Music Arrangement via Quantum Annealing

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30 January 2025

Department of Physics, Durham University

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Overview

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Theory
Music arrangement
Quantum annealing
Methods
Results
Conclusions

- What is music arrangement? What is quantum annealing?
- Methods used to solve the music arrangement problem
- Preliminary results from application of the method
- Concluding thoughts about this process

Theory

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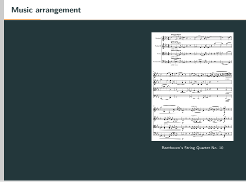
Music arrangement

Beethoven's String Quartet No. 10



- Adaptation of music in terms of instrumentation, medium, or style
- Traditionally a complex process that requires a deep understanding of musical theory and structure
- Musically interesting whilst still remaining faithful to the source material
- Interest in automating this process
- Reduction is the rewriting of music for a smaller number of instruments (for example string quartet)

Music arrangement

- Adaptation of previously composed pieces for practical or artistic reasons

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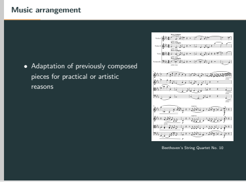

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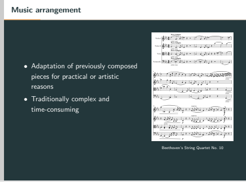

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Music arrangement

- Adaptation of previously composed pieces for practical or artistic reasons
- Traditionally complex and time-consuming
- This study focuses on **reduction**

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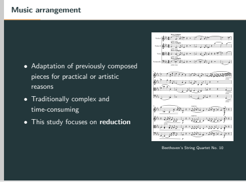

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- Materials science, annealing is a slow heating/cooling process to make a material softer and less brittle
- Quantum computing, slow evolution of a system between Hamiltonians
- Done adiabatically (closed system), system remains in ground state

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[Lucas, 2014]

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Quantum annealing

Quantum annealing

- How is this used to solve problems?
- Ising model, create a lattice of variables with two discrete values (spin up/down)
- Problem Hamiltonian, qubits σ^z, coupling strengths J_{ij} and field strengths h_i
- Initial state is a superposition of all possible states
- If problem solution is encoded within the ground state, system will give solution after evolution

Quantum annealing

Ising model

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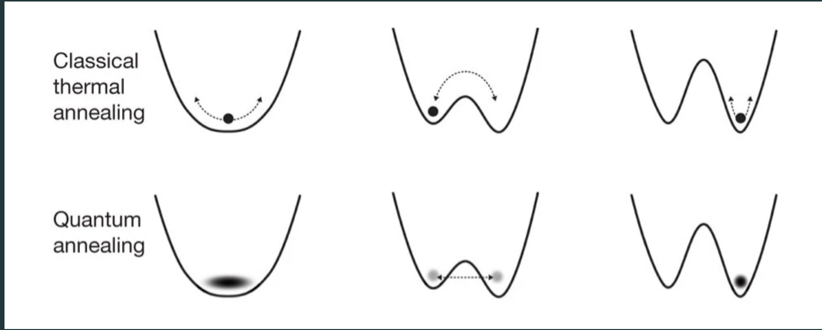
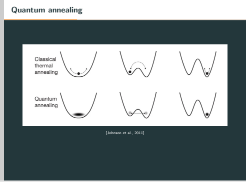


[Johnson et al., 2011]



- What does this look like?
- Evolution of superposition to a particular state
- More efficiently escape from local minima via quantum tunneling
- Can solve harder problems with a more turbulent energy landscape

QUBO

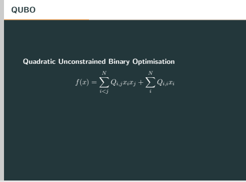
QUBO

- How to encode a problem into a Hamiltonian?
- Similar form to the Ising model, but with binary variables (0 or 1)
- QUBO is a function to be minimised
- Set of binary variables x, matrix Q of real weights that describes interactions between variables
- Can read out variable values after evolution to give solution

QUBO

Quadratic Unconstrained Binary Optimisation

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



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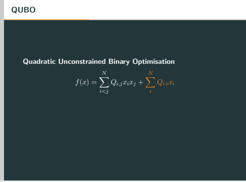

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- How to apply quantum annealing to the problem of music arrangement?

Methods

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Problem formulation

Problem formulation

- Formulating arrangement as a problem to be solved via annealing, four-step process
- Split parts into musical phrases
- Arrange phrases into a graph (nodes and edges)
- Solve corresponding graph problem using quantum computing
- Construct final arrangement from the solution returned

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- 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 between notes (explain equation)
- Check pitch and IOI
- Strengths above a threshold value are considered phrases

Local boundary detection model (LBDM)

$$S_i = x_i \times (r_{i-1,i} + r_{i,i+1})$$

[Cambouropoulos, 2011]

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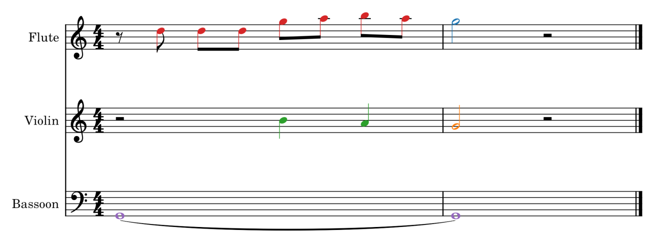

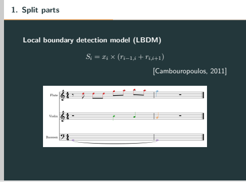

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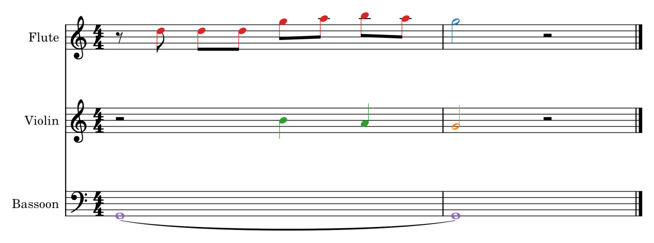

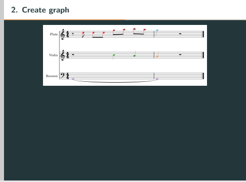

- Construct problem graph
- Each phrase becomes a node, edges between nodes if phrases overlap

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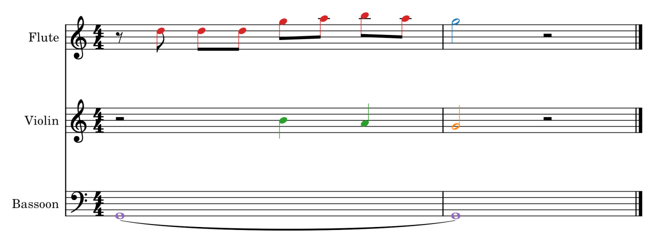

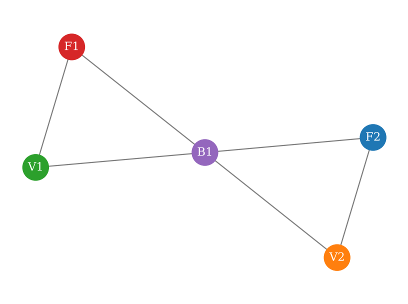

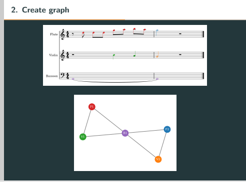

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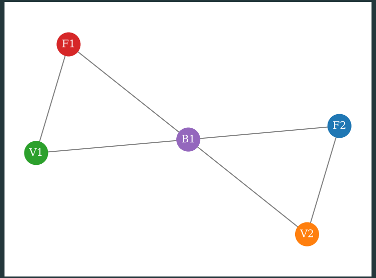
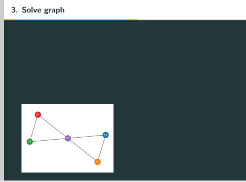




- Special case for reducing to a single monophonic part (one phrase played at a time)
- Solve problem graph using a graph theory problem called MIS
- Find largest subset of nodes such that no nodes within the subset are connected by an edge
- Enforces that only one simultaneous phrase can be played at once
- Constraint term enforces no edges
- Objective term is quantity to be minimised
- Lagrange paramters A/B determine the balance between constraint and objective

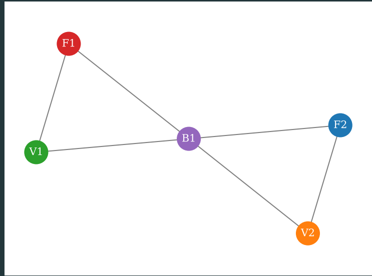
3. Solve graph

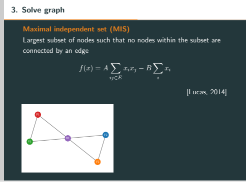
Maximal independent set (MIS)

Largest subset of nodes such that no nodes within the subset are connected by an edge

$$f(x) = A \sum_{ij \in E} x_i x_j - B \sum_i x_i$$

[Lucas, 2014]





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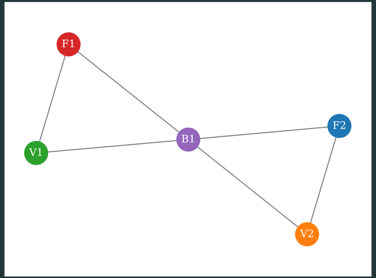

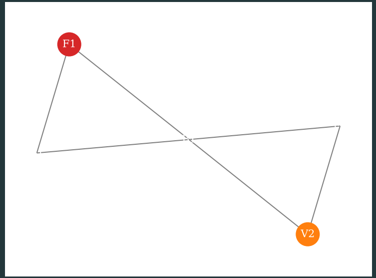

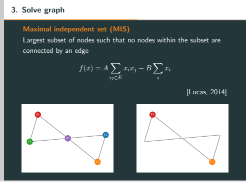

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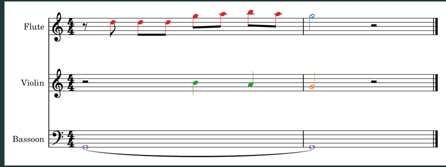
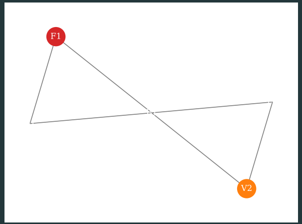
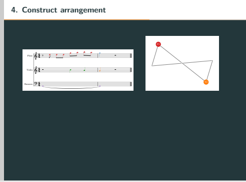
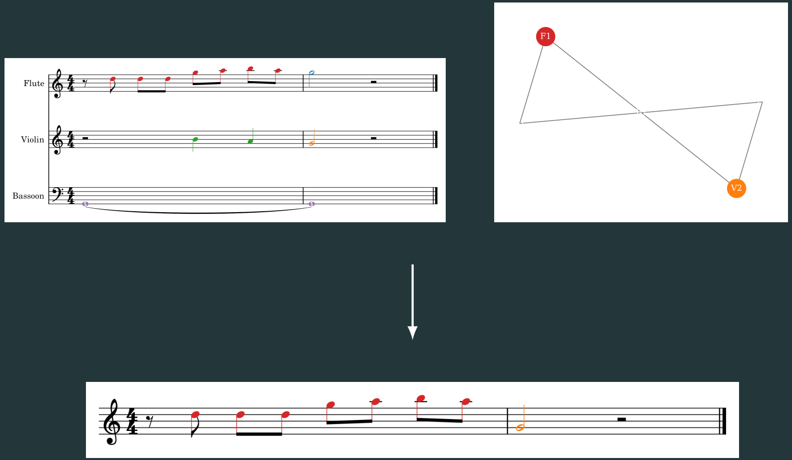


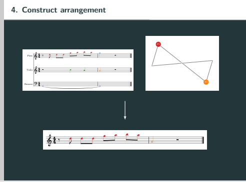




- Take solution graph and combine selected nodes to create final arrangement

4. Construct arrangement





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Results

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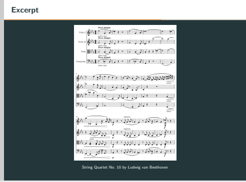
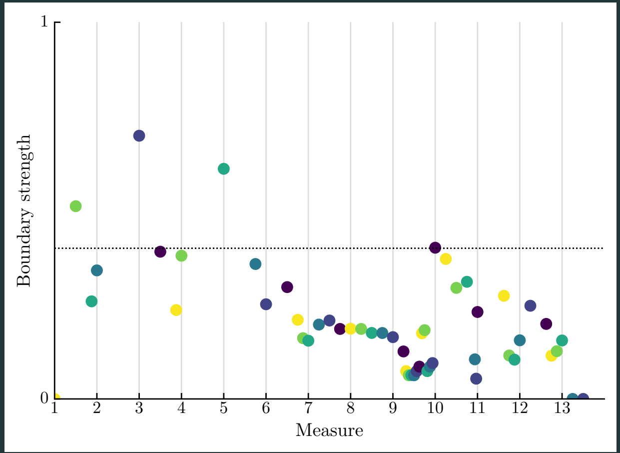
Excerpt

String Quartet No. 10 by Ludwig van Beethoven

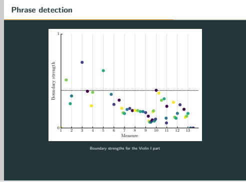


- Excerpt of String Quartet No. 10 in E-flat major, Op. 74, by Ludwig van Beethoven
- Chosen due to its relatively simple structure and smaller instrumentation, keeping the problem graph small

Phrase detection

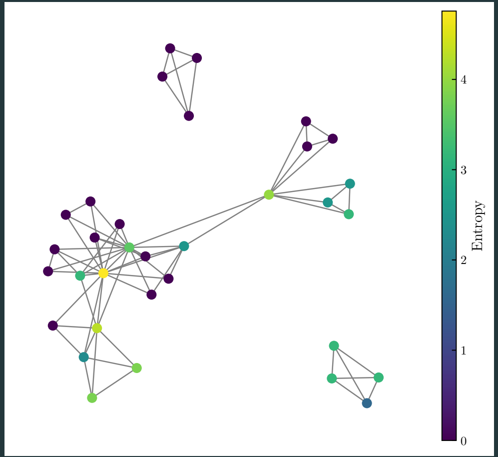


Boundary strengths for the Violin I part

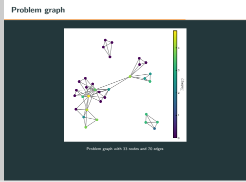


- Example of the LBDM finding suitable boundaries for phrases
- Threshold value of 0.4 chosen, finds five phrases

Problem graph

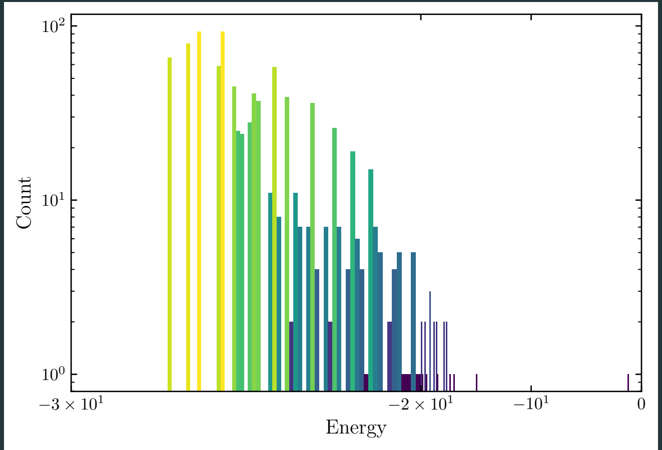


Problem graph with 33 nodes and 70 edges

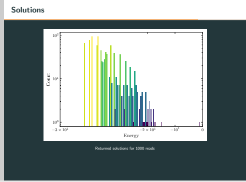


- 33 identified phrases (nodes) with 70 overlaps (edges)
- Nodes are weighted by the phrase entropy, how musically interesting the distribution of notes is

Solutions

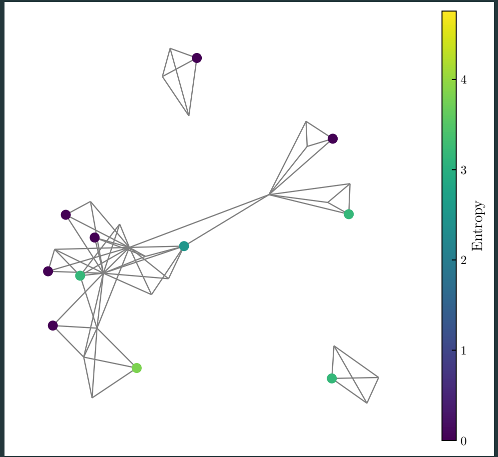


Returned solutions for 1000 reads

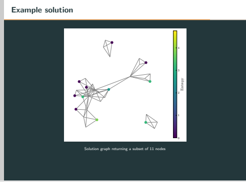


- Histogram of the returned solutions, only energies below zero shown
- Distribution of solutions due to the stochastic nature of annealing
- Not always guaranteed the ground state during evolution
- Lowest energy solution -26.8 with a degeneracy of 34

Example solution



Solution graph returning a subset of 11 nodes

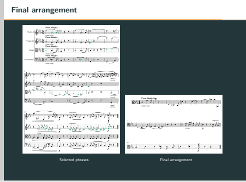


- Selected nodes from one of the lowest energy solutions
- Note in the cliques only one node could be selected

Final arrangement

Selected phrases

Final arrangement



- Selected phrases from solution graph highlighted
- Phrases concatenated to create the final arrangement

Conclusions

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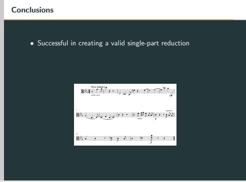
- Valid reduction gained from implemented method
- Monophonic lowest-energy solution
- Phrase identification and selection result in musically interesting final arrangement
- Displays some advantages over classical algorithms
- Does not require training data, costly in both time and resources
- Faster solve time compared to similarly-sized problems
- Method and more advanced versions of it removes the skill barrier for music arrangement

Conclusions

- Successful in creating a valid single-part reduction



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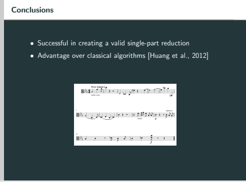

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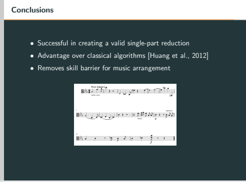

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Future work

Future work

- Problem size — full piece has upwards of 1000 phrases, compare solve times with classical algorithms
- LBDM parameters — phrases should be short and similar in length, prevents important notes being hidden in long phrases with low entropy
- Physical limitations — note ranges, note change speed
- Multiple parts — need different problem formulation, colouring problem with each colour representing a reduced part
- Quality judgement — Turing-like test, present subjects with human-/computer-generated scores

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Music Arrangement via Quantum Annealing

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2025-01-28

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LBDM

Boundary strength

$$S_i = x_i \times (r_{i-1,i} + r_{i,i+1})$$

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

Normalisation

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

Weighting

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

[Cambouropoulos, 2011]

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Weighting
$S = \frac{1}{3}\left(S'_{\text{pitch}} + 2S'_{\text{IOI}}\right)$
[Cambouropoulos, 2011]

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

Phrase entropy

Shannon entropy

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

Probability distribution

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

[Li et al., 2019]

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Probability distribution
$P(x_i) = \frac{n_i}{N}$
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- Shannon entropy units in bits due to $\log_2$
- Distribution calculated for pitch and duration