

# Practical Parallel Hypergraph Algorithms

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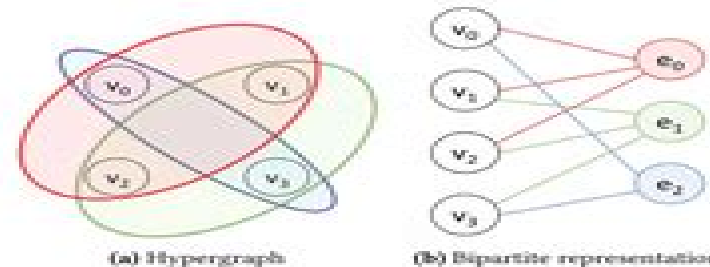
## Abstract

While there has been significant work on parallel graph processing, there has been very surprisingly little work on high-performance hypergraph processing. This paper presents a collection of efficient parallel algorithms for hypergraph processing, including algorithms for betweenness centrality, maximal independent set,  $k$ -core decomposition, hypertrees, hyperpaths, connected components, PageRank, and single-source shortest paths. For these problems, we either provide new parallel algorithms or more efficient implementations than prior work. Furthermore, our algorithms are theoretically-efficient in terms of work and depth. To implement our algorithms, we extend the Ligra graph processing framework to support hypergraphs, and our implementations benefit from graph optimizations including switching between sparse and dense traversals based on the frontier size, edge-aware parallelization, using buckets to prioritize processing of vertices, and compression. Our experiments on a 72-core machine and show that our algorithms obtain excellent parallel speedups, and are significantly faster than algorithms in existing hypergraph processing frameworks.

**CCS Concepts** • Computing methodologies → Parallel algorithms; Shared memory algorithms.

## 1 Introduction

A graph contains vertices and edges, where a vertex represents an entity of interest, and an edge between two vertices represents an interaction between the two corresponding entities. There has been significant work on developing algorithms and programming frameworks for efficient graph processing due to their applications in various domains, such as social network and Web analysis, cyber-security, and scientific computations. One limitation of modeling data using graphs is that only binary relationships can be expressed, and can lead to loss of information from the original data. Hypergraphs are a generalization of graphs where the relationships,



**Figure 1.** An example hypergraph representing the groups  $\{v_0, v_1, v_2\}$ ,  $\{v_1, v_2, v_3\}$ , and  $\{v_0, v_3\}$ , and its bipartite representation.

represented as *hyperedges*, can contain an arbitrary number of vertices. Hyperedges correspond to group relationships among vertices (e.g., a community in a social network). An example of a hypergraph is shown in Figure 1a.

Hypergraphs have been shown to enable richer analysis of structured data in various domains, such as protein network analysis [76], machine learning [100], and image processing [15, 27]. Various graph algorithms have been extended to the hypergraph setting, and we list some examples of algorithms and their applications here. Betweenness centrality on hypergraphs has been used for hierarchical community detection [12] and measuring importance of hypergraphs vertices [77].  $k$ -core decomposition in hypergraphs can be applied to invertible Bloom lookup tables, low-density parity-check codes, and set reconciliation [45]. PageRank and random walks on hypergraphs have been used for image segmentation and spectral clustering and shown to outperform graph-based methods [26, 27, 100]. Shortest paths, hyperpaths, and hypertrees have been used for solving optimization problems [30, 70], satisfiability problems and deriving functional dependencies in databases [30], and modeling information spread and finding important actors in social networks [31]. Independent sets on hypergraphs have been applied to routing problems [2] and determining satisfiability of boolean formulas [48].

Although there are many applications of hypergraphs, there has been little research on parallel hypergraph processing. The main contribution of this paper is a suite of efficient parallel hypergraph algorithms, including algorithms for betweenness centrality, maximal independent set,  $k$ -core

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# Practical Parallel Prog

**Julius T. Tou**



## **Practical Parallel Prog:**

*Practical Parallel Programming* Barr E. Bauer, 2014-06-28 This is the book that will teach programmers to write faster more efficient code for parallel processors The reader is introduced to a vast array of procedures and paradigms on which actual coding may be based Examples and real life simulations using these devices are presented in C and FORTRAN

**Practical Parallel Programming** Gregory V. Wilson, 1995-02-01 Practical Parallel Programming provides scientists and engineers with a detailed informative and often critical introduction to parallel programming techniques **Parallel**

**Programming** Bertil Schmidt, Jorge Gonzalez-Martinez, Christian Hundt, Moritz Schlarb, 2017-11-20 Parallel Programming Concepts and Practice provides an upper level introduction to parallel programming In addition to covering general parallelism concepts this text teaches practical programming skills for both shared memory and distributed memory architectures The authors open source system for automated code evaluation provides easy access to parallel computing resources making the book particularly suitable for classroom settings Covers parallel programming approaches for single computer nodes and HPC clusters OpenMP multithreading SIMD vectorization MPI UPC Contains numerous practical parallel programming exercises Includes access to an automated code evaluation tool that enables students the opportunity to program in a web browser and receive immediate feedback on the result validity of their program Features an example based teaching of concept to enhance learning outcomes **Practical Parallel Programming** Greg Wilson, *Practical*

*PRAM Programming* Jörg Keller, Christoph Keßler, Jesper Träff, 2001 Although PRAM Parallel Random Access Memory is a well known topic in parallel computing its practical application has rarely been explored This groundbreaking work changes all that Written by world experts on this technology it explains how to use PRAM to design algorithms for parallel computers and includes a number of PRAM implementations Readers can also use the book as a self study guide to parallel programming in general Introduction to Parallel Computing Roman Trobec, Boštjan Slivnik, Patricio Bulić, Borut

Robič, 2018-09-27 Advancements in microprocessor architecture interconnection technology and software development have fueled rapid growth in parallel and distributed computing However this development is only of practical benefit if it is accompanied by progress in the design analysis and programming of parallel algorithms This concise textbook provides in one place three mainstream parallelization approaches Open MPP MPI and OpenCL for multicore computers interconnected computers and graphical processing units An overview of practical parallel computing and principles will enable the reader to design efficient parallel programs for solving various computational problems on state of the art personal computers and computing clusters Topics covered range from parallel algorithms programming tools OpenMP MPI and OpenCL followed by experimental measurements of parallel programs run times and by engineering analysis of obtained results for improved parallel execution performances Many examples and exercises support the exposition Multicore Programming Using the ParC Language Yosi Ben-Asher, 2012-05-26 Multicore Programming Using the ParC Language discusses the principles of

practical parallel programming using shared memory on multicore machines It uses a simple yet powerful parallel dialect of C called ParC as the basic programming language Designed to be used in an introductory course in parallel programming and covering basic and advanced concepts of parallel programming via ParC examples the book combines a mixture of research directions covering issues in parallel operating systems and compilation techniques relevant for shared memory and multicore machines Multicore Programming Using the ParC Language provides a firm basis for the delicate art of creating efficient parallel programs Students can exercise parallel programming using a simulation software which is portable on PC Unix multicore computers to gain experience without requiring specialist hardware Students can also help to cement their learning by completing the great many challenging and exciting exercises which accompany each chapter *Strand: a Practical Parallel Programming Tool* Argonne National Laboratory. Mathematics and Computer Science Division, I. Foster, S. Taylor, 1989 *Parallel Programming* Mikhail S. Tarkov, 2014-01-11 Parallel programming is designed for the use of parallel computer systems for solving time consuming problems that cannot be solved on a sequential computer in a reasonable time These problems can be divided into two classes 1 Processing large data arrays including processing images and signals in real time 2 Simulation of complex physical processes and chemical reactions For each of these classes prospective methods are designed for solving problems For data processing one of the most promising technologies is the use of artificial neural networks Particles in cell method and cellular automata are very useful for simulation Problems of scalability of parallel algorithms and the transfer of existing parallel programs to future parallel computers are very acute now An important task is to optimise the use of the equipment including the CPU cache of parallel computers Along with parallelising information processing it is essential to ensure the processing reliability by the relevant organisation of systems of concurrent interacting processes From the perspective of creating qualitative parallel programs it is important to develop advanced methods of learning parallel programming The above reasons are the basis for the creation of this book chapters of which are devoted to solving these problems We hope this book will be of interest to researchers students and all those working in the field of parallel programming and high performance computing Elements of Parallel Computing Eric Aubanel, 2016-12-08 Designed for introductory parallel computing courses at the advanced undergraduate or beginning graduate level Elements of Parallel Computing presents the fundamental concepts of parallel computing not from the point of view of hardware but from a more abstract view of algorithmic and implementation patterns The aim is to facilitate the teaching of parallel programming by surveying some key algorithmic structures and programming models together with an abstract representation of the underlying hardware The presentation is friendly and informal The content of the book is language neutral using pseudocode that represents common programming language models The first five chapters present core concepts in parallel computing SIMD shared memory and distributed memory machine models are covered along with a brief discussion of what their execution models look like The book also discusses decomposition as a fundamental activity in

parallel algorithmic design starting with a naive example and continuing with a discussion of some key algorithmic structures. Important programming models are presented in depth as well as important concepts of performance analysis including work depth analysis of task graphs, communication analysis of distributed memory algorithms, key performance metrics and a discussion of barriers to obtaining good performance. The second part of the book presents three case studies that reinforce the concepts of the earlier chapters. One feature of these chapters is to contrast different solutions to the same problem using select problems that aren't discussed frequently in parallel computing textbooks. They include the Single Source Shortest Path Problem, the Eikonal equation and a classical computational geometry problem: computation of the two dimensional convex hull. After presenting the problem and sequential algorithms, each chapter first discusses the sources of parallelism, then surveys parallel algorithms.

**Parallel Programming with Intel Parallel Studio XE** Stephen Blair-Chappell, Andrew Stokes, 2012-04-19. Optimize code for multi-core processors with Intel's Parallel Studio. Parallel programming is rapidly becoming a must-know skill for developers. Yet where to start? This teach-yourself tutorial is an ideal starting point for developers who already know Windows C and C++ and are eager to add parallelism to their code. With a focus on applying tools, techniques and language extensions to implement parallelism, this essential resource teaches you how to write programs for multicore and leverage the power of multicore in your programs. Sharing hands-on case studies and real-world examples, the authors examine the challenges of each project and show you how to overcome them. Explores conversion of serial code to parallel. Focuses on implementing Intel Parallel Studio. Highlights the benefits of using parallel code. Addresses error and performance optimization of code. Includes real-world scenarios that illustrate the techniques of advanced parallel programming situations. Parallel Programming with Intel Parallel Studio dispels any concerns of difficulty and gets you started creating faster code with Intel Parallel Studio.

*High Performance Computing and the Art of Parallel Programming* Stan Openshaw, Ian Turton, 2005-09-19. This book provides a non-technical introduction to High Performance Computing applications together with advice about how beginners can start to write parallel programs. The authors show what HPC can offer geographers and social scientists and how it can be used in GIS. They provide examples of where it has already been used and suggestions for other areas of application in geography and the social sciences. Case studies drawn from geography explain the key principles and help to understand the logic and thought processes that lie behind the parallel programming.

The Role of Risk and Information in Consumption and Savings Antonella Tutino, 2009. This book studies the implications of information processing limits on the consumption and savings behaviour of households through time. It presents a dynamic model in which consumers rationally choose the size and scope of the information they want to process concerning their financial possibilities constrained by a Shannon channel. The model predicts that people with higher degrees of risk aversion rationally choose more information. This happens for precautionary reasons since with finite processing rate risk-averse consumers prefer to be well informed about their financial possibilities before implementing a consumption plan. Moreover

numerical results show that consumers with processing capacity constraints have asymmetric responses to shocks with negative shocks producing more persistent effects than positive ones This asymmetry results in more savings The author shows that the predictions of the model can be effectively used to study the impact of tax reforms on consumers spending

**Programming Your GPU with OpenMP** Tom Deakin, Timothy G. Mattson, 2023-11-07 The essential guide for writing portable parallel programs for GPUs using the OpenMP programming model Today's computers are complex multi-architecture systems multiple cores in a shared address space graphics processing units GPUs and specialized accelerators To get the most from these systems programs must use all these different processors In Programming Your GPU with OpenMP Tom Deakin and Timothy Mattson help everyone from beginners to advanced programmers learn how to use OpenMP to program a GPU using just a few directives and runtime functions Then programmers can go further to maximize performance by using CPUs and GPUs in parallel true heterogeneous programming And since OpenMP is a portable API the programs will run on almost any system Programming Your GPU with OpenMP shares best practices for writing performance portable programs Key features include The most up to date APIs for programming GPUs with OpenMP with concepts that transfer to other approaches for GPU programming Written in a tutorial style that embraces active learning so that readers can make immediate use of what they learn via provided source code Builds the OpenMP GPU Common Core to get programmers to serious production level GPU programming as fast as possible Additional features A reference guide at the end of the book covering all relevant parts of OpenMP 5.2 An online repository containing source code for the example programs from the book provided in all languages currently supported by OpenMP C, C++ and Fortran Tutorial videos and lecture slides

**Structured Parallel Programming** Michael McCool, James Reinders, Arch Robison, 2012-07-31 Structured Parallel Programming offers the simplest way for developers to learn patterns for high performance parallel programming Written by parallel computing experts and industry insiders Michael McCool Arch Robison and James Reinders this book explains how to design and implement maintainable and efficient parallel algorithms using a composable structured scalable and machine independent approach to parallel computing It presents both theory and practice and provides detailed concrete examples using multiple programming models The examples in this book are presented using two of the most popular and cutting edge programming models for parallel programming Threading Building Blocks and Cilk Plus These architecture independent models enable easy integration into existing applications preserve investments in existing code and speed the development of parallel applications Examples from realistic contexts illustrate patterns and themes in parallel algorithm design that are widely applicable regardless of implementation technology Software developers computer programmers and software architects will find this book extremely helpful The patterns based approach offers structure and insight that developers can apply to a variety of parallel programming models Develops a composable structured scalable and machine independent approach to parallel computing Includes detailed examples in both Cilk Plus and the latest Threading

Building Blocks which support a wide variety of computers      **Computational Science - ICCS 2006** Vassil N. Alexandrov, G. Dick van Albada, Peter M.A. Sloot, J. J. Dongarra, 2006-05-12 This is Volume II of the four volume set LNCS 3991 3994 constituting the refereed proceedings of the 6th International Conference on Computational Science ICCS 2006 The 98 revised full papers and 29 revised poster papers of the main track presented together with 500 accepted workshop papers were carefully reviewed and selected for inclusion in the four volumes The coverage spans the whole range of computational science      Emphasizing Distributed Systems, 2000-06-29 As the computer industry moves into the 21st century the long running *Advances in Computers* is ready to tackle the challenges of the new century with insightful articles on new technology just as it has since 1960 in chronicling the advances in computer technology from the last century As the longest running continuing series on computers *Advances in Computers* presents those technologies that will affect the industry in the years to come In this volume the 53rd in the series we present 8 relevant topics The first three represent a common theme on distributed computing systems using more than one processor to allow for parallel execution and hence completion of a complex computing task in a minimal amount of time The other 5 chapters describe other relevant advances from the late 1990s with an emphasis on software development topics of vital importance to developers today process improvement measurement and legal liabilities Longest running series on computers Contains eight insightful chapters on new technology Gives comprehensive treatment of distributed systems Shows how to evaluate measurements Details how to evaluate software process improvement models Examines how to expand e commerce on the Web Discusses legal liabilities in developing software a must read for developers      *High Performance Heterogeneous Computing* Jack Dongarra, Alexey L. Lastovetsky, 2009-08-11 An analytical overview of the state of the art open problems and future trends in heterogeneous parallel and distributed computing This book provides an overview of the ongoing academic research development and uses of heterogeneous parallel and distributed computing in the context of scientific computing Presenting the state of the art in this challenging and rapidly evolving area the book is organized in five distinct parts Heterogeneous Platforms Taxonomy Typical Uses and Programming Issues Performance Models of Heterogeneous Platforms and Design of Heterogeneous Algorithms Performance Implementation and Software Applications Future Trends High Performance Heterogeneous Computing is a valuable reference for researchers and practitioners in the area of high performance heterogeneous computing It also serves as an excellent supplemental text for graduate and postgraduate courses in related areas      *Advances in Information Systems Science* Julius T. Tou, 2012-12-06 Information systems science is rapidly advancing in many directions Diversified ideas methodologies and techniques as well as applications have been conceived and developed This series intends to discuss some of the recent advances in this field In this volume we cover four timely topics which are of great current interest In each chapter an attempt is made to familiarize the reader with some basic background information on the advances discussed The emphasis of this volume is placed upon parallel programming data structure models in information system

design and the principles of L systems One of the effective means to enhance computation performance is parallel information processing on multiprocessor systems In Chapter I V E Kotov discusses the practical aspects of parallel programming He is concerned with the languages and methods of parallel programming performance analysis and automatic synthesis of parallel programs In Chapter 2 A S Narinani presents the formal theory of parallel computations These two chapters attempt to correlate and classify various methods in parallel programming thus providing the reader with a unified approach to this important subject matter Data structures play an important role in information system design

Computational Logic: Logic Programming and Beyond A.C. Kakas, F. Sadri, 2003-08-02 Alan Robinson This set of essays pays tribute to Bob Kowalski on his 60th birthday an anniversary which gives his friends and colleagues an excuse to celebrate his career as an original thinker a charismatic communicator and a forceful intellectual leader The logic programming community hereby and herein conveys its respect and thanks to him for his pivotal role in creating and fostering the conceptual paradigm which is its raison d'être The diversity of interests covered here reflects the variety of Bob's concerns Read on It is an intellectual feast Before you begin permit me to send him a brief personal but public message Bob how right you were and how wrong I was I should explain When Bob arrived in Edinburgh in 1967 resolution was as yet fairly new having taken several years to become at all widely known Research groups to investigate various aspects of resolution sprang up at several institutions the one organized by Bernard Meltzer at Edinburgh University being among the first For the half dozen years that Bob was a leading member of Bernard's group I was a frequent visitor to it and I saw a lot of him We had many discussions about logic computation and language

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## **Table of Contents Practical Parallel Prog**

1. Understanding the eBook Practical Parallel Prog
  - The Rise of Digital Reading Practical Parallel Prog
  - Advantages of eBooks Over Traditional Books
2. Identifying Practical Parallel Prog
  - Exploring Different Genres
  - Considering Fiction vs. Non-Fiction
  - Determining Your Reading Goals
3. Choosing the Right eBook Platform
  - Popular eBook Platforms
  - Features to Look for in an Practical Parallel Prog
  - User-Friendly Interface
4. Exploring eBook Recommendations from Practical Parallel Prog
  - Personalized Recommendations

- Practical Parallel Prog User Reviews and Ratings
- Practical Parallel Prog and Bestseller Lists
- 5. Accessing Practical Parallel Prog Free and Paid eBooks
  - Practical Parallel Prog Public Domain eBooks
  - Practical Parallel Prog eBook Subscription Services
  - Practical Parallel Prog Budget-Friendly Options
- 6. Navigating Practical Parallel Prog eBook Formats
  - ePub, PDF, MOBI, and More
  - Practical Parallel Prog Compatibility with Devices
  - Practical Parallel Prog Enhanced eBook Features
- 7. Enhancing Your Reading Experience
  - Adjustable Fonts and Text Sizes of Practical Parallel Prog
  - Highlighting and Note-Taking Practical Parallel Prog
  - Interactive Elements Practical Parallel Prog
- 8. Staying Engaged with Practical Parallel Prog
  - Joining Online Reading Communities
  - Participating in Virtual Book Clubs
  - Following Authors and Publishers Practical Parallel Prog
- 9. Balancing eBooks and Physical Books Practical Parallel Prog
  - Benefits of a Digital Library
  - Creating a Diverse Reading Collection Practical Parallel Prog
- 10. Overcoming Reading Challenges
  - Dealing with Digital Eye Strain
  - Minimizing Distractions
  - Managing Screen Time
- 11. Cultivating a Reading Routine Practical Parallel Prog
  - Setting Reading Goals Practical Parallel Prog
  - Carving Out Dedicated Reading Time
- 12. Sourcing Reliable Information of Practical Parallel Prog
  - Fact-Checking eBook Content of Practical Parallel Prog

- Distinguishing Credible Sources
- 13. Promoting Lifelong Learning
  - Utilizing eBooks for Skill Development
  - Exploring Educational eBooks
- 14. Embracing eBook Trends
  - Integration of Multimedia Elements
  - Interactive and Gamified eBooks

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