Ruling out (some) classical models for the D-Wave device

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Outline

- Black box paradigm and what our goal is
- SSSV vs. Quantum Master Equation (ME)
- The test: “Quantum Signature” Hamiltonian
- Predictions of SSSV and ME
- Compare against DW2
Black box paradigm

Given a black box

Can we determine whether it is quantum or classical via solely its classical input-classical output behavior?

The black box paradigm excludes the entanglement results of

T. Lanting et al., arXiv:1401.3500
A “good” model

Goal:
Find a model that fits all the data from the device

Our test is not an entanglement test
nor a no-go result for classical models

Demand predictive power
from the model

Fit parameters of model once

Does it survive a comparison with various
input-output experiments?
Where does D-Wave stand?

Lively discussion so far

**Consistency of quantum models**

- Experimental signature of programmable quantum annealing  
  S. Boixo, TA, et al., arXiv:1212.1739
- Quantum annealing with more than 100 qubits  
  S. Boixo, et al., arXiv:1304.4595
- Distinguishing Classical and Quantum Models for the D-Wave Device  
  W. Vinci, TA, et al., arXiv:1403.4228v1

**Consistency of classical models**

- Classical signature of quantum annealing  
- How “Quantum” is the D-Wave Machine?  
  S. Shin, et al., arXiv:1401.7087
- Comment on "Distinguishing Classical and Quantum Models for the D-Wave Device"  

All comparisons of success probabilities  
i.e. total ground state probabilities
What is at stake?

Do quantum effects play a role in determining the final outcome (which is a classical state)?

So far, classical models and quantum models correlate equally well with the success probability of the device.

Is this an issue of the type of Ising problems being solved, or is it an issue of the device?
Quantum Model: Open Quantum System


\[ H(t) = H_S(t) + H_B + H_{S-B} \]

\[ H_S(t) = -A(t) \sum_i \sigma_i^x + B(t)H_{\text{Ising}} \]

Trace out bath

Markovian adiabatic master equation (ME)

Assumptions

• Weak system-bath coupling.

• Born-Markov

• Slow system evolution with respect to bath
Important features of the ME


Dephasing occurs in the instantaneous energy eigenbasis
Not harmful for an adiabatic computation

Thermalizing towards instantaneous Gibbs state
Can be harmful for an adiabatic computation

Fix the bath
Independent harmonic oscillator baths with an Ohmic spectrum
Classical Model: SSSV

\[ H_{\text{SSSV}}(t) = \langle \Omega | H_S(t) | \Omega \rangle \]

\[ \sigma_i^x \rightarrow \sin \theta_i \]

\[ \sigma_i^z \rightarrow \cos \theta_i \]

Evolution is determined by
Metropolis update steps

Can be thought of as a “mean-field” limit of quantum Monte Carlo, whereby
all the replicas along the imaginary time direction are forced to be identical
Is this a fair comparison?

ME is a microscopic model
SSSV is a phenomenological model

SSSV has been very successful in reproducing the success probability of the D-Wave devices so understanding where it could fail could be useful in order to find “quantum” signatures.
“Quantum Signature” Hamiltonian

\[ H_{\text{Ising}} = - \sum_i h_i \sigma_i^z - \sum_{i,j} J_{ij} \sigma_i^z \sigma_j^z \]


17-fold degenerate ground state

\[ | \begin{array}{cccc} \downarrow \downarrow \downarrow \downarrow \downarrow \downarrow \end{array} \rangle \quad \text{isolated state} \]

\[ | \begin{array}{cccc} \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \end{array} \rangle \quad \text{cluster states} \]
Quantum Prediction

Late time ground state and excited states
are uniform superposition of cluster states

Master equation simulations

Result is robust even if noise is placed on the \((h, J)\)

(Hamming distance, Multiplicity)
SSSV Prediction

Any slight deviation from
\[
\theta = 0
\]
for the inner spins tilts the energy landscape
to favor a single cluster state
Cluster state distribution

Exact cluster state distribution is a robust feature

\[ H_{\text{Ising}} \rightarrow \alpha H_{\text{Ising}} \]

Noisy SSSV

Increasing HD from Isolated state

Ideal ME

Uniform cluster state population
Realistic Noise Model for D-Wave 2


Gaussian noise on \((h, J)\)

Cross-talk among qubits

Increasing HD from isolated state

Effective D-Wave 2 graph is no longer chimera
And the winner is...

Fit value of $\chi$ at $\alpha = 1$

Noisy SSSV

Ideal ME
Beyond 8 qubits

SSSV continues to fail to capture the right cluster state distribution as we increase the number of qubits to 20
Entanglement?

W. Vinci, TA, et al., arXiv:1403.4228

\[ \mathcal{N}(\rho) = \frac{1}{2} (\| \rho^{\Gamma_\alpha} \|_1 - 1) \]
Conclusions

- “Quantum signature” Hamiltonian reveals a feature of SSSV that can be exploited: a preference for a particular cluster state.

- With a physically motivated noise model for the DW2, this feature can be used to rule out SSSV as microscopic model of the device. The quantum ME reproduces all the features of the device.

- SSSV ruled out for spin systems up to $N = 20$.

- This is *not* a proof of quantum-ness!
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My collaborators:

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Distinguishing Classical and Quantum Models for the D-Wave Device
arXiv:1403.4228v2

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