

# Quantum Information and Computing 2021-2022

8<sup>th</sup> week assignment  
Real State Renormalization Group  
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- the transverse-field Ising model of  $N$   $\frac{1}{2}$ -spins is described by the Hamiltonian

$$\hat{H}_N = - \sum_{i=1}^N \sigma_i^x \sigma_{i+1}^x + \lambda \sum_{i=1}^N \sigma_i^z, \quad \hat{H}_N : \mathbb{C}^{d^N} \rightarrow \mathbb{C}^{d^N}, \quad d = 2$$

where  $\lambda$  is the magnitude of the magnetic field applied along  $\hat{z}$

- the notation used implies that

$$\sigma_i^x \sigma_{i+1}^x = \mathbb{1}_1 \otimes \cdots \otimes \mathbb{1}_{i-1} \sigma_i^x \otimes \sigma_{i+1}^x \otimes \mathbb{1}_{i+2} \cdots \otimes \mathbb{1}_N$$

$$\sigma_i^z = \mathbb{1}_1 \otimes \cdots \otimes \mathbb{1}_{i-1} \otimes \sigma_i^z \otimes \mathbb{1}_{i+1} \cdots \otimes \mathbb{1}_N$$

- to retrieve the Ground State energy density of this system (in the thermodynamic limit) the Real State Renormalization Group (RSRG) algorithm is exploited
- the RSRG algorithm is based on the hypothesis that the ground state of the global system is composed by the lowest energy eigenstates of its sub-partitions. This is trivial in the case in which the sub-systems of which it is composed are not interacting.

Given the Hamiltonian  $\hat{H}_N$  of an  $N$ -units system, the RSRG algorithm iterations follows this steps:

- build the Hamiltonian  $\hat{H}_{2N}$  of the doubled system as

$$\hat{H}_{2N} = \hat{H}_N \otimes \mathbb{1}_N + \mathbb{1}_N \otimes \hat{H}_N + \hat{H}_{int}, \quad \hat{H}_{2N} : \mathbb{C}^{d^{2N}} \rightarrow \mathbb{C}^{d^{2N}}$$

with

$$H_{int} = \hat{H}_L + \hat{H}_R$$

that for the Transverse Field Ising model reads as

$$\hat{H}_{int} = \left[ \bigotimes_{1}^{N-1} \mathbb{1} \otimes \sigma^x \right] \otimes \left[ \sigma^x \otimes \bigotimes_{1}^{N-1} \mathbb{1} \right]$$

- diagonalize  $\hat{H}_{2N}$  and construct the projector  $\hat{P} : \mathbb{C}^{d^{2N}} \rightarrow \mathbb{C}^{d^N}$  along the  $d^N$  lowest eigenvectors
- retrieve the truncated Hamiltonian of the doubled system

$$\tilde{H}_{2N} = \hat{P}^\dagger \hat{H}_{2N} \hat{P}, \quad \mathbb{C}^{d^N} \rightarrow \mathbb{C}^{d^N}$$

and the truncated interaction terms

$$\tilde{H}_L = P^\dagger \left( \bigotimes_{1}^N \mathbb{1} \otimes H_L \right) \hat{P}, \quad \tilde{H}_R = P^\dagger \left( H_R \otimes \bigotimes_{1}^N \mathbb{1} \right) \hat{P}$$

- iterate until the desired number of iterations/convergence parameter is reached

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subroutine RSRG_iteration(H_N, H_L, H_R, N)

  double complex :: H_N(:, :), H_L(:, :), H_R(:, :)
  integer        :: N
  double complex :: H_2N(2**(2*N), 2**(2*N))
  double complex :: PJ(2**(2*N), 2**(2*N))
  double complex :: PJ_ADJ(2**N, 2**(2*N))
  double complex :: H_L_int(2**(2*N), 2**(2*N)), H_R_int(2**(2*N), 2**(2*N))
  double complex :: eigvctrs(2**(2*N), 2**(2*N))
  real(8)         :: eigvls(2**(2*N))

  H_2N = kronecker_product_cplx( H_N, ising_identity(N) ) +&
        kronecker_product_cplx( ising_identity(N), H_N ) +&
        kronecker_product_cplx( H_L, H_R )

  call ising_diagonalize_hamiltonian(H_2N, eigvctrs, eigvls)

  PJ = eigvctrs(:, :2**N)
  PJ_ADJ = ADJOINT( PJ )

  H_N = MATMUL ( MATMUL( PJ_ADJ, H_2N ), PJ)

  H_L_int = kronecker_product_cplx( ising_identity(N), H_L )
  H_R_int = kronecker_product_cplx( H_R , ising_identity(N) )

  H_L = MATMUL( MATMUL( PJ_ADJ , H_L_int), PJ)
  H_R = MATMUL( MATMUL( PJ_ADJ , H_R_int), PJ)

end subroutine

```

Figure: RSRG algorithm implementing subroutine

- The results reported are evaluated for a starting number of spins  $N = 2, 3, 4$  and  $n_{iters} = 100$
- the displayed quantity is the ground-state energy density  $\rho_{GS} = \frac{E_{GS}}{1+d^{n_{iters}}}$ , where  $E_{GS}$  is the Ground State energy obtained diagonalizing the truncated Hamiltonian obtained after the last iteration
- the comparison with the mean-field result is performed

$$\rho_{GS} = \begin{cases} -1 - \frac{\lambda^2}{4}, & \lambda \in [-2, 2] \\ |\lambda|, & \lambda \notin [-2, 2] \end{cases}$$

