

Qubit-efficient quantum local search for combinatorial optimization

M. Podobrii, V. Kuzmin, V. Voloshinov, M. Veshchezerova, and M. R. Perelshtein

Terra Quantum AG, Kornhausstrasse 25, 9000 St. Gallen, Switzerland

An essential component of many sophisticated metaheuristics for solving combinatorial optimization problems is some variation of a local search routine that iteratively searches for a better solution within a chosen set of immediate neighbors. The size l of this set is limited due to the computational costs required to run the method on classical processing units. We present a qubit-efficient variational quantum algorithm that implements a quantum version of local search with only $\lceil \log_2 l \rceil$ qubits and, therefore, can potentially work with classically intractable neighborhood sizes when realized on near-term quantum computers. Increasing the amount of quantum resources employed in the algorithm allows for a larger neighborhood size, improving the quality of obtained solutions. This trade-off is crucial for present and near-term quantum devices characterized by a limited number of logical qubits. Numerically simulating our algorithm, we successfully solved the largest graph coloring instance that was tackled by a quantum method. This achievement highlights the algorithm's potential for solving large-scale combinatorial optimization problems on near-term quantum devices.

1 Introduction

Local search is one of the most fundamental heuristic algorithms successfully applied to many challenging combinatorial optimization problems. The so-called r -local search (or r -flip) algorithm [1] starts from a candidate solution and iteratively explores a chosen neighborhood, of size l , of solutions that differ by at most r bits (or Hamming distance r). The process stops when all the neighbors are not better than the current solution. Many metaheuristics, such as simulated annealing [2], tabu search [3], and memetic algorithms [4], are based on local search [5]. Increasing the size of the neighborhood by increasing r can yield better solutions at the cost of an exponentially growing runtime that follows the binomial coefficient $l \sim C_n^r \sim O(n^r)$ where n is the total number of variables. Therefore, the parameter r typically must be chosen as small.

In this work, we address the aforementioned problem by introducing a Variational Quantum Algorithm (VQA) that uses a parametrized quantum-circuit ansatz of sufficient depth to implement the r -local search heuristic. The distinct feature of our approach is that the number, N_q , of employed qubits adapts to the chosen parameter r , ranging from $N_q = \lceil \log_2 n \rceil$ when $r = 1$ to $N_q = n$ when $r = n$. In contrast to the previously proposed

M. Podobrii: mp2@terraquantum.swiss

M. R. Perelshtein: mpe@terraquantum.swiss

Local Search In Combinatorial Optimization

Wil Michiels, Emile Aarts, Jan Korst



Local Search In Combinatorial Optimization:

Local Search in Combinatorial Optimization Emile Aarts, Jan Karel Lenstra, 2018-06-05 In the past three decades local search has grown from a simple heuristic idea into a mature field of research in combinatorial optimization that is attracting ever increasing attention Local search is still the method of choice for NP hard problems as it provides a robust approach for obtaining high quality solutions to problems of a realistic size in reasonable time Local Search in Combinatorial Optimization covers local search and its variants from both a theoretical and practical point of view each topic discussed by a leading authority This book is an important reference and invaluable source of inspiration for students and researchers in discrete mathematics computer science operations research industrial engineering and management science In addition to the editors the contributors are Mihalis Yannakakis Craig A Tovey Jan H M Korst Peter J M van Laarhoven Alain Hertz Eric Taillard Dominique de Werra Heinz Mhlenbein Carsten Peterson Bo S derberg David S Johnson Lyle A McGeoch Michel Gendreau Gilbert Laporte Jean Yves Potvin Gerard A P Kindervater Martin W P Savelsbergh Edward J Anderson Celia A Glass Chris N Potts C L Liu Peichen Pan Iiro Honkala and Patric R J sterg rd Approximate Local Search in Combinatorial Optimization James B. Orlin, 2007 Local search algorithms for combinatorial optimization problems are generally of pseudopolynomial running time and polynomial time algorithms are not often known for finding locally optimal solutions for NP hard optimization problems We introduce the concept of ϵ local optimality and show that for every $\epsilon > 0$ an ϵ local optimum can be identified in time polynomial in the problem size and $1/\epsilon$ whenever the corresponding neighborhood can be searched in polynomial time If the neighborhood can be searched in polynomial time for a ϵ local optimum a variation of our main algorithm produces a ϵ local optimum in time polynomial in the problem size and $1/\epsilon$ As a consequence a combinatorial optimization problem has a fully polynomial time approximation scheme if and only if the problem of determining a better neighbor in an exact neighborhood has a fully polynomial time approximation scheme

Approximate Local Search in Combinatorial Optimization James B. Orlin, Abraham P. Punnen, Andreas S. Schulz, Sloan School of Management, 2004 Local search algorithms for combinatorial optimization problems are in general of pseudopolynomial running time and polynomial time algorithms are often not known for finding locally optimal solutions for NP hard optimization problems We introduce the concept of ϵ local optimality and show that an ϵ local optimum can be identified in time polynomial in the problem size and $1/\epsilon$ whenever the corresponding neighborhood can be searched in polynomial time for $\epsilon > 0$ If the neighborhood can be searched in polynomial time for a δ local optimum we present an algorithm that produces a δ/ϵ local optimum in time polynomial in the problem size and $1/\epsilon$ As a consequence a combinatorial optimization problem has a fully polynomial time approximation scheme if and only if it has a fully polynomial time augmentation scheme Keywords Local Search Neighborhood Search Approximation Algorithms Computational Complexity Combinatorial Optimization 0 1 Integer Programming **Local Search In Combinatorial**

Optimization Emile Aarts, 2007-01-01 *Theoretical Aspects of Local Search* Wil Michiels, Emile Aarts, Jan Korst, 2007-01-17 Local search has been applied successfully to a diverse collection of optimization problems It is appreciated for its basic conceptual foundation its general applicability and its power to serve as a source for new search paradigms The typical characteristics of combinatorial optimization problems to which local search can be applied its relation to complexity theory and the combination with randomized search features have led to a wealth of interesting theoretical results However these results are scattered throughout the literature This is the first book that presents a large collection of theoretical results in a consistent manner thus providing the reader with a coherent overview of the achievements obtained so far but also serving as a source of inspiration for the development of novel results in the challenging field of local search

Handbook of Approximation Algorithms and Metaheuristics Teofilo F. Gonzalez, 2018-05-15 Handbook of Approximation Algorithms and Metaheuristics Second Edition reflects the tremendous growth in the field over the past two decades Through contributions from leading experts this handbook provides a comprehensive introduction to the underlying theory and methodologies as well as the various applications of approximation algorithms and metaheuristics Volume 1 of this two volume set deals primarily with methodologies and traditional applications It includes restriction relaxation local ratio approximation schemes randomization tabu search evolutionary computation local search neural networks and other metaheuristics It also explores multi objective optimization reoptimization sensitivity analysis and stability Traditional applications covered include bin packing multi dimensional packing Steiner trees traveling salesperson scheduling and related problems Volume 2 focuses on the contemporary and emerging applications of methodologies to problems in combinatorial optimization computational geometry and graphs problems as well as in large scale and emerging application areas It includes approximation algorithms and heuristics for clustering networks sensor and wireless communication bioinformatics search streams virtual communities and more About the Editor Teofilo F Gonzalez is a professor emeritus of computer science at the University of California Santa Barbara He completed his Ph D in 1975 from the University of Minnesota He taught at the University of Oklahoma the Pennsylvania State University and the University of Texas at Dallas before joining the UCSB computer science faculty in 1984 He spent sabbatical leaves at the Monterrey Institute of Technology and Higher Education and Utrecht University He is known for his highly cited pioneering research in the hardness of approximation for his sublinear and best possible approximation algorithm for k tMM clustering for introducing the open shop scheduling problem as well as algorithms for its solution that have found applications in numerous research areas as well as for his research on problems in the areas of job scheduling graph algorithms computational geometry message communication wire routing etc *Mathematical Programming Solver Based on Local Search* Frédéric Gardi, Thierry Benoist, Julien Darlay, Bertrand Estellon, Romain Megel, 2014-07-09 This book covers local search for combinatorial optimization and its extension to mixed variable optimization Although not yet understood from the theoretical

point of view local search is the paradigm of choice for tackling large scale real life optimization problems Today s end users demand interactivity with decision support systems For optimization software this means obtaining good quality solutions quickly Fast iterative improvement methods like local search are suited to satisfying such needs Here the authors show local search in a new light in particular presenting a new kind of mathematical programming solver namely LocalSolver based on neighborhood search First an iconoclast methodology is presented to design and engineer local search algorithms The authors concern regarding industrializing local search approaches is of particular interest for practitioners This methodology is applied to solve two industrial problems with high economic stakes Software based on local search induces extra costs in development and maintenance in comparison with the direct use of mixed integer linear programming solvers The authors then move on to present the LocalSolver project whose goal is to offer the power of local search through a model and run solver for large scale 0 1 nonlinear programming They conclude by presenting their ongoing and future work on LocalSolver toward a full mathematical programming solver based on local search

Oblivious and Non-Oblivious Local Search for Combinatorial Optimization Justin Ward,2012 Local Search in Combinatorial Optimization Yves Crama,Anthonius

Wilhelmus Johannes Kolen,Erwin Pesch,Rijksuniversiteit te Limburg. Faculty of Economics,1992* **Handbook of Computational and Numerical Methods in Finance** Svetlozar T. Rachev,2011-06-28 Numerical Methods in Finance have recently emerged as a new discipline at the intersection of probability theory finance and numerical analysis They bridge the gap between financial theory and computational practice and provide solutions to problems where analytical methods are often non applicable Numerical methods are more and more used in several topics of financial analysis computation of complex derivatives market credit and operational risk assessment asset liability management optimal portfolio theory financial econometrics and others Although numerical methods in finance have been studied intensively in recent years many theoretical and practical financial aspects have yet to be explored This volume presents current research focusing on various numerical methods in finance The contributions cover methodological issues Genetic Algorithms Neural Networks Monte Carlo methods Finite Difference Methods Stochastic Portfolio Optimization as well as the application of other numerical methods in finance and risk management As editor I am grateful to the contributors for their fruitful collaboration I would particularly like to thankStefan Trueck and Carlo Marinelli for the excellent editorial assistance received over the progress of this project Thomas Plum did a splendid word processingjob in preparing the manuscript lowe much to George Anastassiou ConsultantEditor Birkhauser and Ann Kostant Executive Editor Mathematics and Physics Birkhauser for their help and encouragement

Recent Advances in Parallel Virtual Machine and Message Passing Interface Dieter Kranzlmüller,Peter Kacsuk,Jack Dongarra,2004-09-10 This book constitutes the refereed proceedings of the 11th European PVM MPI users Group Meeting held in Budapest Hungary in September 2004 The 50 revised papers presented together with abstracts of 10 invited contributions were carefully reviewed and selected from numerous submissions The papers are

organized in topical sections on MPI PVM extensions and improvements algorithms applications tools and environments cluster and grid computing performance and parallel numerical simulation Local Search in Combinatorial Optimization Yves Crama,1992 Annotated Bibliographies in Combinatorial Optimization Mauro Dell'Amico,Francesco Maffioli,Silvano Martello,1997-08-28 Wiley Interscience Series in Discrete Mathematics and Optimization Advisory Editors Ronald L Graham Jan Karel Lenstra Robert E Tarjan Discrete Mathematics and Optimization involves the study of finite structures and is one of the fastest growing areas in mathematics today The level and depth of recent advances in the area and the wide applicability of its evolving techniques point to the rapidity with which the field is moving and presage the ever increasing interaction between it and computer science The Series provides a broad coverage of discrete mathematics and optimization ranging over such fields as combinatorics graph theory enumeration mathematical programming and the analysis of algorithms and including such topics as Ramsey theory transversal theory block designs finite geometries Polya theory graph and matroid algorithms network flows polyhedral combinatorics and computational complexity The Wiley Interscience Series in Discrete Mathematics and Optimization will be a substantial part of the record in this extraordinary development Recent titles in the Series Local Search in Combinatorial Optimization Edited by Emile H L Aarts Philips Research Laboratories Eindhoven and Eindhoven University of Technology Eindhoven Jan Karel Lenstra Eindhoven University of Technology Eindhoven and CWI Amsterdam In the past three decades local search has grown from a simple heuristic idea into a mature field of research in combinatorial optimization Local search is still the method of choice for NP hard problems as it provides a robust approach for obtaining high quality solutions to problems of a realistic size in a reasonable time This area of discrete mathematics is of great practical use and is attracting ever increasing attention The contributions to this book cover local search and its variants from both a theoretical and practical point of view each with a chapter written by leading authorities on that particular aspect Chapters 1 to 7 deal with the theory of local search and describe the principal search strategies such as simulated annealing tabu search genetic algorithms and neural networks The remaining chapters present a wealth of results on applications of local search to problems in management science and engineering including the traveling salesman problem vehicle routing machine scheduling VLSI design and code design This book is an important reference volume and an invaluable source of inspiration for advanced students and researchers in discrete mathematics computer science operations research industrial engineering and management science *Genetic Local Search in Combinatorial Optimization* Anthonius Wilhelmus Johannes Kolen,Erwin Pesch,Rijksuniversiteit te Limburg. Faculty of Economics,1991* *Learning and Intelligent Optimization* Vittorio Maniezzo,Roberto Battiti,Jean-Paul Watson,2008-12-18 This book constitutes the thoroughly refereed post conference proceedings of the Second International Conference on Learning and Intelligent Optimization LION 2007 II held in Trento Italy in December 2007 The 18 revised full papers were carefully reviewed and selected from 48 submissions for inclusion in the book The papers cover current issues of machine learning artificial intelligence mathematical

programming and algorithms for hard optimization problems and are organized in topical sections on improving optimization through learning variable neighborhood search insect colony optimization applications new paradigms cliques stochastic optimization combinatorial optimization fitness and landscapes and particle swarm optimization **Clever Algorithms**

Jason Brownlee, 2011 This book provides a handbook of algorithmic recipes from the fields of Metaheuristics Biologically Inspired Computation and Computational Intelligence that have been described in a complete consistent and centralized manner These standardized descriptions were carefully designed to be accessible usable and understandable Most of the algorithms described in this book were originally inspired by biological and natural systems such as the adaptive capabilities of genetic evolution and the acquired immune system and the foraging behaviors of birds bees ants and bacteria An encyclopedic algorithm reference this book is intended for research scientists engineers students and interested amateurs Each algorithm description provides a working code example in the Ruby Programming Language **Uncertainty and Optimality**

J. C. Misra, 2002 This text deals with different modern topics in probability statistics and operations research Wherever necessary the theory is explained in great detail with illustrations Numerous references are given in order to help young researchers who want to start their work in a particular area The contributors are distinguished statisticians and operations research experts from all over the world Handbook of Memetic Algorithms Ferrante Neri, Carlos Cotta, Pablo Moscato, 2011-10-29 Memetic Algorithms MAs are computational intelligence structures combining multiple and various operators in order to address optimization problems The combination and interaction amongst operators evolves and promotes the diffusion of the most successful units and generates an algorithmic behavior which can handle complex objective functions and hard fitness landscapes Handbook of Memetic Algorithms organizes in a structured way all the the most important results in the field of MAs since their earliest definition until now A broad review including various algorithmic solutions as well as successful applications is included in this book Each class of optimization problems such as constrained optimization multi objective optimization continuous vs combinatorial problems uncertainties are analysed separately and for each problem memetic recipes for tackling the difficulties are given with some successful examples Although this book contains chapters written by multiple authors a great attention has been given by the editors to make it a compact and smooth work which covers all the main areas of computational intelligence optimization It is not only a necessary read for researchers working in the research area but also a useful handbook for practitioners and engineers who need to address real world optimization problems In addition the book structure makes it an interesting work also for graduate students and researchers in related fields of mathematics and computer science **Parallel Algorithms for Irregular Problems: State of the Art**

Alfonso Ferreira, José Rolim, 2013-04-17 Efficient parallel solutions have been found to many problems Some of them can be obtained automatically from sequential programs using compilers However there is a large class of problems irregular problems that lack efficient solutions IRREGULAR 94 a workshop and summer school

organized in Geneva addressed the problems associated with the derivation of efficient solutions to irregular problems This book which is based on the workshop draws on the contributions of outstanding scientists to present the state of the art in irregular problems covering aspects ranging from scientific computing discrete optimization and automatic extraction of parallelism Audience This first book on parallel algorithms for irregular problems is of interest to advanced graduate students and researchers in parallel computer science

Artificial Intelligence Methods and Applications Nikolaos G. Bourbakis, 1992 This volume is the first in a series which deals with the challenge of AI issues gives updates of AI methods and applications and promotes high quality new ideas techniques and methodologies in AI This volume contains articles by 38 specialists in various AI subfields covering theoretical and application issues

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