Quantum Annealing for Music Arrangement

Lucas Kirby

4 March 2025

Department of Physics, Durham University

2025-03-09

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Overview

Theory

Adiabatic quantum computing

Quantum annealing

Motivations

Music arrangement

Method

Results

Conclusions

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Results
Conclusions

- AQC, more general umbrella term for the technique
- Quantum annealing as a subset of AQC and what that involves
- Music arrangement and why we're looking at this problem
- How the problem is solved, and the following results
- Conclusions and future work

Theory

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Adiabatic quantum computing

Adiabatic principle

A system remains in its instantaneous eigenstate if a given perturbation is acting on it slowly enough.[1]

[1] Born and Fock, 'Beweis des Adiabatensatzes'.

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- Adiabatic principle — system remains in the same eigenstate if perturbed slowly enough (without transferring heat)
- Equation shows evolution from initial Hamiltonian H_0 to final H_p over time T
- Importantly, if the system starts in the ground state, it will end in the ground state
- Impossible in practice as true adiabatic evolution would take infinite time, infinitely many steps

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$$H(t) = \left(1 - \frac{t}{T}\right) H_0 + \frac{t}{T} H_p$$

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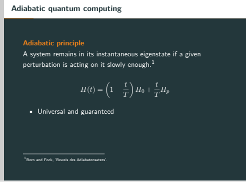

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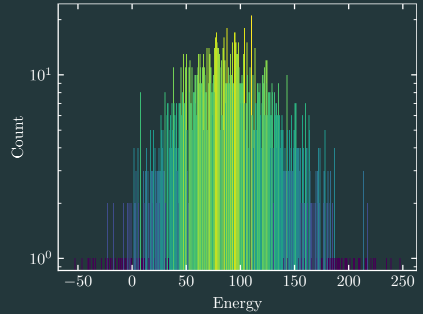
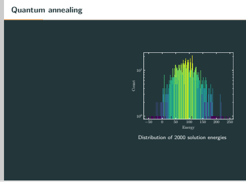
Quantum annealing



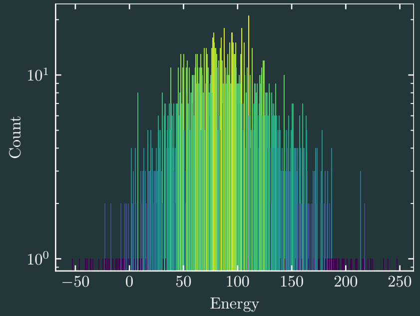
Distribution of 2000 solution energies



- Subset of AQC, relaxes the adiabaticity condition
- Annealing — slow heating of a material to change its properties
- Evolution time shortened (order of a few μs)
- End state no longer guaranteed, if started in ground state could end in excited state
- Able to run the evolution many times
- Probabilistic distribution of outcomes, sometimes will get lucky

Quantum annealing

- Relaxes the adiabaticity



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└Theory
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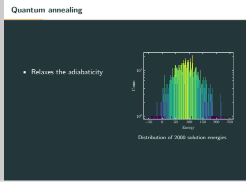

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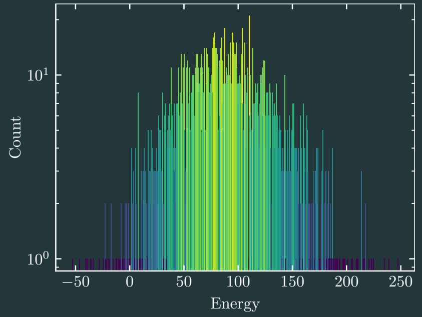

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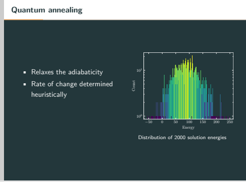

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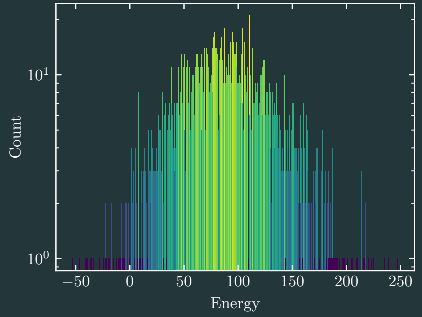
Quantum annealing

- Relaxes the adiabaticity
- Rate of change determined heuristically
- Final state is probabilistic, not deterministic



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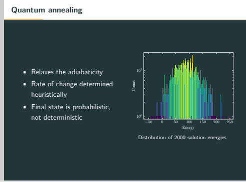

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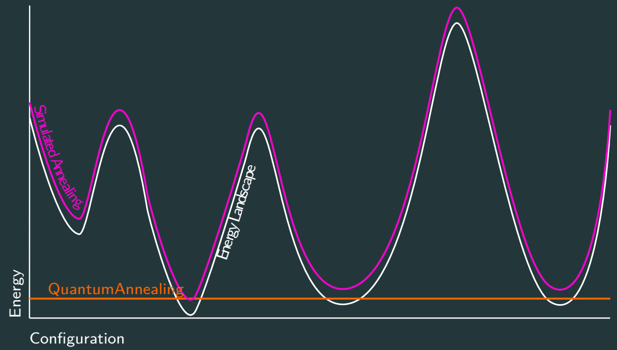
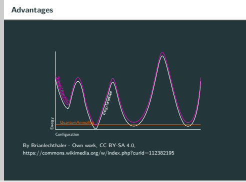
Advantages



By Brianlechthaler - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=112382195



- Why is this technique useful?
- Allows us to find the ground state of complicated Hamiltonians by starting from an easy one
- Diagram — energy against configuration space, simulated annealing (classical) traverses the "energy landscape" whereas quantum annealing tunnels through it
- As opposed to classical methods, does not get affected by local minima
- Technique very good for solving optimisation problems e.g. travelling salesman, with complicated energy landscapes

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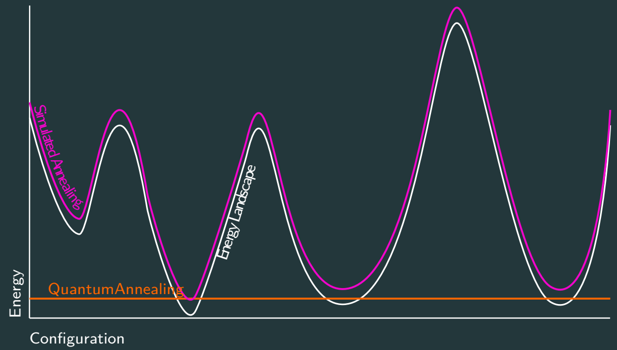

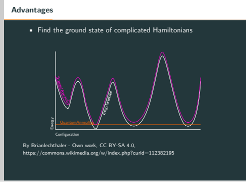

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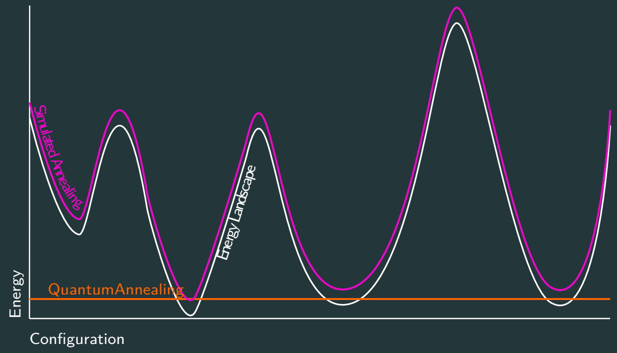
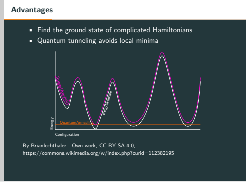
Advantages

- Find the ground state of complicated Hamiltonians
- Quantum tunneling avoids local minima





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Ising model

Lattice of variables with two discrete values

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- How can we model the Hamiltonians?
- Ising model, a lattice of variables with two discrete values (+1/-1), acted on by spin operators σ
- Start with initial Hamiltonian, superposition of all possible states, easy to prepare and find the ground state
- Problem Hamiltonian, coupling strengths J_{ij} and field strengths h_i, describe interactions (biases) of the spins
- Want to encode the problem solution into the ground state of this Hamiltonian so that the system will give the solution after evolution

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Initial Hamiltonian

$$H_0 = h_0 \sum_{i=1}^{N} \sigma_i^x$$

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QUBO

QUBO

- How to encode a problem into a Hamiltonian?
- Similar form to the Ising model, but with binary variables (0/1)
- Minimisation of this function should be the problem solution
- Set of binary variables x, matrix Q of real weights that describes interactions between variables
- After evolution, can read out the values of x to give solution

QUBO

Quadratic Unconstrained Binary Optimisation

Vector x of qubits, matrix Q of weights

$$f(x) = \sum_{i<j}^{N} Q_{i,j} x_i x_j + \sum_{i}^{N} Q_{i,i} x_i$$

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- Encodes problem solution into Hamiltonian's ground state

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Motivations

What problems can we solve?

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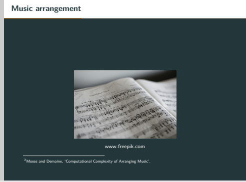
Music arrangement

www.freepik.com

[2] Moses and Demaine, 'Computational Complexity of Arranging Music'.



- Adaptation of music in terms of instrumentation, medium, or style
- Traditionally a complex process that requires a deep understanding of musical theory and structure
- Reduction is the rewriting of music for a smaller number of instruments (for example string quartet)
- Very large configuration space, many different combinations of notes that could produce the final arrangement
- For those interested, NP-hard in computational complexity theory, cannot be solved in polynomial time
- NB: all scores shown are own reproductions from public domain files

Music arrangement

- Adaptation of previously composed pieces for practical or artistic reasons

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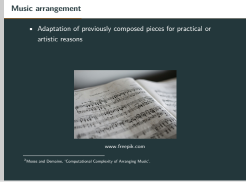

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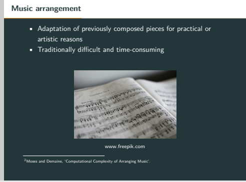

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- *Reduction* can be shown to be computationally complex[2]

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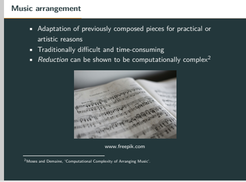

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[4] Freedline, ‘Algorhythms’; Arya et al., ‘Music Composition Using Quantum Annealing’.

[5] Miranda, *Quantum Computer Music*.

- Context of previous work
- Classical methods — machine learning, statistical analysis, rule-based systems, iterative and slow
- Applying quantum computing to music in the last five years, still a very young technology with limitations
- Has been used to generate music, not arrange it
- Methods shown here have not been found in the literature

Motivations

- Already exist classical methods of automatic arrangement[3]

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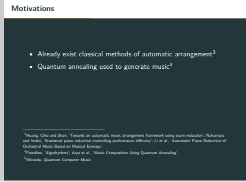

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- Field of quantum computer music is very new[5]

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- Novel adaption of this method to a new problem
- *This has never been done before!*

[3] Huang, Chiu and Shan, 'Towards an automatic music arrangement framework using score reduction'; Nakamura and Yoshii, 'Statistical piano reduction controlling performance difficulty'; Li et al., 'Automatic Piano Reduction of Orchestral Music Based on Musical Entropy'.

[4] Freedline, 'Algorhythms'; Arya et al., 'Music Composition Using Quantum Annealing'.

[5] Miranda, *Quantum Computer Music*.

Motivations

- Already exist classical methods of automatic arrangement[3]
- Quantum annealing used to generate music[4]
- Field of quantum computer music is very new[5]
- Novel adaption of this method to a new problem
- *This has never been done before!*

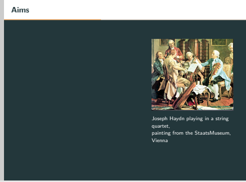
- Context of previous work
- Classical methods — machine learning, statistical analysis, rule-based systems, iterative and slow
- Applying quantum computing to music in the last five years, still a very young technology with limitations
- Has been used to generate music, not arrange it
- Methods shown here have not been found in the literature

Method

Method

Aims

Joseph Haydn playing in a string quartet,
painting from the StaatsMuseum, Vienna



- What are we trying to do? What are the constraints to our problem?
- Take a musical score and reduce it to a smaller ensemble
- All notes must be taken from the original score, no new notes can be added
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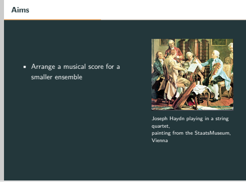

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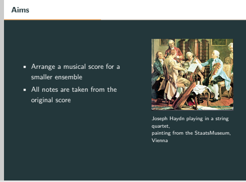

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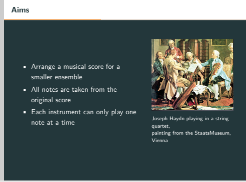

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- Formulating arrangement as a problem to be solved via annealing, five-step process
- Split parts into musical phrases
- Arrange phrases into a graph (will explain later)
- Formulate the optimisation problem
- Solve corresponding graph problem using a quantum computer
- Construct final arrangement from the solution returned

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[6]Cambouropoulos, 'The Local Boundary Detection Model (LBDM) and its Application in the Study of Expressive Timing'.

- First stage to separate each part of original score into phrases
- Phrases — smallest unit of music that preserves melody and structure
- Boundaries between phrases found using LBDM
- Measures the degree of change of a certain parameter (x) between notes (i) (explain equation)
- Strength calculated for both pitch and IOI, weighted and summed to give the final strength
- Strengths above a threshold value are considered phrases

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- Musical phrases chosen as smallest unit of music
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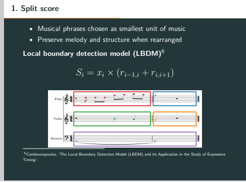

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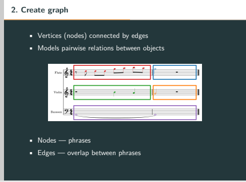
- Nodes — phrases
- Edges — overlap between phrases



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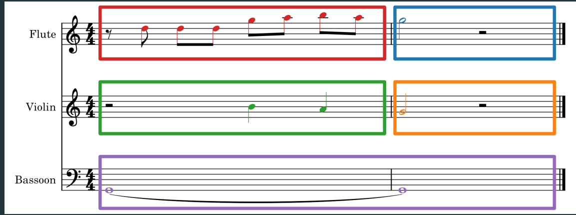

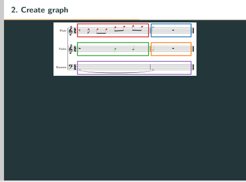

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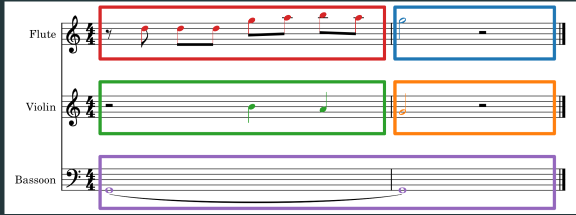

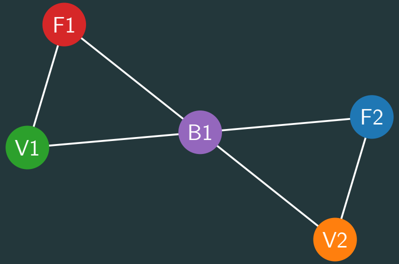

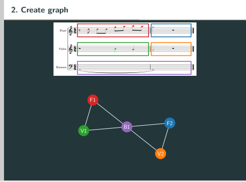

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- Use a graph theory problem to create the optimisation problem that matches our constraints
- Here each colour represents an instrument we are arranging for
- QUBO, set of n colours, $x_{v,i}$ is 1 if node v is colour i
- A — each node is only coloured once, sum over colours is one
- B — penalise adjacent nodes with the same colour
- C — weight of each node, preference for certain nodes
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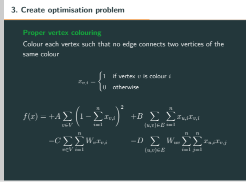

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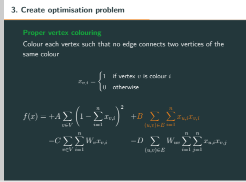

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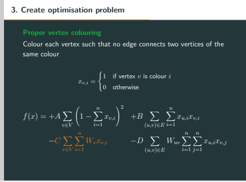

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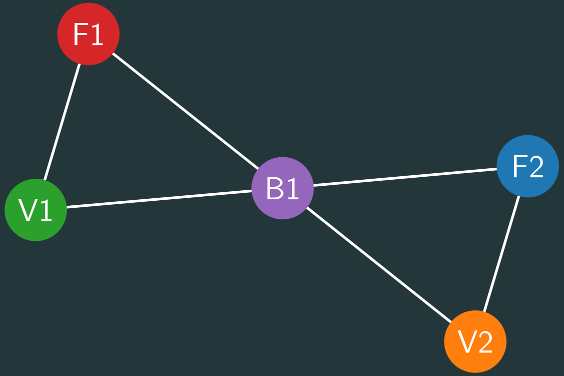

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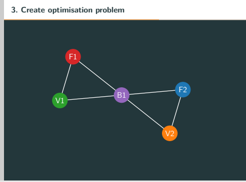

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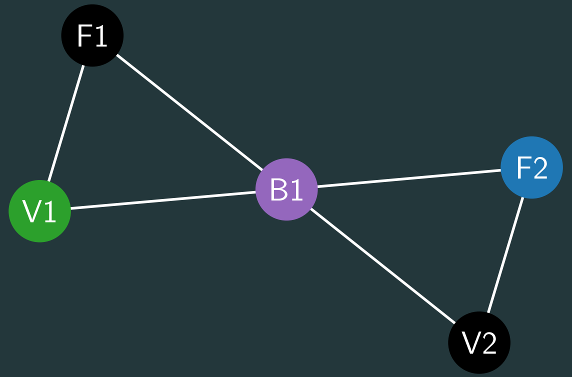
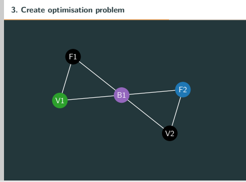
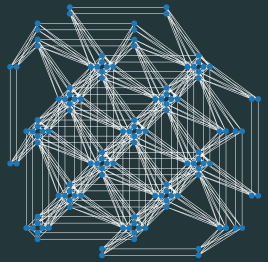


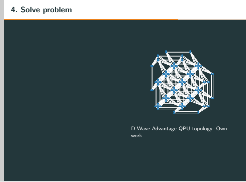


- $n = 1$
- One of many possible solutions

4. Solve problem



D-Wave Advantage QPU topology. Own work.



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- Interact via a Python SDK, submit problems to the QPU
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- Run the problem thousands of times to find the lowest-energy solutions

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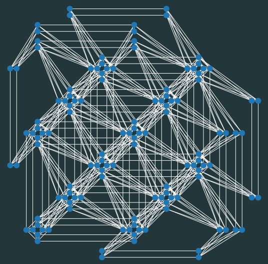
- Problem embedded onto D-Wave quantum hardware



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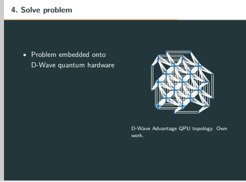

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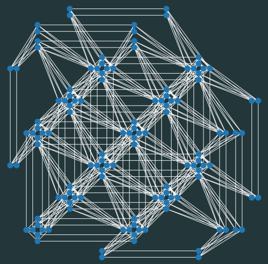

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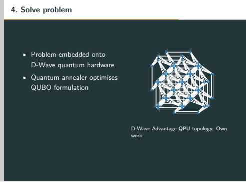

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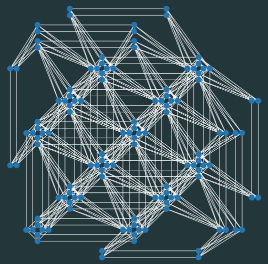

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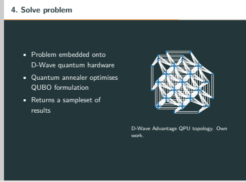

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- Problem embedded onto D-Wave quantum hardware
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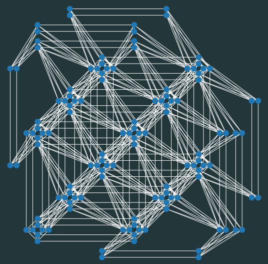

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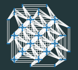

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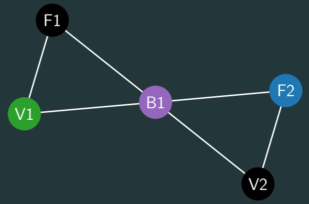

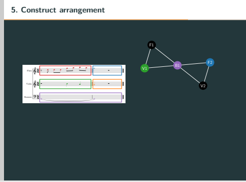

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- Map each node back to its phrase, with colour corresponding to the instrument

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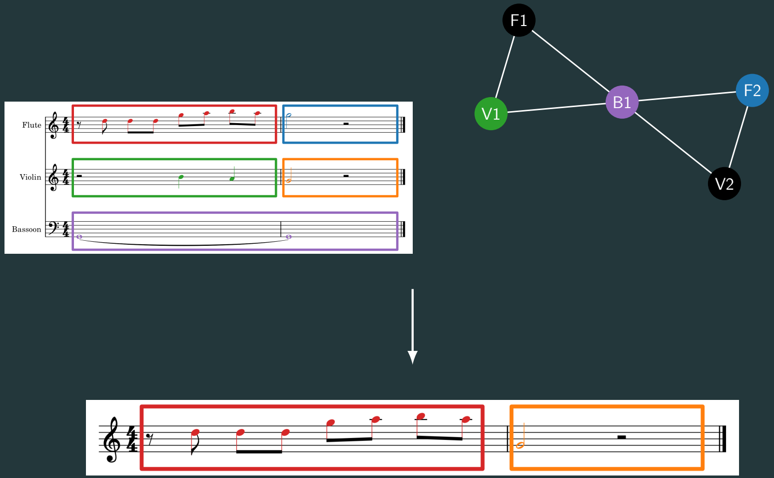

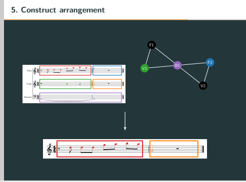

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Results

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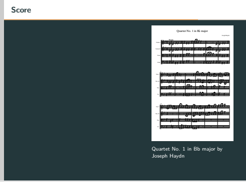

- Quartet No. 1 in Bb major by Joseph Haydn
- Smaller instrumentation and length (about 3 min), keeping the problem graph small and manageable
- Musical style has well-defined structure and phrases

Score

- Smaller ensemble chosen for problem size

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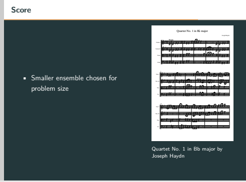

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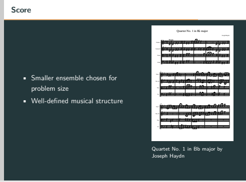

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Score

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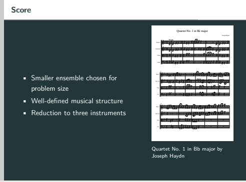
- Well-defined musical structure
- Reduction to three instruments

Quartet No. 1 in Bb major by Joseph Haydn



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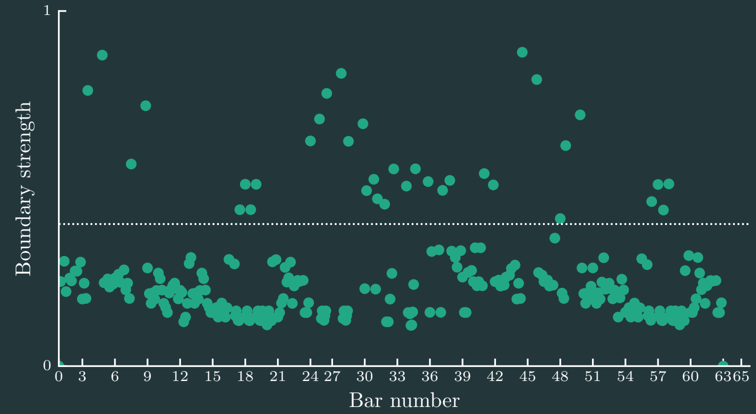
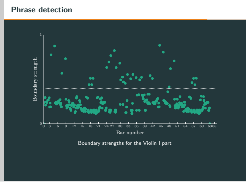
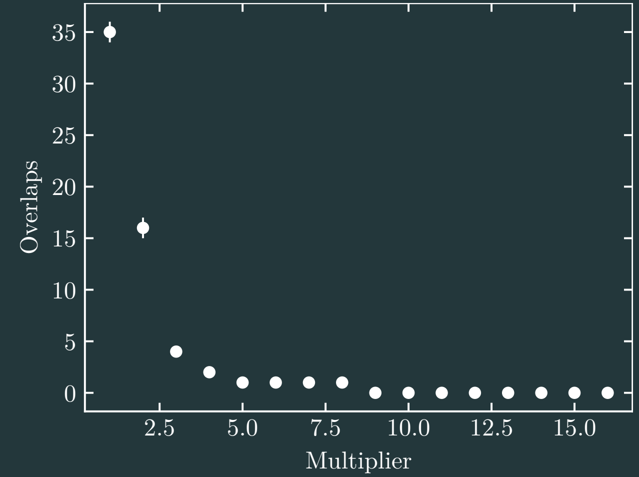


Boundary strengths for the Violin I part

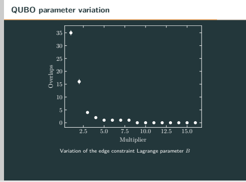


- Example of the LBDM finding suitable boundaries for phrases
- Threshold value of 0.4 chosen manually

QUBO parameter variation

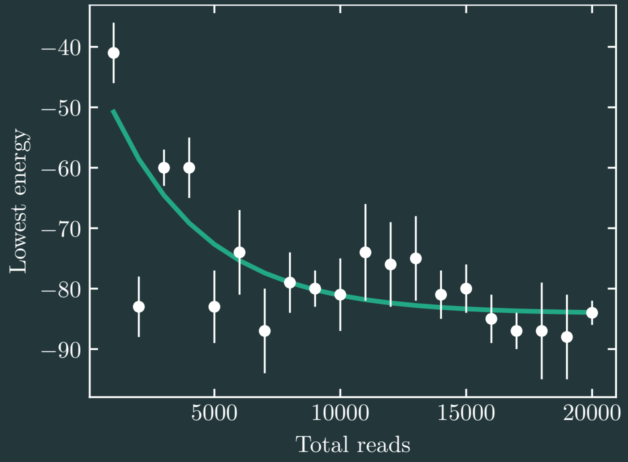


Variation of the edge constraint Lagrange parameter B

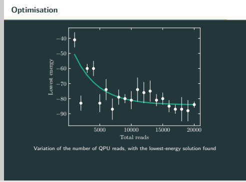


- Each QUBO problem submitted five times with different edge constraint Lagrange parameter
- Checking against fulfillment of the desired constraint
- Lagrange parameters taken as multipliers of the maximum node weight for normalisation
- 12.0 chosen as the best parameter, with all others equal to one

Optimisation



Variation of the number of QPU reads, with the lowest-energy solution found



- Once Lagrange parameters chosen, can check how well the annealer optmises the problem
- In general, more reads is more likely to find lower-energy solutions
- Sometimes the annealer gets lucky (see 2000 reads)
- Each number of reads repeated five times, exponential decay fitted

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- Successful application of this method on a new problem
- QPU returns samples that fulfill the constraints of the problem, creating a valid arrangement
- New technology, limited in power
- What would it take for quantum to show advantage?

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Future work

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Thank you!

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LBDM

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$$r_{i,i+1} = \frac{|x_i - x_{i+1}|}{x_i + x_{i+1}}$$

Normalisation

$$S_i' = \frac{S_i - \min(S_i)}{\max(S_i) - \min(S_i)}$$

Weighting

$$S = \frac{1}{3}\left(S'_{\text{pitch}} + 2S'_{\text{IOI}}\right)$$

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- Boundaries always taken at beginning/end of piece
- Weightings derived by trial and error

Phrase entropy

x_i — parameter x of note i

Shannon entropy

$$H(X) := -\sum_i P(x_i)\log_2 P(x_i)$$

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$$P(x_i) = \frac{n_i}{N}$$

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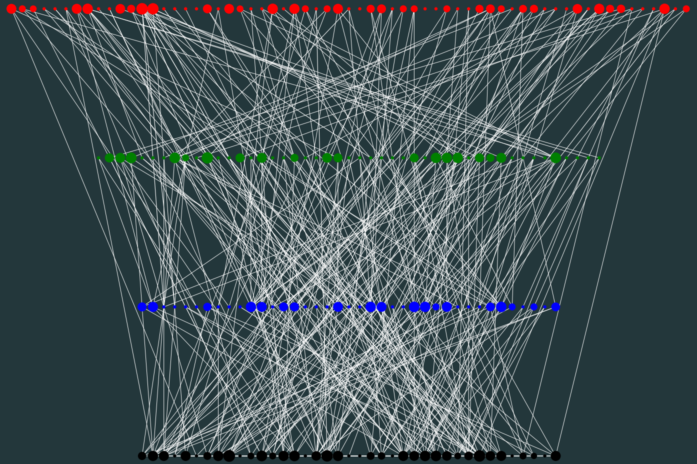
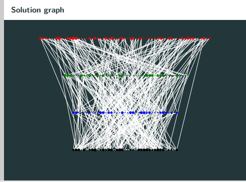
- Shannon entropy units in bits due to $\log_2$
- Distribution calculated for pitch and duration

Solution graph





Solution score