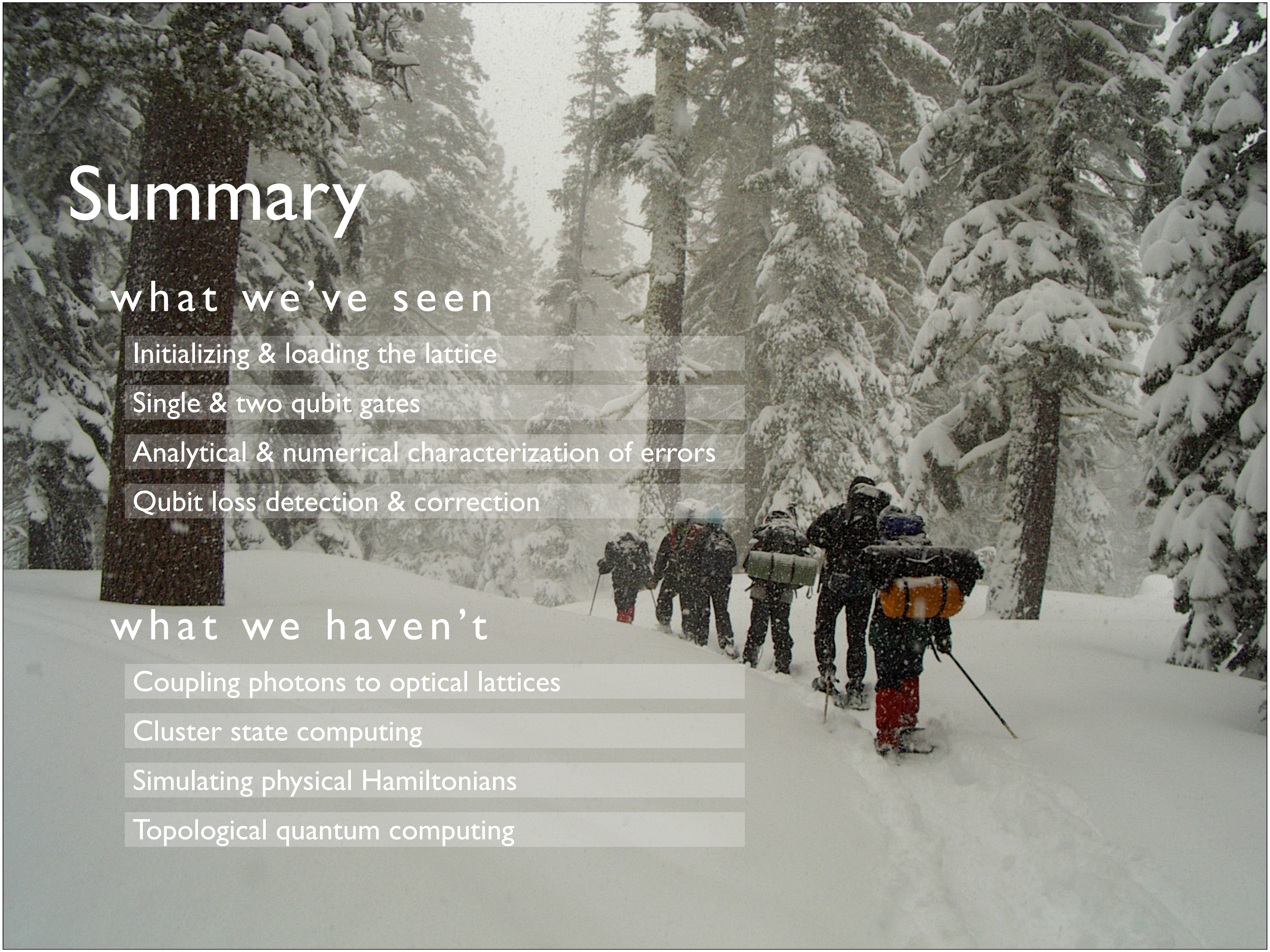
Quantum non-demolition qubit loss-detecting circuit



Input	$\vert 0\rangle$	$\vert 1\rangle$	$\vert X\rangle$ (missing atom)
Ancilla	$\vert 1\rangle$	$\vert 1\rangle$	$\vert 0\rangle$

Qubit loss detection (2)

- Downsides of loss detection circuit:
  - Need an ancilla qubit
  - Hard to do in parallel
- Alternate idea (borrowed from ion trap quantum computing)—store qubit state temporarily in motional degrees of freedom of atoms
  - Can then perhaps "look" at the atoms without disturbing qubit state
  - Could use magnetic field to address & image an entire plane of atoms at a time
  - Still need to work out details



Summary

what we've seen

- Initializing & loading the lattice
- Single & two qubit gates
- Analytical & numerical characterization of errors
- Qubit loss detection & correction

what we haven't

- Coupling photons to optical lattices
- Cluster state computing
- Simulating physical Hamiltonians
- Topological quantum computing

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