Developing a Minor Embedding Algorithm for Oscillator based Ising Machines using Reinforcement Learning

TECHNISCHE UNIVERSITÄT DARMSTADT

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Description

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Oscillator-based Ising Machines (OIMs) are a promising metaheuristic approach for solving NP-hard and NP-complete combinatorial optimization problems, such as the well-known Traveling Salesman Problem (TSP). Compared to conventional methods, OIMs offer significant advantages in terms of computational speed and energy efficiency. Our OIM consists of a network of 1,440 coupled oscillators.

In the context of Ising machines, an optimization problem can be reformulated as an Ising model and represented as a graph. The vertices of this graph are assigned to oscillators, while the edge weights determine the coupling strengths between them. Once initialized, the oscillator network dynamically evolves toward a minimum-energy state. The oscillator phases in this final state correspond to the computed solution of the optimization problem.

To make practical use of an OIM, however, the graph representing the optimization problem must first be mapped onto the physical oscillator network of the hardware. This process, known as **minor embedding**, involves adapting the logical problem graph to the limited connectivity of the hardware topology. In general, the minor embedding problem is NP-complete.

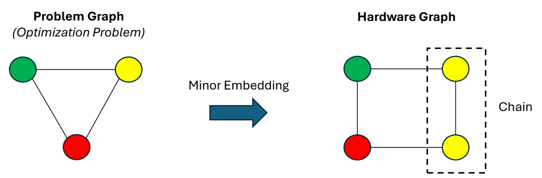

Figure 1: Embedding Example

Task Description and Objectives

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The objective of this master's thesis is the development and investigation of a minor embedding algorithm that uses **Reinforcement Learning (RL)** to generate mappings (embeddings) of logical graphs onto a given hardware topology. Minor embedding is a central subproblem in the application of Ising machines, since real hardware typically provides only limited connectivity.

As part of this work, an RL-based approach shall be designed that makes embedding decisions step by step, for example by placing nodes or constructing chains. The focus is particularly on the **design of effective reward functions**. Since reward design strongly influences the learning behavior and final embedding quality, different reward formulations will be developed and analyzed.

Main Topics

The thesis should particularly address the following aspects:

- Introduction to Minor Embedding, Formal definition of the minor embedding problem
- Overview of existing approaches like MinorMiner, RL-based approaches and Key challenges
- Formulation as a Reinforcement Learning Problem
- Definition of state space, actions, and transitions
- **Design and evaluation of suitable reward functions (e.g., chain length, embedding success)**
- Selection and justification of an RL method (e.g., Q-learning, Policy Gradients, Actor-Critic)
- Implementation of the RL agent
- Experimental investigation using suitable benchmark graphs
- Comparison with established minor embedding algorithms (MinorMiner)
- Analysis of success rates, runtime, and embedding quality (e.g. chain length)

Methodology

The thesis is primarily algorithmic and experimental in nature. In addition to the theoretical modeling of the problem, a functional prototype shall be implemented and systematically evaluated. The results should be documented in a reproducible manner and critically discussed.

Expected Results

At the end of the thesis, a working RL-based minor embedding algorithm should be available, whose performance has been evaluated using suitable metrics. The thesis should demonstrate to what extent the design of suitable reward functions enables Reinforcement Learning to provide added value compared to classical heuristic embedding methods. In particular, it should analyze how different reward formulations influence learning efficiency, embedding quality, and generalization performance, as well as identify remaining limitations and open research questions in reward design for RL-based minor embedding.

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Requirements

- Basic knowledge of graph theory
- Experience with machine learning, especially Reinforcement Learning
- Programming skills (e.g., Python or similar)
- Interest in algorithmic design

Language

German or English

Thesis Type

Master thesis

Contact

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