TEBD for Rydberg Atom Arrays

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The goal of this problem is to test your ability to (i) implement algorithms, (ii) use numerical packages, (iii) search for and find information, and (iv) be creative. Try to complete this task within one week, and if you need more time let us know.

Create a new private repository on Github and use it to develop your code. Then prepare a short summary (up to two pages) in LaTeX and send it to me; make sure you include a link to your Github repo. The summary should only contain the major results/plots and the corresponding discussion. Note that, using external literature/google is allowed, but you have to provide your sources. External help (e.g., from friends) is NOT allowed. You should aim to submit your summary within one week.

Problem: In this problem we will implement the Time Evolving Block Decimation (TEBD) algorithm to study quench dynamics of a quasi-1D chain of Rydberg atoms. The ultimate goal is to reproduce Fig. 4 of arXiv:2405.21019.

The Hamiltonian of a Rydberg quantum simulator is given by

$$H(t) = \frac{\Omega(t)}{2}\sum_j \sigma_j^x - \Delta(t)\sum_j n_j + V_0 \sum_{i,j} \frac{n_j n_j}{|\vec{r}_i - \vec{r}_j|^6}, \tag{1}$$

where Ω is the coupling to the Rydberg state (Rabi frequency), Δ is the detuning, and V_0 is the strength of the Rydberg interaction. The Pauli matrices are σ_j^α and $n_j = (1+\sigma_j^z)/2$. The Rydberg atoms are arranged in a doublet chain, see Fig. 1(left). The Rabi frequency and the detuning change in time according to the sweep-quench-sweep (SQS) protocol, shown in Fig. 1(right) (see paper for precise timescales, but feel free to adjust these if necessary).

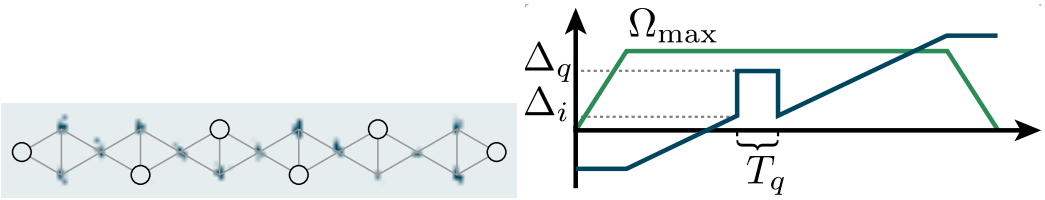

Figure 1: Left: zig-zag doublet chain: each vertex of an equilateral triangle contains an atom (ignore the blurry clouds which correspond to experimental data; there are atoms on these sites too). Right: drive protocol defining the shape of $\Omega(t)$ (green) and $\Delta(t)$ (dark blue) with the square-shaped pulse denoting the quench. See arXiv:2405.21019 for more details.

For this problem, we can **truncate the long-range interaction to nearest and next-nearest neighbors** and set any longer-range interactions to zero. The atoms are initialized at $t = 0$ in the ground state at $\Omega(0) = 0$ for $\Delta(0) < 0$. The target state is the ground state at positive $\Delta(T) > 0$ (so-called maximally independent set or MIS state) where $t \in [0, T]$.

Part 1: Read carefully the paper and make a list which contains: (i) the values of the nearest-neighbor and next-nearest neighbor interactions strengths, taking into account the distance factor $1/r_{ij}^6$; (ii) the parameters defining the initial and target ground states, and (iii) the precise parameters defining the protocol $\Omega(t), \Delta(t)$ and their functional dependence. What is the main effect of the SQS protocol?

Part 2: Write your own TEBD code to evolve the initial state in matrix product state (MPS) form. An excellent source explaining the algorithm are Frank Pollmann's notes, but feel free to use your own

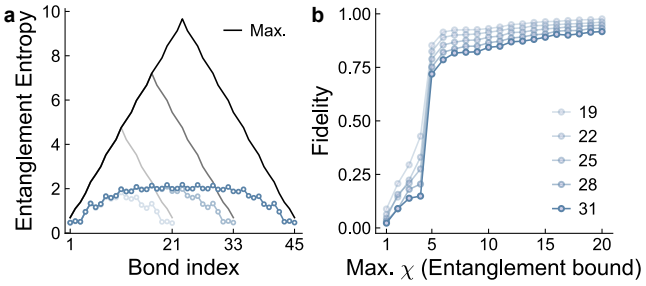

Figure 2: This is the figure you have to reproduce; for details, see Fig. 4 in arXiv:2405.21019.

sources. A useful function to implement tensor contractions is numpy.einsum. Perform benchmarks to test your code.

Part 3: Find the TEBD hyperparameters for Fig. 4 in the paper. Then reproduce Fig. 4 from arXiv:2405.21019 (here shown as Fig. 2). Start with small system sizes first, and then scale up your code. If necessary, find ways to speed up your code.

Part 4: Can you adjust the protocol parameters to improve the final fidelity?