Design and Analysis of Algorithms

The text introduces readers to different paradigms of computing in addition to the traditional approach of discussing fundamental computational problems and design techniques in the random access machine model. Alternate models of computation including parallel, cache-sensitive design and streaming algorithms are dealt in separate chapters to underline the significant role of the underlying computational environment in the algorithm design. The treatment is made rigorous by demonstrating new measures of performances along with matching lower bound arguments.

The importance of greedy algorithms, divide-and-conquer technique and dynamic programming is highlighted by additional applications to approximate algorithms that come with guarantees. In addition to several classical techniques, the book encourages liberal use of probabilistic analysis and randomized techniques that have been pivotal for many recent advances in this area. There is also a chapter introducing techniques for dimension reduction which is at the heart of many interesting applications in data analytics as well as statistical machine learning. While these techniques have been known for a while in other communities, their adoption into mainstream computer science has been relatively recent.

Concepts are discussed with the help of rigorous mathematical proofs, theoretical explanations and their limitations. Problems have been chosen from a diverse landscape including graphs, geometry, strings, algebra and optimization. Some exposition of approximation algorithms has also been included, which has been a very active area of research in algorithms. Real life applications and numerical problems are spread throughout the text. The reader is expected to test her understanding by trying out a large number of exercise problems accompanying every chapter.

The book assumes familiarity with basic data structures, to focus on more algorithmic aspects and topics of contemporary importance.

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A Contemporary Perspective

Sandeep Sen
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To the loving memory of my parents, Sisir Sen and Krishna Sen who nourished and inspired my academic pursuits and all my teachers who helped me imbibe the beauty and intricacies of various subjects

– Sandeep Sen

To my parents

– Amit Kumar

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978-1-108-49682-7 — Design and Analysis of Algorithms
Sandeep Sen , Amit Kumar
Frontmatter
More Information

Content

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Frontmatter
More Information

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More Information

Figures

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Frontmatter
More Information

Tables

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Frontmatter
More Information

Preface

This book embodies a distillation of topics that we, as educators, have frequently covered in the past two decades in various postgraduate and undergraduate courses related to *Design and Analysis of Algorithms* in IIT Delhi. The primary audience were the junior level (3rd year) computer science (CS) students and the first semester computer science post-graduate students. This book can also serve the purpose of material for a more advanced level algorithm course where the reader is exposed to alternate and more contemporary computational frameworks that are becoming common and more suitable.

A quick glance through the contents will reveal that about half of the topics are covered by many standard textbooks on algorithms like those by Aho et al. [7], Horowitz et al. [65], Cormen et al. [37], and more recent ones like those by Kleinberg and Tardos [81] and Dasgupta et al. [40]. The first classic textbook in this area, viz., that by Aho et al., introduces the subject with the observation 'The study of algorithms is at the very heart of computer science' and this observation has been reinforced over the past five decades of rapid development of computer science as well as of the more applied field of information technology. Because of its foundational nature, many of the early algorithms discovered about five decades ago continue to be included in every textbook written including this one – for example, algorithms like FFT, quicksort, Dijkstra's shortest paths, etc.

What motivated us to write another book on algorithms are the several important and subtle changes in the understanding of many computational paradigms and the relative importance of techniques emerging out of some spectacular discoveries and changing technologies. As teachers and mentors, it is our responsibility to inculcate the right focus in the younger generation so that they continue to enjoy this intellectually critical activity and contribute to the enhancement of the field of study. As more and more human activities are becoming computer-assisted, it becomes obligatory to emphasize and reinforce the importance of efficient and faster algorithms, which is the core of any automated process. We are often limited and endangered by the instictive use of ill-designed and brute force algorithms, which are often erroneous, leading to fallacious scientific conclusions or incorrect policy decisions. It is therefore important to introduce some formal aspects of algorithm design and analysis into the school curriculum at par with maths and science, and sensitize students about this subject.

Who can use it

The present book is intended for students who have acquired skills in programming as well as basic data structures like arrays, stacks, lists, and even some experience with balanced trees. The authors, with a long experience behind them in teaching this subject, are convinced that algorithm design can be a deceptively hard subject and a gentle exposure is important for, both, understanding and sustaining interest. In IIT Delhi, CS undergraduates do a course in programming followed by a course in data structures with some exposure to basic algorithmic techniques. This book is intended for students having this background and so we have avoided any formal introduction of basic data structures including elementary graph searching methods like BFS/DFS. Instead, the book focusses on a mathematical treatment of the previously acquired knowledge and emphasizes a clean and crisp analysis of any new idea and technique. The CS students in IIT Delhi would have done a course in discrete mathematics and probability before they do this course. The design of efficient algorithms go hand-in-hand with our ability to quickly screen intuitions that lead to poor algorithms – both in terms of efficiency and correctness. We have consciously avoided topics that require long and dry formalism, although we have emphasized rigor at every juncture.

An important direction that we have pursued is based on the significance of adapting algorithm design to the computational environment. Although there has been a long history of research in designing algorithms for real-world models such as parallel and cache-hierarchy models, these have remained in the realms of niche and specialized graduate courses. The tacit assumption in basic textbooks is that we are dealing with uniform cost random access machines (RAMs). It is our firm belief that algorithm design is as much a function of the specific problem as the target model of execution, and failing to recognize this aspect makes the exercise somewhat incomplete and ineffective. Therefore, trying to execute the textbook data structures on a distributed model or Dijkstra's algorithm in a parallel computer would be futile. In summary,

$$Algorithms = ProblemDefinition + Model$$

The last three chapters specifically address three very important environments, namely parallel computing, memory hierarchy, and streaming. They form the core of a course taught in IIT Delhi, *Model Centric Algorithm Design* – some flavor can add diversity to a core course in algorithms. Of course, any addition to a course would imply proportionate exclusion of some other equally important topic – so it is eventually the instructor's choice.

Another recurring theme in the book is the liberal use of randomized techniques in algorithm design. To help students appreciate this aspect, we have described some basic tools and applications in Chapter 2. Even for students who are proficient in the use of probabilistic calculations (we expect all CS majors to have one college level course in probability), may find these applications somewhat non-intuitive and surprising – however, this may also turn into a very versatile and useful tool for anyone who is mathematically minded.

The other major development over the past decade is an increasing popularity of algebraic (particularly spectral) methods for combinatorial problems. This has made the role of conventional continuous mathematics more relevant and important. Reconciling and bridging the two distinct worlds of discrete and continuous methods is a huge challenge to even an experienced researcher, let alone an average student. It is too difficult to address this in a book like ours but we have tried to present some flavor in Chapter 12, which is an introduction to the technique of random projections.

Each chapter is followed by some brief discussion on some historical origins of the problem and pointers to relevant existing literature. The subsections/sections/chapters marked with * are more suitable for the advanced reader and may be skipped by others without loss of continuity.

One of the primary objectives of a course on algorithms is to encourage an appreciation for creativity without sacrificing rigor – this aspect makes algorithm design one of the most challenging and fascinating intellectual pursuit.

Suggested use of the chapters

The material presented in the sixteen chapters can be taught over two semesters at a leisurely pace, for example, in a two sequence course on algorithms. Alternately, for a first course on algorithms (with prior background in basic data structures), the instructor can choose majority portions from Chapters 3 to 11 and parts of Chapter 12. An advanced course can be taught using material from Chapters 12–16. Chapters 14–16 can form the crux of a course on *model centric algorithm design* which can be thought of as a more pragmatic exposure to theory of computation using contemporary frameworks.

Sandeep Sen
Amit Kumar
New Delhi, 2019

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Since typists have long become defunct, it is obligatory to acknowledge the contributions of Donald Knuth for TEX and Leslie Lamport's LATEX manual for the ease and convenience of writing such textbooks. For the sake of the environment and future of the world, we hope that long-term dissemination of such books will be in the electronic medium.