NASA QuAIL Core competences at service of Q.E.O.

- **Tailor physics-based problems to unveil Quantum Enhancement**
  - *How to show the effect and use of tunneling, entanglement, localization, etc. in quantum annealing testbeds?*

- **Design and benchmark QA on application-derived problems, establish baseline performance**
  - *What optimization problems make sense to target, against which methods, with what parameters?*

- **Develop novel programming approaches to optimize QA approaches**
  - *Best techniques for mapping and embedding application problems onto testbed chips, and for determining annealing protocol parameters?*

- **Evaluate and mitigate the imperfections/noise in real QA devices**
  - *How to model and overcome limits of physical implementations including environmental noise and control errors resulting in problem misspecification?*

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National Aeronautics and Space Administration

Ames
Discovery Innovations Solutions

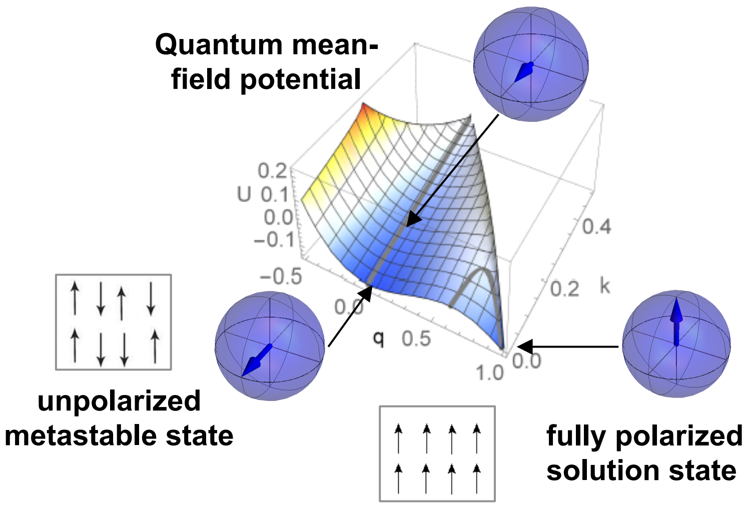
TAILORED PROBLEMS

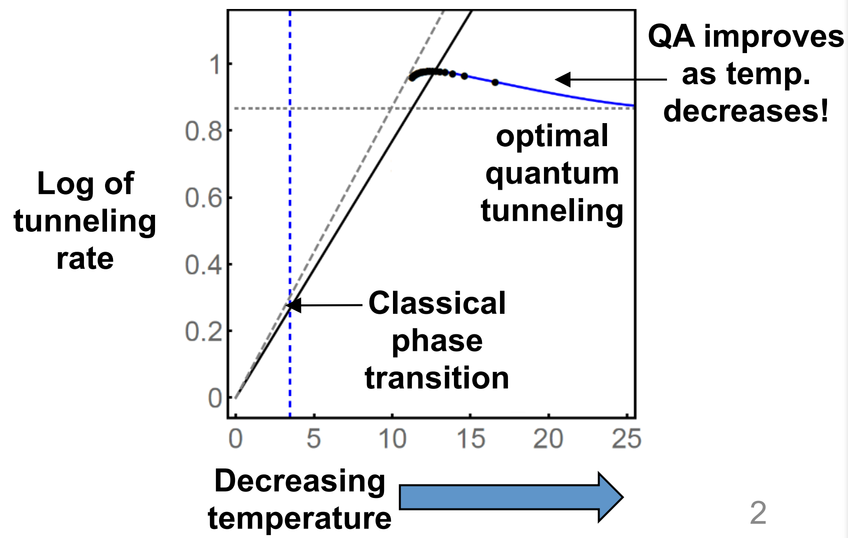
Role of degeneracy and entropy in quantum enhancement

arXiv:1505.05878 Kechedzhi et al.

First example of quantum enhancement in a tailored problem in the presence of noise, via 3-spin interactions – candidate for testbed as an enhancement witness

- **Problem design: Fully connected cluster of spins with *uniform* 3-spin interactions**
- **Analysis technique: quasiclassical mapping onto particle in a 2D potential**
- **Model incorporates incoherent, multi-spin tunneling**





Analytic calculation of annealing time possible in a mean-field model: potential + entropy barriers

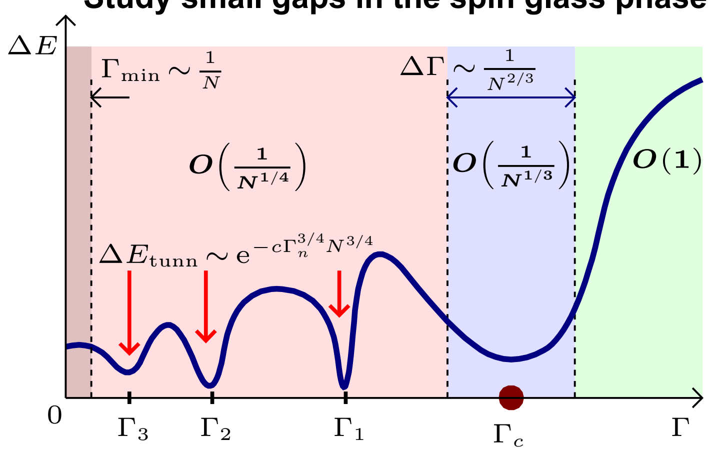
TAILORED PROBLEMS

Hardness Metric: Density of QA bottlenecks

arXiv:1506.08608 Knysh

"Uncharted territory" for ordinary thermodynamics, which does not capture hard bottlenecks.

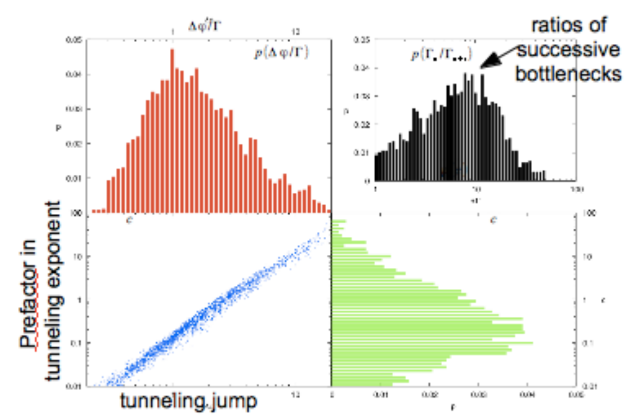
Study small gaps in the spin glass phase



Rather than specific instances, quantify hardness of ensembles deep in spin-glass phase where universal behavior is expected

- **Scaling of gap and density of bottlenecks can tell us the largest tractable problem size -**
- **Predict tractability of application problems by estimating correlation properties of energy levels**

Histograms of distribution of bottlenecks

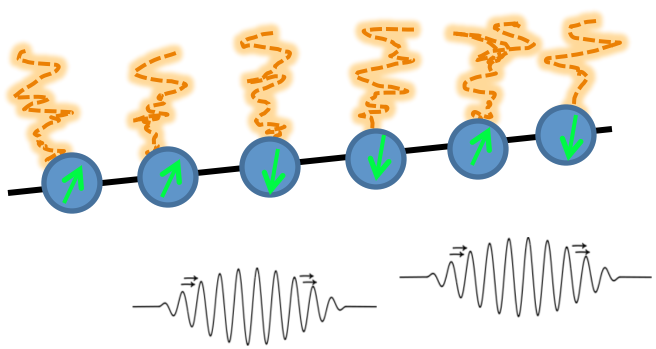


TAILORED PROBLEMS

Theory of dissipative QA on linear chains

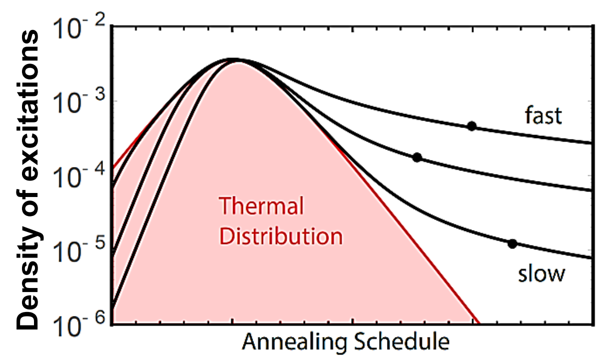
to appear on arXiv

Treat quantum annealing as physics of domain-wall wavepackets in 1D: Scalable to large systems



Dissipation turns extended eigenstates into localized wavepackets (superposition of domain walls) which are diffusing in the chain

Established speedup of realistic open system QA against fully coherent annealing up to a maximum concentration of excitations



Linear chains or trees are fundamental primitives and basis for all problem embedding

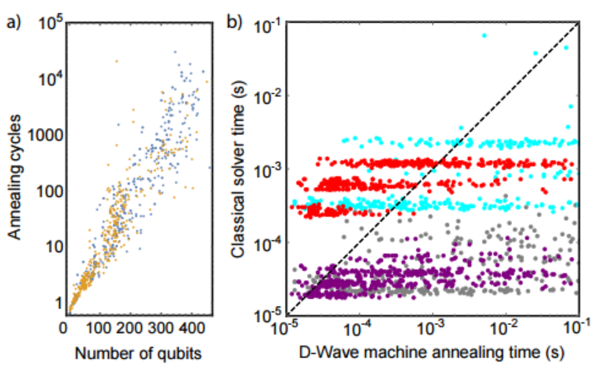
Similar phenomena on highly connected graphs so insights gained likely to apply to more general systems

DESIGN AND BENCHMARK APPLICATIONS

Scheduling Applications

arXiv:1506.08479 Venturelli et al.

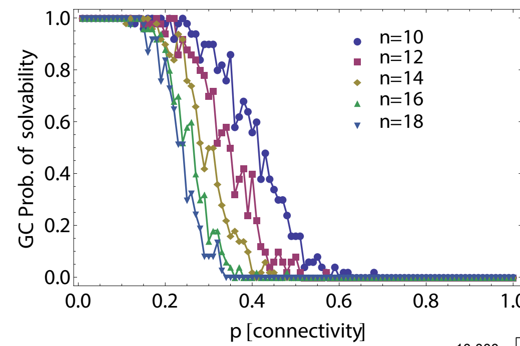
AAAI-14 Rieffel et al.
Q.I.P. 14, 1-36 Rieffel et al.



D-Wave 2 run results: establishing baseline performance for QA on these applications

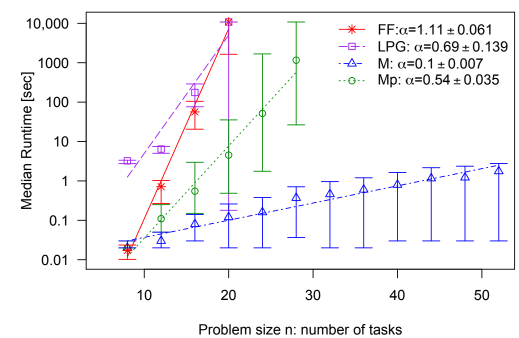
Solved problems with 6 machines and 6 jobs: analyzed scaling of tractability in quantum annealers

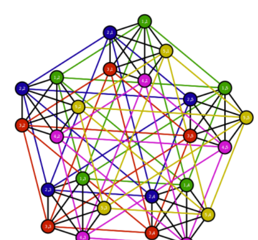
Job-Shop scheduling: Complete quantum-classical solver framework with pre-processing, compilation/run strategies, decomposition methods



Benchmarks sets with hard small problems enabling QA-QA comparisons, and QA-CC comparisons, scaling analysis

Comparison with state-of-the-art application-specific algorithms: current best planners



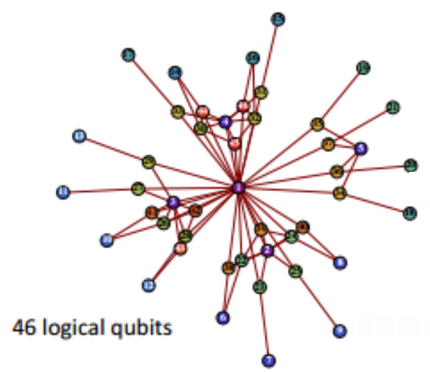


Structures common to application problems: intersecting-clique graphs for cross-cutting constraints. Provides good embedding benchmarks

Fault diagnosis applications

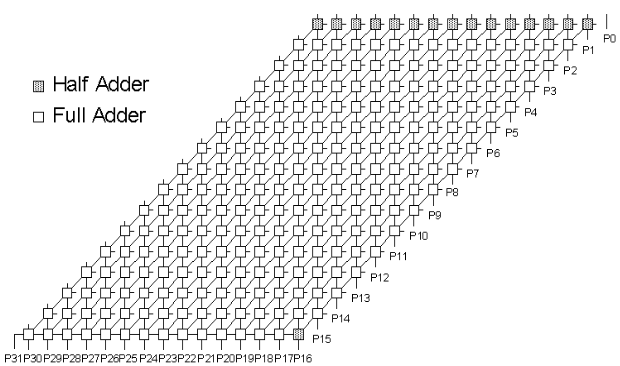
EPJ Spec. Top., Perdomo-Ortiz et al.

Developed new techniques for efficiently mapping problems in the domain of advanced diagnostics

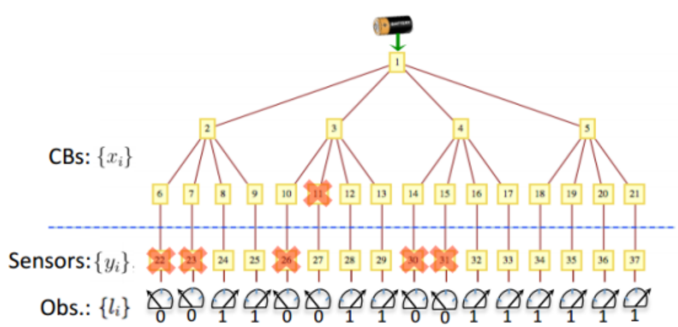


- Code takes any digital circuit and a fault-model for each component
- Determined well-defined smaller benchmarks to test implementations

ISCAS-85 C6288 16x16 Multiplier



Case study: Multiple-fault diagnosis with Uncertainty in the Sensors



Developed a general mapping for any circuit of the ISCAS85 benchmark dataset.

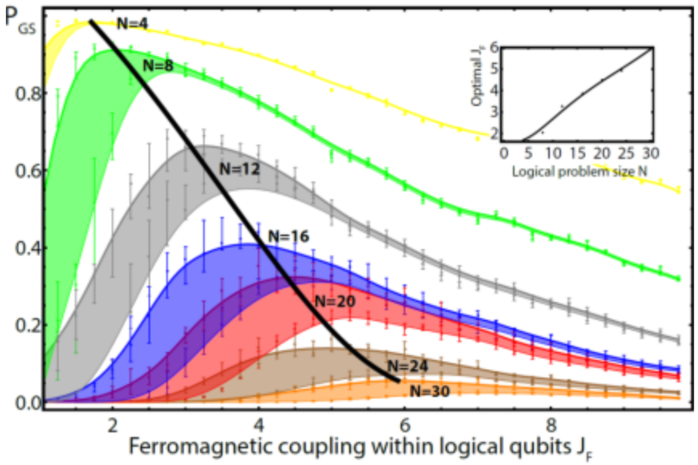
To appear on arXiv

NOVEL PROGRAMMING

Fine-Tuning by Extensive Empirical analysis

PRX 5, 031040 Venturelli et al.

- Considering the dynamics of the chains for the embedding
- Pre-characterization of instance ensembles

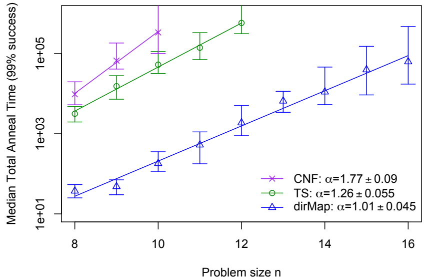


Best parameter setting quantum theory for embedding fully-connected graphs

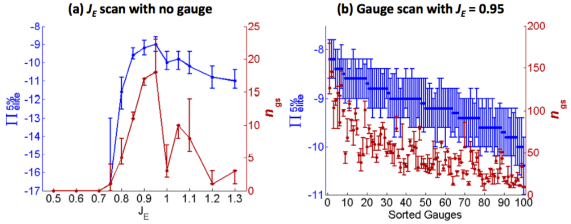
Q.I.P. 14, 1-36 Rieffel et al.

Comparison of different mappings, two general purpose, one problem specific, on D-Wave 2 machine

- General mappings had similar numbers of qubits, mean and worst case size of embedded components, etc.
- Time-slice proved better of the two



arXiv:1503.01083 Perdomo-Ortiz et al.



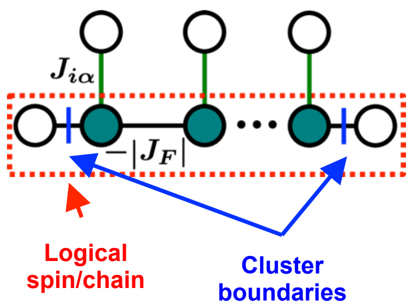
General strategy to quickly predict the best gauge and improve performance 5x or more

NOVEL PROGRAMMING

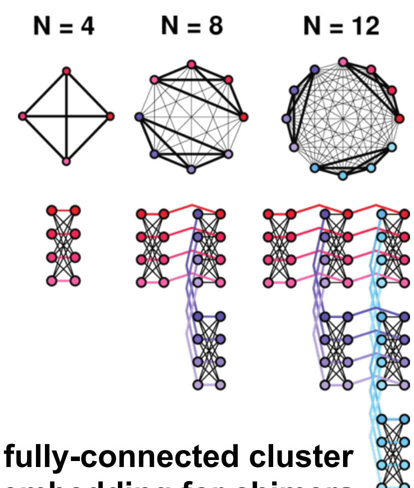
Spin-Glass Transition for Embedded Problems

PRX 5, 031040 Venturelli et al.

Hybrid Cluster method:

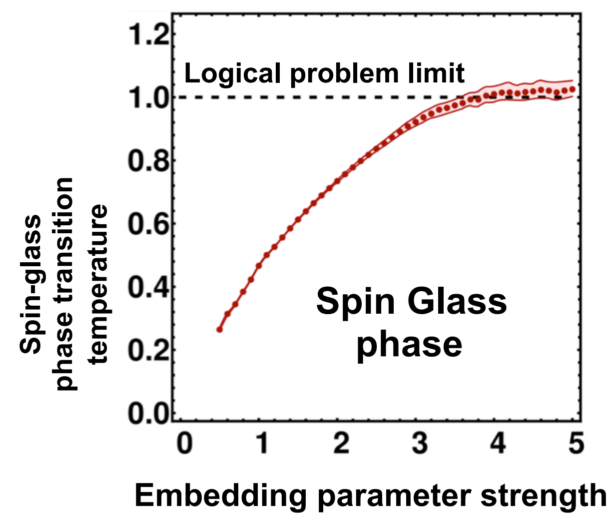


The hybrid cluster method exponentially reduces thermalization time for doing simulated annealing/QMC for embedded problems, for any architecture/embedding.



fully-connected cluster embedding for chimera

Hard problems can be embedded even on architectures for which random native problems are easy – enables finding hard problems in which quantum enhancement could be found



Extremely demanding simulation: (200k computational hours ~ 22 years!)

EVALUATE AND MITIGATE IMPERFECTIONS/NOISE

Robustness: device characterization, misspecification

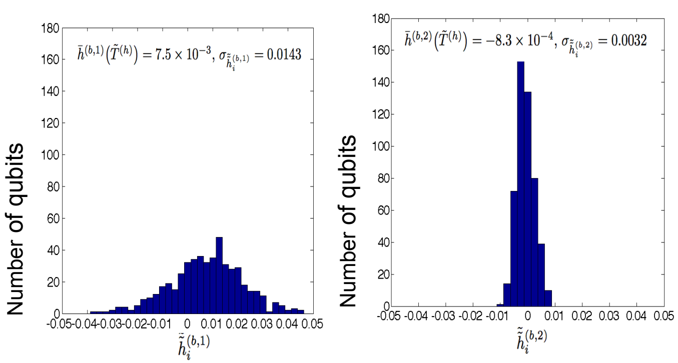
arXiv:1503.05679 Perdomo-Ortiz et al.

- Enhanced quantum annealer performance by over an order of magnitude

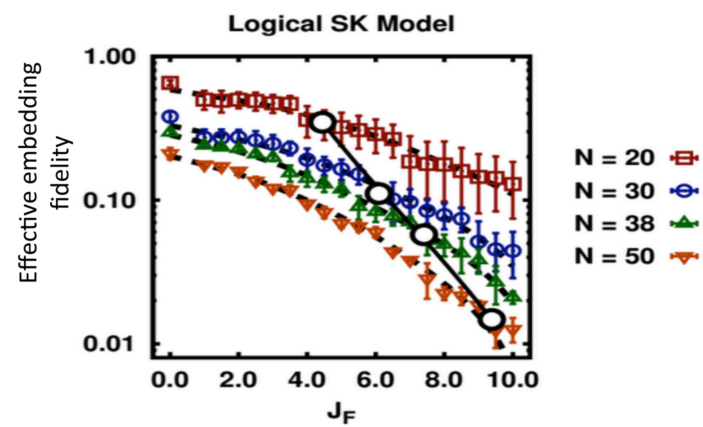
- DWave II noise values
  - 0.035 couplers, 0.05 local fields
- Estimate of precision needed for quantum enhancement

Offset spread

Before correction **After correction**



Optimal choices of embedding parameters: optimize solution probability = embedding fidelity x ground state probability



Developed user recalibration procedure capable of detecting offsets in QA programmable parameters

Quantified sensitivity of quantum annealing to problem misspecification

National Aeronautics and Space Administration

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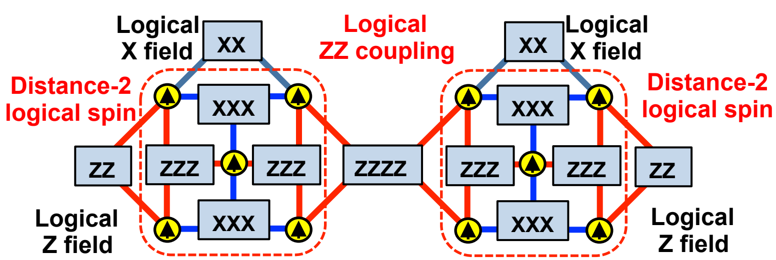
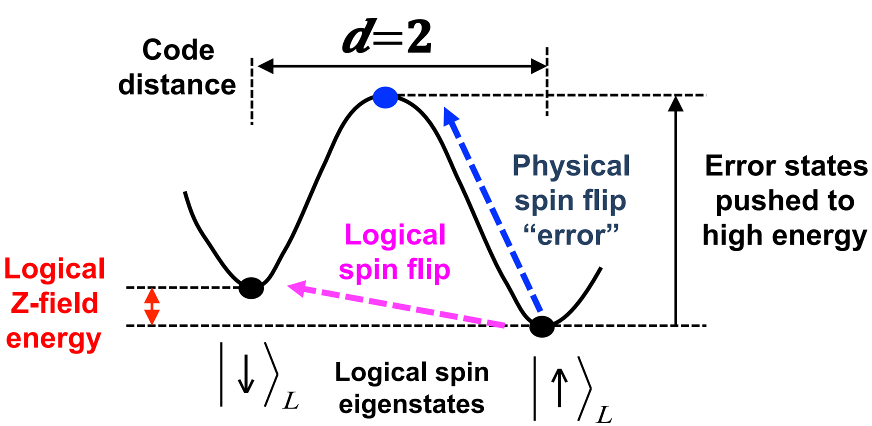
EVALUATE AND MITIGATE IMPERFECTIONS/NOISE

Analysis of effectiveness of error suppression in QA

Rieffel et al., **to appear on arXiv**





Engineer interactions to "penalize" both X (flip) and Z (phase) physical errors: full quantum error suppression

$$W^{\mathrm{env}}_{\mathrm{g}\to\mathrm{e}}(t)$$

$$= \omega_{\mathrm{P}}^2 \int_{-\infty}^{\infty} \left(\frac{S(t)}{\omega_{\mathrm{P}}^2}\right)^d e^{i\omega_{\mathrm{e,g}} t}\, dt \qquad \text{in general}$$

$$= \frac{\eta^d}{(2\pi)^{d-1}} \frac{1}{(2d-1)!} \left(\frac{\omega_{\mathrm{e,g}}}{\omega_{\mathrm{P}}}\right)^{2(d-1)} \frac{\omega_{\mathrm{e,g}}}{e^{\beta\omega_{\mathrm{e,g}}} - 1} \qquad \text{for Ohmic noise}$$

Developed general analytic techniques for estimating transition and dephasing rates due to noise at small gaps

Basis of design for QEO logical coupling primitives.

NASA QEO-related publications

- Published/Accepted
  - E. G. Rieffel, D. Venturelli, B. O'Gorman, M. B. Do, E. Prystay, V.N. Smelyanskiy, *A case study in programming a quantum annealer for hard operational planning problems*, Quantum Information Processing, 14, pp. 1-36. (2014)
  - H. Nishimori, J. Tsuda, S. Knysh, *Comparative Study of the Performance of Quantum Annealing and Simulated Annealing,* Phys. Rev. E, 91, 012104. (2014)
  - B. O'Gorman, E. Rieffel, M. Do, D. Venturelli, J. Frank, *Compiling Planning Into Quantum Optimization Problems: A Comparative Study*, ICAPS-15 (COPLAS workshop)
  - A. Perdomo-Ortiz, J. Fluegemann, S. Narasimhan, R. Biswas, V.N. Smelyanskiy, *A Quantum Annealing Approach for Fault Detection and Diagnosis of Graph-Based Systems,* Eur. Phys. J. Spec. Top., 224 (1), 131-148 (2015)
  - B. O'Gorman, A. Perdomo-Ortiz, R. Babbush, A, Aspuru-Guzik, V. Smelyanskiy, *Bayesian Network Structure Learning Using Quantum Annealing*, Eur. Phys. J. Spec. Top., 225 (1), 163 (2015)
  - D. Venturelli, S. Mandrà, S. Knysh, B. O'Gorman, R. Biswas, V.N. Smelyanskiy, *Quantum Optimization of Fully-Connected Spin Glasses,* PRX 5, 031040
- On arXiv
  - D. Venturelli, D. J.J. Marchand, , G. Rojo, *Quantum Annealing Implementation of Job Shop Scheduling*, arXiv:1506.08479
  - K. Kechedzhi, V.N. Smelyanskiy, *Open system quantum annealing in mean field models with exponential degeneracy* arXiv:1505.05878
  - A. Perdomo-Ortiz, J. Fluegemann, R. Biswas, V.N. Smelyanskiy. *A performance estimator for quantum annealers: Gauge selection and parameter setting*. arXiv: 1503.01083
  - A. Perdomo-Ortiz, B. O'Gorman, R. Biswas, and V. N. Smelyanskiy. *Determination and correction of persistent biases in quantum annealers*. arXiv: 1503.05679.
  - S. Knysh, *Computational Bottlenecks of Quantum Annealing* arXiv:1506.08608