Data-Flow Algorithms for Parallel Matrix Computations

DIANNE P. O'LEARY and G.W. STEWART

ABSTRACT: In this article we develop some algorithms and tools for solving matrix problems on parallel processing computers. Operations are synchronized through data-flow alone, which makes global synchronization unnecessary and enables the algorithms to be implemented on machines with very simple operating systems and communication protocols. As examples, we present algorithms that form the main modules for solving Liapounov matrix equations. We compare this approach to wave front array processors and systolic arrays, and note its advantages in handling missized problems, in evaluating variations of algorithms or architectures, in moving algorithms from system to system, and in debugging parallel algorithms on sequential machines.

1. INTRODUCTION

In this article we shall be concerned with algorithms partitioned into computational processes, called nodes, whose computations are triggered by the flow of data from neighboring nodes. Each node proceeds independently through cycles of waiting for data, computing, and sending data to other nodes. Such *data-flow algorithms* are well suited for parallel implementation on networks of processors, since they require no global control: once a data-flow algorithm is started, it continues to completion without the need for external intervention.

Our purpose is to describe how data-flow algorithms may be applied to the parallel solution of problems in numerical linear algebra. There are three reasons why such an article is timely. First, the data-flow paradigm places a large number of parallel matrix algorithms,

derived from different points of view, into a common framework. Second, these algorithms form a nontrivial test bed for general data-flow schemes. Here it is particularly important that most of the algorithms are adaptations of existing sequential algorithms with well established numerical properties, so that one can ignore rounding error analysis and concentrate on data-flow properties. Finally, a detailed consideration of how data-flow algorithms for matrix computations might be implemented suggests architectural features that would be desirable in a data-flow computer for matrix computations.

Because the term data-flow is used variously in the literature it is important that we specify at the outset what we mean by it. We shall essentially follow Treleaven, Brownbridge, and Hopkins [21] in regarding a data-flow algorithm as a collection of "instructions" in a directed graph that represents the flow of data between the instructions. Instructions execute only when the data they require have arrived. However, our "instructions" can be rather complex algorithm segments that can vary their input requirements and can direct their outputs to different instructions at different times.[*] To avoid confusion with the low-level instructions assumed in much of the data-flow literature, we shall call our instructions *computational nodes* (or, for short, simply *nodes*) and the graphs in which they lie *computational networks*.

Parallel matrix algorithms are by no means new. Since the time of the ILLIAC IV, it has been recognized that many algorithms in numerical linear algebra have

[*] Formally, our model of computation is the same as the one described by Karp and Miller [9], with the exception that an operation is allowed to change the parameters related to the input queues and the quantity of the output.

Parallel Algorithms And Matrix Computation

Sanguthevar Rajasekaran,John Reif

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   Parallel Algorithms for Matrix Computations K. Gallivan,M. Heath,E. Ng,B. Peyton,R. Plemmons,J. Ortega,C. Romine,A. Sameh,R. Voigt,1990-01-01 Describes a selection of important parallel algorithms for matrix computations Reviews the current status and provides an overall perspective of parallel algorithms for solving problems arising in the major areas of numerical linear algebra including 1 direct solution of dense structured or sparse linear systems 2 dense or structured least squares computations 3 dense or structured eigenvaluen and singular value computations and 4 rapid elliptic solvers The book emphasizes computational primitives whose efficient execution on parallel and vector computers is essential to obtain high performance algorithms Consists of two comprehensive survey papers on important parallel algorithms for solving problems arising in the major areas of numerical linear algebra direct solution of linear systems least squares computations eigenvalue and singular value computations and rapid elliptic solvers plus an extensive up to date bibliography 2 000 items on related research   Parallel Algorithms and Matrix Computation Jagdish J. Modi,1988 An introduction to parallel computation and the application of parallel algorithms to numerical linear algebra based on a lecture course at the University of Cambridge The emphasis is on the design and analysis of algorithms which are of importance to industrial and academic research   **Parallelism in Matrix Computations** Efstratios Gallopoulos,Bernard Philippe,Ahmed H. Sameh,2015-07-25 This book is primarily intended as a research monograph that could also be used in graduate courses for the design of parallel algorithms in matrix computations It assumes general but not extensive knowledge of numerical linear algebra parallel architectures and parallel programming paradigms The book consists of four parts I Basics II Dense and Special Matrix Computations III Sparse Matrix Computations and IV Matrix functions and characteristics Part I deals with parallel programming paradigms and fundamental kernels including reordering schemes for sparse matrices Part II is devoted to dense matrix computations such as parallel algorithms for solving linear systems linear least squares the symmetric algebraic eigenvalue problem and the singular value decomposition It also deals with the development of parallel algorithms for special linear systems such as banded Vandermonde Toeplitz and block Toeplitz systems Part III addresses sparse matrix computations a the development of parallel iterative linear system solvers with emphasis on scalable preconditioners b parallel schemes for obtaining a few of the extreme eigenpairs or those contained in a given interval in the spectrum of a standard or generalized symmetric eigenvalue problem and c parallel methods for computing a few of the extreme singular triplets Part IV focuses on the development of parallel algorithms for matrix functions and special characteristics such as the matrix pseudospectrum and the determinant The book also reviews the theoretical and practical background necessary when designing these algorithms and includes an extensive bibliography that will be useful to researchers and students alike The book brings together many existing algorithms for the fundamental matrix computations that have a proven track record of efficient implementation in terms of data locality and data transfer on state of the art

systems as well as several algorithms that are presented for the first time focusing on the opportunities for parallelism and algorithm robustness **Parallel Algorithms for Numerical Linear Algebra** H. van der Vorst,P. van Dooren,2014-06-28 This is the first in a new series of books presenting research results and developments concerning the theory and applications of parallel computers including vector pipeline array fifth future generation computers and neural computers All aspects of high speed computing fall within the scope of the series e g algorithm design applications software engineering networking taxonomy models and architectural trends performance peripheral devices Papers in Volume One cover the main streams of parallel linear algebra systolic array algorithms message passing systems algorithms for parallel shared memory systems and the design of fast algorithms and implementations for vector supercomputers <u>Parallel Processing and Parallel Algorithms</u> Seyed H Roosta,2012-12-06 Motivation It is now possible to build powerful single processor and multiprocessor systems and use them efficiently for data processing which has seen an explosive ex pansion in many areas of computer science and engineering One approach to meeting the performance requirements of the applications has been to utilize the most powerful single processor system that is available When such a system does not provide the performance requirements pipelined and parallel process ing structures can be employed The concept of parallel processing is a depar ture from sequential processing In sequential computation one processor is in volved and performs one operation at a time On the other hand in parallel computation several processors cooperate to solve a problem which reduces computing time because several operations can be carried out simultaneously Using several processors that work together on a given computation illustrates a new paradigm in computer problem solving which is completely different from sequential processing From the practical point of view this provides sufficient justification to investigate the concept of parallel processing and related issues such as parallel algorithms Parallel processing involves utilizing several factors such as parallel architectures parallel algorithms parallel programming lan guages and performance analysis which are strongly interrelated In general four steps are involved in performing a computational problem in parallel The first step is to understand the nature of computations in the specific application domain <u>Parallel Algorithms for Linear Models</u> Erricos Kontoghiorghes,2000-01-31 Parallel Algorithms for Linear Models provides a complete and detailed account of the design analysis and implementation of parallel algorithms for solving large scale linear models It investigates and presents efficient numerically stable algorithms for computing the least squares estimators and other quantities of interest on massively parallel systems The monograph is in two parts The first part consists of four chapters and deals with the computational aspects for solving linear models that have applicability in diverse areas The remaining two chapters form the second part which concentrates on numerical and computational methods for solving various problems associated with seemingly unrelated regression equations SURE and simultaneous equations models The practical issues of the parallel algorithms and the theoretical aspects of the numerical methods will be of interest to a broad range of researchers working in the areas of

numerical and computational methods in statistics and econometrics parallel numerical algorithms parallel computing and numerical linear algebra The aim of this monograph is to promote research in the interface of econometrics computational statistics numerical linear algebra and parallelism   **Parallel Algorithms in Computational Science and Engineering** Ananth Grama,Ahmed H. Sameh,2020-07-06 This contributed volume highlights two areas of fundamental interest in high performance computing core algorithms for important kernels and computationally demanding applications The first few chapters explore algorithms numerical techniques and their parallel formulations for a variety of kernels that arise in applications The rest of the volume focuses on state of the art applications from diverse domains By structuring the volume around these two areas it presents a comprehensive view of the application landscape for high performance computing while also enabling readers to develop new applications using the kernels Readers will learn how to choose the most suitable parallel algorithms for any given application ensuring that theory and practicality are clearly connected Applications using these techniques are illustrated in detail including Computational materials science and engineering Computational cardiovascular analysis Multiscale analysis of wind turbines and turbomachinery Weather forecasting Machine learning techniques Parallel Algorithms in Computational Science and Engineering will be an ideal reference for applied mathematicians engineers computer scientists and other researchers who utilize high performance computing in their work

Analysis and Design of Parallel Algorithms S. Lakshmivarahan,Sudarshan Kumar Dhall,1990   *Parallel Algorithms* Henri Casanova,Arnaud Legrand,Yves Robert,2008-07-17 Focusing on algorithms for distributed memory parallel architectures Parallel Algorithms presents a rigorous yet accessible treatment of theoretical models of parallel computation parallel algorithm design for homogeneous and heterogeneous platforms complexity and performance analysis and essential notions of scheduling The book extract   **Handbook of Parallel Computing** Sanguthevar Rajasekaran,John Reif,2007-12-20 The ability of parallel computing to process large data sets and handle time consuming operations has resulted in unprecedented advances in biological and scientific computing modeling and simulations Exploring these recent developments the Handbook of Parallel Computing Models Algorithms and Applications provides comprehensive coverage on a   **Parallel Processing and Parallel Algorithms** Seyed H Roosta,1999-12-10 Motivation It is now possible to build powerful single processor and multiprocessor systems and use them efficiently for data processing which has seen an explosive ex pansion in many areas of computer science and engineering One approach to meeting the performance requirements of the applications has been to utilize the most powerful single processor system that is available When such a system does not provide the performance requirements pipelined and parallel process ing structures can be employed The concept of parallel processing is a depar ture from sequential processing In sequential computation one processor is in volved and performs one operation at a time On the other hand in parallel computation several processors cooperate to solve a problem which reduces computing time because several operations can be carried out simultaneously Using several

processors that work together on a given computation illustrates a new paradigm in computer problem solving which is completely different from sequential processing From the practical point of view this provides sufficient justification to investigate the concept of parallel processing and related issues such as parallel algorithms Parallel processing involves utilizing several factors such as parallel architectures parallel algorithms parallel programming lan guages and performance analysis which are strongly interrelated In general four steps are involved in performing a computational problem in parallel The first step is to understand the nature of computations in the specific application domain   **Parallel Algorithms** Pranay Chaudhuri,1992 Mathematics of Computing Parallelism   **Parallel Matrix Computations** G. W. Stewart,Dianne P. O'Leary,MARYLAND UNIV COLLEGE PARK DEPT OF COMPUTER SCIENCE.,MARYLAND UNIV COLLEGE PARK.,1985 This project concerns the design and analysis of algorithms to be run in a processor rich environment It focuses primarily on algorithms that require no global control and that can be run on systems with only local connections among processors The properties of these algorithms both theoretically and experimentally are investigated The experimental work is done on the ZMOB a working parallel computer operated by the Laboratory for Parallel Computation of the Computer Science Department at the University of Maryland The emphasis is on two areas 1 Dense problems from numerical linear algebra and 2 The iterative and direct solution of sparse linear systems Additional keywords parallel algorithms and software development   <u>The Characteristics of Parallel Algorithms</u> Leah H. Jamieson,Dennis B. Gannon,Robert J. Douglass,1987 Mathematics of Computing Parallelism   **Parallel Scientific Computing and Optimization** Raimondas Ciegis,David Henty,Bo Kågström,Julius Žilinskas,2008-10-08 Parallel Scientific Computing and Optimization introduces new developments in the construction analysis and implementation of parallel computing algorithms This book presents 23 self contained chapters including survey chapters and surveys written by distinguished researchers in the field of parallel computing Each chapter is devoted to some aspects of the subject parallel algorithms for matrix computations parallel optimization management of parallel programming models and data with the largest focus on parallel scientific computing in industrial applications This volume is intended for scientists and graduate students specializing in computer science and applied mathematics who are engaged in parallel scientific computing   **Polynomial and Matrix Computations: Fundamental algorithms** Dario Bini,1994   *PARALLEL ALGORITHMS FOR SOLVING AGGREGATED SHORTEST PATH PROBLEMS* H. Edwin Romeijin,1993   *Parallel Scientific Computing and Optimization* Raimondas Ciegis,David Henty,Bo Kågström,Julius Žilinskas,2008-11-21 Parallel Scientific Computing and Optimization introduces new developments in the construction analysis and implementation of parallel computing algorithms This book presents 23 self contained chapters including survey chapters and surveys written by distinguished researchers in the field of parallel computing Each chapter is devoted to some aspects of the subject parallel algorithms for matrix computations parallel optimization management of parallel programming models and data with the largest focus on parallel scientific computing in industrial applications This volume is intended for

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