CU to CZ

From Zero to QuEra Target

QuEra Creator's Challenge

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Abstract

Controlled-Z (CZ) gates are the native entangling operation in neutral-atom quantum computers, yet their physical realization is often hidden behind abstract circuit symbols and static diagrams. In this project, we present a hardware-faithful visual narrative of the CZ gate that explicitly shows how laser-driven dynamics, Rydberg blockade, and time-dependent phase accumulation generate entanglement.

Rather than depicting CZ as an instantaneous algebraic operation, our animations recover the intermediate physical processes that are typically omitted: partial excitation, collective dynamics, and state-dependent phase evolution. Using a simplified, physically motivated Hamiltonian solved with QuTiP and rendered using Manim, we visualize the distinct phase trajectories of the $|01\rangle$ and $|11\rangle$ states and directly connect these trajectories to experimental control parameters such as detuning and Rabi frequency.

This work is designed to be transparent, reproducible, and accessible. All animations are provided as standalone media files and linked through the project `README.md`. The goal is not only to communicate correctness, but to introduce a reusable visual design framework that bridges abstract quantum logic with the physical execution of neutral-atom quantum hardware.

1 Challenge Alignment and Documentation Strategy

The iQuHACK Creator's Challenge emphasizes correctness, clarity, novelty, and reproducibility in the visual communication of neutral-atom quantum computing processes. This project was structured from the outset to satisfy these criteria by pairing each animation with a precise written explanation of its physical meaning, limitations, and relationship to real hardware behavior.

All visual outputs referenced in this document are provided as separate `.gif` or `.mp4` files and are linked directly in the project `README.md`. The repository also includes a link to the original QuEra Creator's Challenge prompt, ensuring proper contextual grounding and attribution. This document is intended to function simultaneously as technical documentation, explanatory guide, and judging reference.

2 Motivation: The Abstraction Gap in CZ Gates

In circuit-level descriptions, the CZ gate is commonly presented as

$$\mathrm{CZ} = \mathrm{diag}(1, 1, 1, -1),$$

which suggests that entanglement arises from a simple, instantaneous phase assignment. While mathematically correct, this representation conceals the fact that, in neutral-atom platforms, the CZ gate is a time-resolved physical process governed by laser pulses, atomic structure, and interaction-induced energy shifts.

Existing visualizations often assume that:

- Phase accumulation is already understood,
- Intermediate dynamics are not essential,
- Population transfer and phase evolution need not be distinguished.

As a result, critical questions remain visually unanswered: when does phase accumulate, why do $|01\rangle$ and $|11\rangle$ behave differently under the same pulse, and how does Rydberg blockade alter the effective Hamiltonian while populations return to their initial states?

Our work addresses this abstraction gap by making these hidden dynamics explicit and unavoidable.

3 Theoretical Model and Explicit Approximations

We model the CZ gate using a simplified two-atom Hamiltonian that captures the essential physics of

Rydberg-mediated interactions:

$$H(t) = \sum_{i=1}^{2} \left[\frac{\Omega(t)}{2} \left(|r\rangle\langle 1|_i + |1\rangle\langle r|_i \right) - \Delta(t)|r\rangle\langle r|_i \right] + V|rr\rangle\langle rr|$$

Here, $\Omega(t)$ is the effective Raman Rabi frequency, $\Delta(t)$ is the detuning, and V represents the Rydberg interaction energy.

Explicit approximations:

- Atomic motion and decoherence are neglected.
- Pulse shapes are chosen for conceptual clarity rather than experimental optimality.
- Only the dominant Rydberg level is included.

These approximations are intentional and explicitly stated to ensure that visual clarity does not compromise physical correctness.

4 Visual Narrative and Animation Design

Our visualization framework consists of three synchronized animations, each addressing a different layer of abstraction.

Single-Qubit Phase Accumulation

We begin by visualizing a single-qubit Z rotation on the Bloch sphere. This establishes that phase evolution alone—without population transfer—constitutes a meaningful quantum operation. This animation prepares the viewer to interpret later phase accumulation as a physical process rather than an abstract label.

Energy-Level Dynamics and Rydberg Blockade

Next, we depict the $|0\rangle$, $|1\rangle$, and $|r\rangle$ energy levels for two atoms. A glowing amplitude representation illustrates partial excitation driven by a Raman laser. For $|11\rangle$, the animation emphasizes collective excitation and the absence of $|rr\rangle$ population, visually encoding Rydberg blockade as an energetic constraint rather than a rule.

Bloch-Sphere Phase Trajectories

Finally, we visualize the effective two-level evolution of $|01\rangle$ and $|11\rangle$ on the Bloch sphere. The $|01\rangle$ state accumulates a phase $e^{i\phi}$, while $|11\rangle$ follows a distinct trajectory due to the interaction term V, accumulating an additional conditional phase. Both states return to their original populations, making the emergence of the relative π phase difference explicit.

5 Implementation and Reproducibility

Time-dependent state evolution was computed using QuTiP. Bloch-sphere trajectories and energy-level animations were rendered in Manim, with color gradients and synchronized timelines used to encode phase accumulation. Final videos were assembled and exported in standard formats.

The repository includes:

- All source code,
- Rendered animation files,
- A README describing reproduction steps and file structure.

This ensures that both the visual outputs and the underlying methodology are transparent and reproducible.

6 Future Directions and Broader Impact

This visualization framework naturally extends to multi-qubit controlled-phase gates (CCZ, CkZ), GHZ and W states, and algorithm-level execution visualizations. By treating phase accumulation as the central computational resource, the framework supports hardware-aware reasoning about compilation, debugging, and education in neutral-atom quantum computing.

More broadly, this work demonstrates how carefully designed visual narratives can bridge the gap between quantum algorithms and physical hardware, supporting both expert understanding and accessibility to broader audiences.

7 References

1. Contributors' names. (Last edited date). Title of resource. Site Name. http://Web address for OWL resource

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