Featureless Bosonic Insulators

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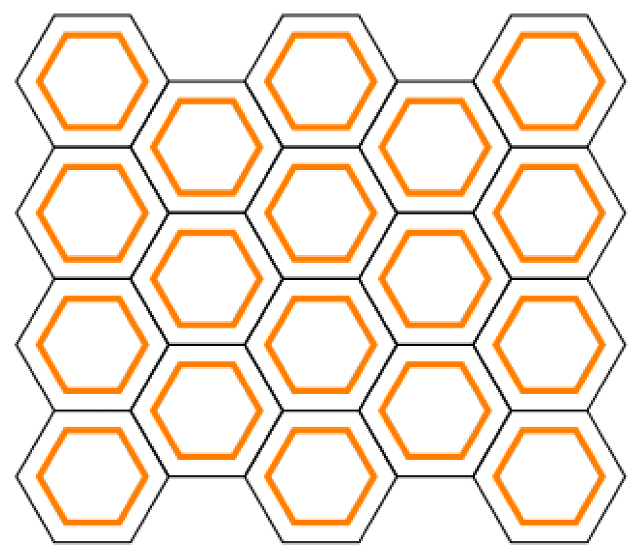
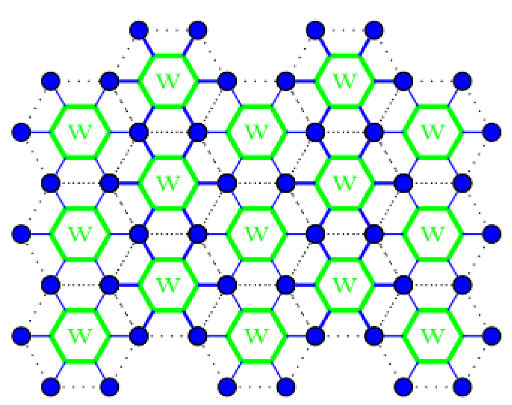
Honeycomb Lattice Proposed Wavefunction



$$|\psi\rangle = \prod_{\hexagon}\left(\sum_{i\in\hexagon} b_i^\dagger\right)|0\rangle$$

PEPS Construction of Honeycomb F.B.I.

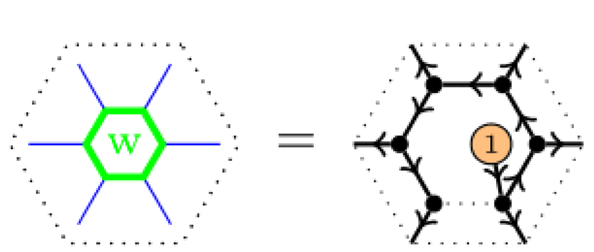
A wavefunction written as a product of local operators acting on a product state can be turned into a tensor network.

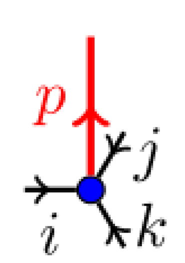


Virtual W-state on each plaquette used to synchronize the creation operators in the sum $\sum_{i\in\hexagon} b_i^\dagger$

$$|W) = |000001) + |000010) + |000100) + |001000) + |010000) + |100000)$$

PEPS Construction of Honeycomb FBI



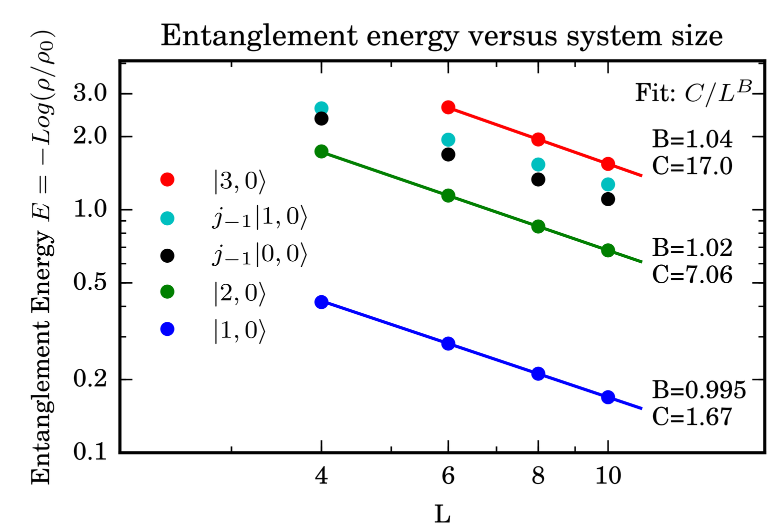


$$|W) = |100\ldots) + \ldots$$

- W-State can be factored and put on hexagon sites
- Each black directed string has either charge 0 or 1
- Charge conserved

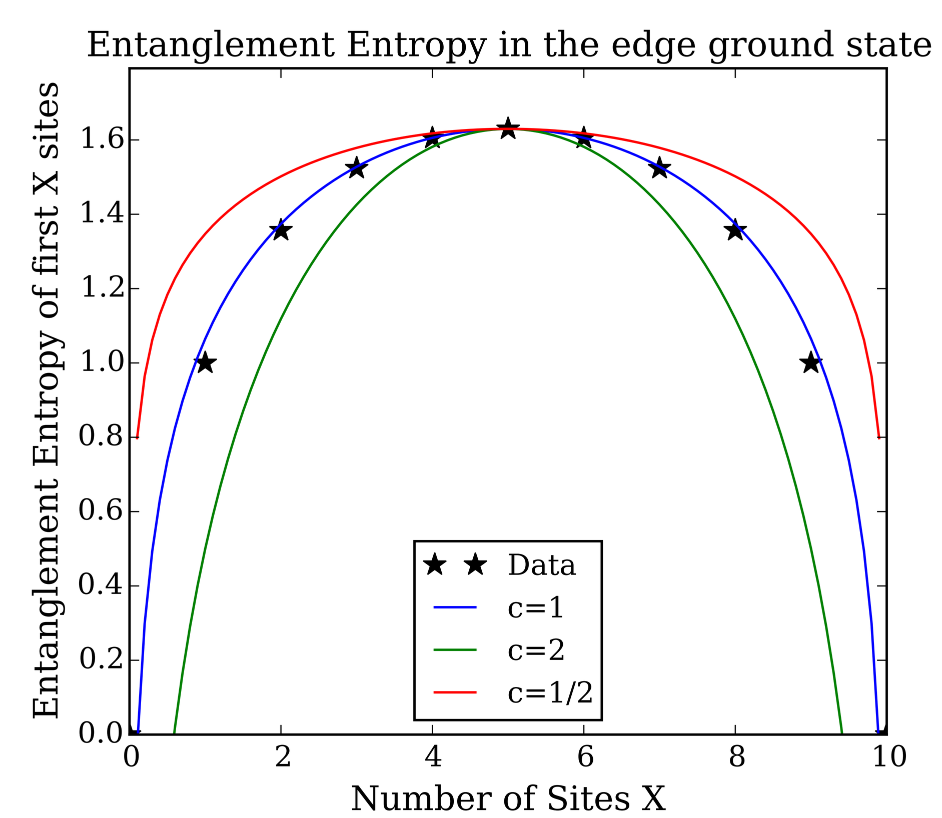
- 'Projects' the three virtual qubits coming into each vertex on to a state in physical Hilbert space
- Physical state is either $|0\rangle, |1\rangle, |2\rangle, |3\rangle$
- Charge conserved

Finite Size Analysis of Entanglement Spectra



- Fix this to show topological entanglement entropy is 0
- Low energy modes show gapless $1/L$ behavior

Conformal Charge



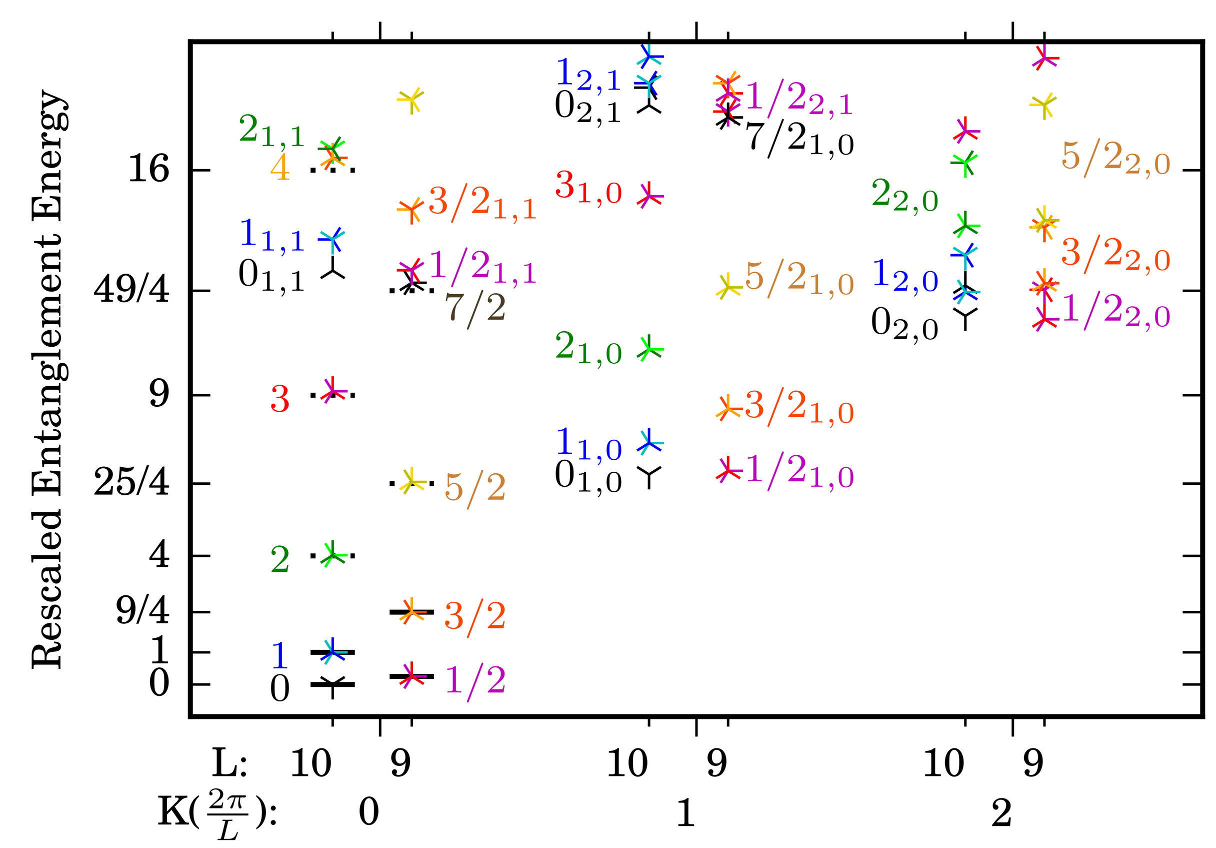
$$\boxed{c = 1}$$

Conformal Weights

We can match the rescaled entanglement energies to the conformal weights of a free bosonic CFT.

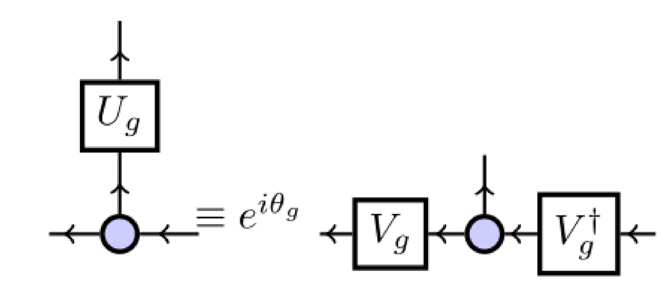
$$\mathbf{P} = \frac{2\pi}{L}(\mathbf{L_0} - \bar{\mathbf{L}}_0)$$
$$= \frac{2\pi}{L}(em + n - \bar{n})$$
$$\widetilde{\mathbf{P}} = em + n - \bar{n}$$
$$\mathbf{H} = \frac{2\pi}{L}(\mathbf{L_0} + \bar{\mathbf{L}}_0)$$
$$= \frac{2\pi}{L}\left(\frac{\kappa e^2}{2} + \frac{m^2}{2\kappa} + \frac{n+\bar{n}}{2}\right)$$
$$\widetilde{\mathbf{H}} = \frac{L}{2\pi\kappa}\mathbf{H}$$
$$= e^2 + \frac{m^2}{4\kappa^2} + \frac{1}{\kappa}(n+\bar{n})$$

CFT Identification of Gapless Entanglement Edge

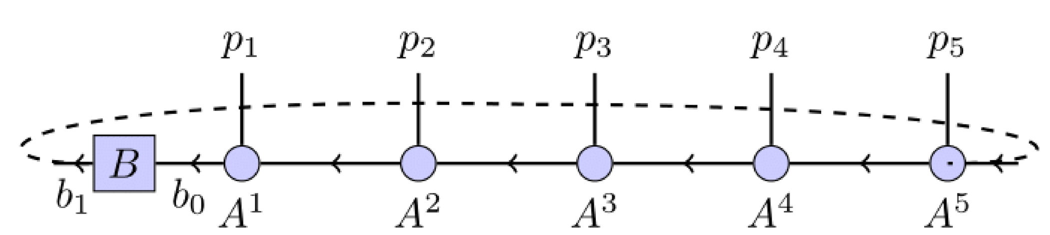


Detecting 1D SPT Order

If U_g is a global symmetry and $|\psi\rangle$ is translationally invariant, then the MPS representation satisfies:



Boundary conditions on a MPS can be represented by a matrix B which acts like:



With PBC ($B = I$), the group action leaves the state invariant.
With OBC ($B = |i\rangle\langle i|$), the group action rotates between states that differ only near the boundary; these edge states transform as $V_g \otimes V_g^\dagger$. V_g represents the group projectively. Equivalence classes of projective representations (enumerated by $H^2(G; U(1))$) classify 1D SPT phases.

Symmetry Protection of the Honeycomb FBI

For the state on a cylinder with odd circumference, and the zig-zag entanglement cut defined in the upper left picture, we have the following:

G	U_g	θ_g	V_g	$V_gV_g^*$
$U(1)$				
π				
$\mathcal{I}$				
$\pi\mathcal{I}$				

Since

$$V_{\pi\mathcal{I}}V_{\pi\mathcal{I}}^* = -I \quad \text{or} \quad V_\pi V_{\mathcal{I}} = -V_{\mathcal{I}}V_\pi,$$

the representation is in the nontrivial class of

$$\boxed{H^2(\mathbb{Z}_2 \times \mathbb{Z}_2^{\mathcal{I}}; U(1)) = \mathbb{Z}_2.}$$

Relation to known 1D physics

- Haldane insulator
  - Unitarily equivalent to the AKLT state
  - Distinct phase under $\mathbb{Z}_2 \times \mathbb{Z}_2^{\mathcal{I}}$
  - Can be connected adiabatically to $L = 1$ cylinder FBI
- Two dimensional classification is $H^3(\mathbb{Z}_2 \times \mathbb{Z}_2^{\mathcal{I}}; U(1)) = \mathbb{Z}_2^4$

References

- D. W. Kribs, R. Laflamme, D. Poulin, M. Lesosky, Quantum Inf. & Comp. **6** (2006), 383-399.
- P. Zanardi, M. Rasetti, Phys. Rev. Lett. **79**, 3306 (1997).