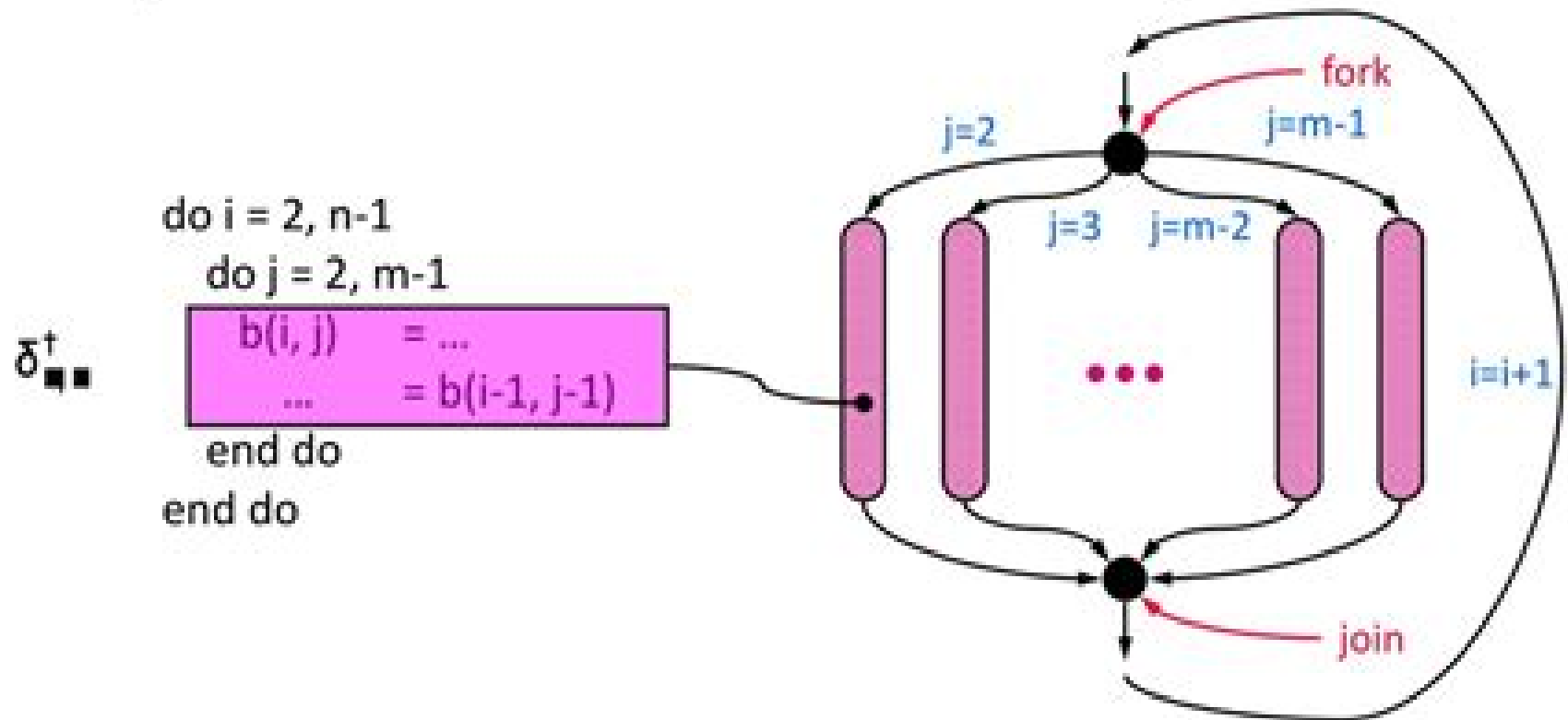


# Loop Parallelization - Example



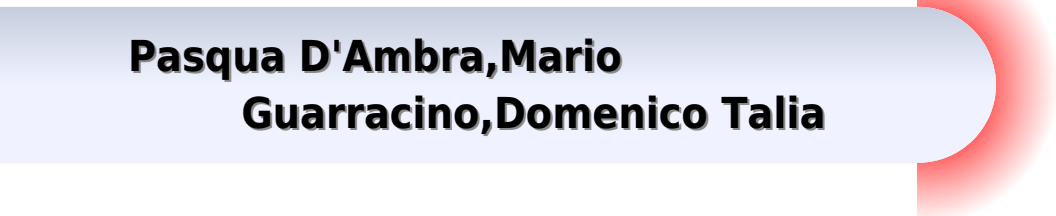
- Iterations of loop  $i$  must be executed sequentially, but the iterations of loop  $j$  may be executed in parallel.

Why?

- Inner loop parallelism.

# Loop Parallelization

**Pasqua D'Ambra, Mario  
Guarracino, Domenico Talia**



## **Loop Parallelization:**

**Loop Parallelization** Utpal Banerjee, 2013-06-29 Automatic transformation of a sequential program into a parallel form is a subject that presents a great intellectual challenge and promises a great practical award. There is a tremendous investment in existing sequential programs and scientists and engineers continue to write their application programs in sequential languages primarily in Fortran. The demand for higher speedups increases. The job of a restructuring compiler is to discover the dependence structure and the characteristics of the given machine. Much attention has been focused on the Fortran do loop. This is where one expects to find major chunks of computation that need to be performed repeatedly for different values of the index variable. Many loop transformations have been designed over the years and several of them can be found in any parallelizing compiler currently in use in industry or at a university research facility. The book series on KappaLoop Transformations for Restructuring Compilers provides a rigorous theory of loop transformations and dependence analysis. We want to develop the transformations in a consistent mathematical framework using objects like directed graphs, matrices, and linear equations. Then the algorithms that implement the transformations can be precisely described in terms of certain abstract mathematical algorithms. The first volume, Loop Transformations for Restructuring Compilers: The Foundations, provided the general mathematical background needed for loop transformations, including those basic mathematical algorithms discussed, data dependence, and introduced the major transformations. The current volume, Loop Parallelization, builds a detailed theory of iteration level loop transformations based on the material developed in the previous book.

**Automatic Parallelization** Samuel Midkiff, 2022-06-01 Compiling for parallelism is a longstanding topic of compiler research. This book describes the fundamental principles of compiling regular numerical programs for parallelism. We begin with an explanation of analyses that allow a compiler to understand the interaction of data reads and writes in different statements and loop iterations during program execution. These analyses include dependence analysis, use-def analysis, and pointer analysis. Next, we describe how the results of these analyses are used to enable transformations that make loops more amenable to parallelization and discuss transformations that expose parallelism to target shared memory, multicore, and vector processors. We then discuss some problems that arise when parallelizing programs for execution on distributed memory machines. Finally, we conclude with an overview of solving Diophantine equations and suggestions for further readings in the topics of this book to enable the interested reader to delve deeper into the field. Table of Contents: Introduction and overview; Dependence analysis: dependence graphs and alias analysis; Program parallelization: Transformations to modify and eliminate dependences; Transformation of iterative and recursive constructs; Compiling for distributed memory machines; Solving Diophantine equations; A guide to further reading.

[Symbolic Parallelization of Nested Loop Programs](#) Alexandru-Petru Tanase, Frank Hannig, Jürgen Teich, 2018-02-22 This book introduces new compilation techniques using the polyhedron model for the resource adaptive parallel execution of loop programs on massively parallel

processor arrays The authors show how to compute optimal symbolic assignments and parallel schedules of loop iterations at compile time for cases where the number of available cores becomes known only at runtime The compile runtime symbolic parallelization approach the authors describe reduces significantly the runtime overhead compared to dynamic or just in time compilation The new on demand fault tolerant loop processing approach described in this book protects loop nests for parallel execution against soft errors

Languages and Compilers for Parallel Computing Samuel P. Midkiff, Jose E. Moreira, Manish Gupta, Siddhartha Chatterjee, Jeanne Ferrante, Jan Prins, William Pugh, Chau-Wen Tseng, 2003-06-29 This volume contains the papers presented at the 13th International Workshop on Languages and Compilers for Parallel Computing It also contains extended abstracts of submissions that were accepted as posters The workshop was held at the IBM T J Watson Research Center in Yorktown Heights New York As in previous years the workshop focused on issues in optimizing compilers languages and software environments for high performance computing This continues a trend in which languages compilers and software environments for high performance computing and not strictly parallel computing has been the organizing topic As in past years participants came from Asia North America and Europe This workshop reflected the work of many people In particular the members of the steering committee David Padua Alex Nicolau Utpal Banerjee and David Gelernter have been instrumental in maintaining the focus and quality of the workshop since it was first held in 1988 in Urbana Champaign The assistance of the other members of the program committee Larry Carter Sid Chatterjee Jeanne Ferrante Jans Prins Bill Pugh and Chau wen Tseng was crucial The infrastructure at the IBM T J Watson Research Center provided trouble free logistical support The IBM T J Watson Research Center also provided financial support by underwriting much of the expense of the workshop Appreciation must also be extended to Marc Snir and Pratap Pattnaik of the IBM T J Watson Research Center for their support

*Parallel Processing and Applied Mathematics* Roman Wyrzykowski, Jack Dongarra, Ewa Deelman, Konrad Karczewski, 2018-03-22 The two volume set LNCS 10777 and 10778 constitutes revised selected papers from the 12th International Conference on Parallel Processing and Applied Mathematics PPAM 2017 held in Lublin Poland in September 2017 The 49 regular papers presented in this volume were selected from 98 submissions For the workshops and special sessions that were held as integral parts of the PPAM 2017 conference a total of 51 papers was accepted from 75 submissions The papers were organized in topical sections named as follows Part I numerical algorithms and parallel scientific computing particle methods in simulations task based paradigm of parallel computing GPU computing parallel non numerical algorithms performance evaluation of parallel algorithms and applications environments and frameworks for parallel distributed cloud computing applications of parallel computing soft computing with applications and special session on parallel matrix factorizations Part II workshop on models algorithms and methodologies for hybrid parallelism in new HPC systems workshop power and energy aspects of computations PEAC 2017 workshop on scheduling for parallel computing SPC 2017 workshop on language based parallel programming models WLPP 2017 workshop on PGAS

programming minisymposium on HPC applications in physical sciences minisymposium on high performance computing interval methods workshop on complex collective systems      **Introduction to Parallel Computing** Wesley Petersen, Peter Arbenz, 2004-01-08 In the last few years courses on parallel computation have been developed and offered in many institutions in the UK Europe and US as a recognition of the growing significance of this topic in mathematics and computer science There is a clear need for texts that meet the needs of students and lecturers and this book based on the author's lecture at ETH Zurich is an ideal practical student guide to scientific computing on parallel computers working up from a hardware instruction level to shared memory machines and finally to distributed memory machines Aimed at advanced undergraduate and graduate students in applied mathematics computer science and engineering subjects covered include linear algebra fast Fourier transform and Monte Carlo simulations including examples in C and in some cases Fortran This book is also ideal for practitioners and programmers      Languages and Compilers for Parallel Computing Utpal

Banerjee, 1993-12-08 The articles in this volume are revised versions of the best papers presented at the Fifth Workshop on Languages and Compilers for Parallel Computing held at Yale University August 1992 The previous workshops in this series were held in Santa Clara 1991 Irvine 1990 Urbana 1989 and Ithaca 1988 As in previous years a reasonable cross section of some of the best work in the field is presented The volume contains 35 papers mostly by authors working in the U S or Canada but also by authors from Austria Denmark Israel Italy Japan and the U K      *Languages and Compilers for Parallel Computing* James Brodman, Peng Tu, 2015-04-30 This book constitutes the thoroughly refereed post conference proceedings of the 27th International Workshop on Languages and Compilers for Parallel Computing LCPC 2014 held in Hillsboro OR USA in September 2014 The 25 revised full papers were carefully reviewed and selected from 39 submissions The papers are organized in topical sections on accelerator programming algorithms for parallelism compilers debugging vectorization

**Compiler Optimizations for Scalable Parallel Systems** Santosh Pande, Dharma P. Agrawal, 2003-06-29 Scalable parallel systems or more generally distributed memory systems offer a challenging model of computing and pose fascinating problems regarding compiler optimization ranging from language design to run time systems Research in this area is foundational to many challenges from memory hierarchy optimizations to communication optimization This unique handbook like monograph assesses the state of the art in the area in a systematic and comprehensive way The 21 coherent chapters by leading researchers provide complete and competent coverage of all relevant aspects of compiler optimization for scalable parallel systems The book is divided into five parts on languages analysis communication optimizations code generation and run time systems This book will serve as a landmark source for education information and reference to students practitioners professionals and researchers interested in updating their knowledge about or active in parallel computing      **Instruction Level Parallelism** Alex Aiken, Utpal Banerjee, Arun Kejariwal, Alexandru Nicolau, 2016-11-26 This book precisely formulates and simplifies the presentation of Instruction Level Parallelism ILP compilation techniques It uniquely offers consistent and

uniform descriptions of the code transformations involved Due to the ubiquitous nature of ILP in virtually every processor built today from general purpose CPUs to application specific and embedded processors this book is useful to the student the practitioner and also the researcher of advanced compilation techniques With an emphasis on fine grain instruction level parallelism this book will also prove interesting to researchers and students of parallelism at large in as much as the techniques described yield insights that go beyond superscalar and VLIW Very Long Instruction Word machines compilation and are more widely applicable to optimizing compilers in general ILP techniques have found wide and crucial application in Design Automation where they have been used extensively in the optimization of performance as well as area and power minimization of computer designs

### **Shared Memory Parallel Programming with Open MP** Barbara M.

Chapman, 2005-01-25 This book contains the Proceedings of the 5th Workshop on OpenMP Applications and Tools

WOMPAT2004 which took place at the University of Houston Houston Texas on May 17 and 18 2004 Previous workshops in this series took place in Toronto Canada Fairbanks Alaska Purdue Indiana and San Diego California

The purpose of the workshop was to bring together users and developers of the OpenMP API for shared memory parallel programming to disseminate their ideas and experiences and discuss the latest developments in OpenMP and its application To support this aim the program comprised a mixture of invited talks from research and industry experience reports and submitted papers the last of which are presented in this volume A tutorial introduction to OpenMP was held at the same location on May 18 by Ruud van der Pas from Sun Microsystems Further a two day lab session called OMPlab was held immediately following the workshop and the tutorial on May 19 and 20 and was attended by both novice and advanced users Many of the hardware vendors and several researchers gave in depth tutorials on their

software and made their systems available to both novice and advanced attendees during OMPlab Contributors to the WOMPAT 2004 OMPlab included IBM Intel Sun the University of Tennessee NASA the University of Greenwich Cornell University the University of Oregon and the University of Houston The OpenMP API is a widely accepted standard for high level shared memory parallel programming that was put forth by a consortium of vendors in 1997

### **Software Engineering for Parallel and Distributed Systems** Innes Jelly, Ian Gorton, Peter Croll, 2016-01-09

A wide range of modern computer applications require the performance and flexibility of parallel and distributed systems Better software support is required if the technical advances in these systems are to be fully exploited by commerce and industry This involves the provision of specialised techniques and tools as well as the integration of standard software engineering methods This book will reflect current advances in this area and will address issues of theory and practice with contributions from academia and industry It is the aim of the book to provide a focus for information on this developing which will be of use to both researchers and practitioners

### **Languages and Compilers for Parallel Computing**

Chua-Huang Huang, 1996-01-24 This book presents the refereed proceedings of the Eighth Annual Workshop on Languages and Compilers for Parallel Computing held in

Columbus Ohio in August 1995 The 38 full revised papers presented were carefully selected for inclusion in the proceedings and reflect the state of the art of research and advanced applications in parallel languages restructuring compilers and runtime systems The papers are organized in sections on fine grain parallelism interprocedural analysis program analysis Fortran 90 and HPF loop parallelization for HPF compilers tools and libraries loop level optimization automatic data distribution compiler models irregular computation object oriented and functional parallelism Exploitation of Fine-Grain Parallelism Günter Böckle,1995-07-18 Many parallel computer architectures are especially suited for particular classes of applications However there are only a few parallel architectures equally well suited for standard programs Much effort is invested into research in compiler techniques to make programming parallel machines easier This book presents methods for automatic parallelization so that programs need not to be tailored for specific architectures here the focus is on fine grain parallelism offered by most new microprocessor architectures The book addresses compiler writers computer architects and students by demonstrating the manifold complex relationships between architecture and compiler technology

*Encyclopedia of Parallel Computing* David Padua,2011-09-08 Containing over 300 entries in an A Z format the Encyclopedia of Parallel Computing provides easy intuitive access to relevant information for professionals and researchers seeking access to any aspect within the broad field of parallel computing Topics for this comprehensive reference were selected written and peer reviewed by an international pool of distinguished researchers in the field The Encyclopedia is broad in scope covering machine organization programming languages algorithms and applications Within each area concepts designs and specific implementations are presented The highly structured essays in this work comprise synonyms a definition and discussion of the topic bibliographies and links to related literature Extensive cross references to other entries within the Encyclopedia support efficient user friendly searchers for immediate access to useful information Key concepts presented in the Encyclopedia of Parallel Computing include laws and metrics specific numerical and non numerical algorithms asynchronous algorithms libraries of subroutines benchmark suites applications sequential consistency and cache coherency machine classes such as clusters shared memory multiprocessors special purpose machines and dataflow machines specific machines such as Cray supercomputers IBM s cell processor and Intel s multicore machines race detection and auto parallelization parallel programming languages synchronization primitives collective operations message passing libraries checkpointing and operating systems Topics covered Speedup Efficiency Isoefficiency Redundancy Amdahls law Computer Architecture Concepts Parallel Machine Designs Benmarks Parallel Programming concepts design Algorithms Parallel applications This authoritative reference will be published in two formats print and online The online edition features hyperlinks to cross references and to additional significant research Related Subjects supercomputing high performance computing distributed computing **Euro-Par 2002. Parallel Processing** Burkhard Monien,2002-08-21 This book constitutes the refereed proceedings of the 8th European Conference on Parallel Computing Euro Par 2002 held in

Paderborn Germany in August 2002 The 67 revised full papers and 55 research note papers presented together with 6 invited papers were carefully reviewed and selected from 265 submissions The papers presented give a unique survey of the state of the art in parallel computing research ranging from algorithms software hardware and application in various fields

**Euro-Par 2010 - Parallel Processing** Pasqua D'Ambra, Mario Guarracino, Domenico Talia, 2010-09-02 Annotation This book constitutes the refereed proceedings of the 16th International Euro Par Conference held in Ischia Italy in August September 2010 The 90 revised full papers presented were carefully reviewed and selected from 256 submissions The papers are organized in topical sections on support tools and environments performance prediction and evaluation scheduling and load balancing high performance architectures and compilers parallel and distributed data management grid cluster and cloud computing peer to peer computing distributed systems and algorithms parallel and distributed programming parallel numerical algorithms multicore and manycore programming theory and algorithms for parallel computation high performance networks and mobile and ubiquitous computing

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Keshav Pingali, 1995-01-26 This volume presents revised versions of the 32 papers accepted for the Seventh Annual Workshop on Languages and Compilers for Parallel Computing held in Ithaca NY in August 1994 The 32 papers presented report on the leading research activities in languages and compilers for parallel computing and thus reflect the state of the art in the field The volume is organized in sections on fine grain parallelism alignment and distribution postlinear loop transformation parallel structures program analysis computer communication automatic parallelization languages for parallelism scheduling and program optimization and program evaluation

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**Symbolic Analysis for Parallelizing Compilers** Mohammad R.

Haghighat, 2007-08-19 In Symbolic Analysis for Parallelizing Compilers the author presents an excellent demonstration of the effectiveness of symbolic analysis in tackling important optimization problems some of which inhibit loop parallelization The framework that Haghighat presents has proved extremely successful in induction and wraparound variable analysis strength reduction dead code elimination and symbolic constant propagation The approach can be applied to any program transformation or optimization problem that uses properties and value ranges of program names Symbolic analysis can be used on any transformational system or optimization problem that relies on compile time information about program variables This covers the majority of if not all optimization and parallelization techniques The book makes a compelling case for the potential of symbolic analysis applying it for the first time and with remarkable results to a number of classical optimization problems loop scheduling static timing or size analysis and dependence analysis It demonstrates how symbolic analysis can solve these problems faster and more accurately than existing hybrid techniques



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