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Practical Optimization

Algorithms and Engineering Applications

Second Edition

Springer

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ISSN 1868-0941 ISSN 1868-095X (electronic)
Texts in Computer Science
ISBN 978-1-0716-0841-8 ISBN 978-1-0716-0843-2 (eBook)
https://doi.org/10.1007/978-1-0716-0843-2

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To
Lynne
and
Chi-Tang Catherine
with our love

Preface to the Second Edition

Optimization methods and algorithms continue to evolve at a tremendous rate and are providing solutions to many problems that could not be solved before in economics, finance, geophysics, molecular modeling, computational systems biology, operations research, and all branches of engineering (see the following link for details: https://en.wikipedia.org/wiki/Mathematical_optimization#Molecular_modeling).

The growing demand for optimization methods and algorithms has been addressed in the second edition by updating some material, adding more examples, and introducing some recent innovations, techniques, and methodologies. The emphasis continues to be on practical methods and efficient algorithms that work.

Chapters 1–8 continue to deal with the basics of optimization. Chapter 5 now includes two increasingly popular line search techniques, namely, the so-called *two-point* and *backtracking* line searches. In Chap. 6, a new section has been added that deals with the application of the conjugate-gradient method for the solution of linear systems of equations.

In Chap. 9, some state-of-the art applications of unconstrained optimization to machine learning and source localization are added. The first application is in the area of character recognition and it is a method for classifying handwritten digits using a regression technique known as *softmax*. The method is based on an accelerated gradient descent algorithm. The second application is in the area of communications and it deals of the problem formulation and solution methods for identifying the location of a radiating source given the distances between the source and several sensors.

The contents of Chaps. 10–12 are largely unchanged except for some editorial changes whereas Chap. 13 combines the material found in Chaps. 13 and 14 of the first edition.

Chapter 14 is a new chapter that presents additional concepts and properties of convex functions that are not covered in Chapter 2. It also describes several algorithms for the solution of general convex problems and includes a detailed exposition of the so-called *alternating direction method of multipliers (ADMM)*.

Chapter 15 is a new chapter that focuses on sequential convex programming, sequential quadratic programming, and convex-concave procedures for general nonconvex problems. It also includes a section on heuristic ADMM techniques for nonconvex problems.

In Chap. 16, we have added some new state-of-the art applications of constrained optimization for the design of Finite-Duration Impulse Response (FIR) and Infinite-Duration Impulse Response (IIR) digital filters, also known as nonrecursive and recursive filters, respectively, using second-order cone programming. Digital filters that would satisfy multiple specifications such as maximum passband gain, minimum stopband gain, maximum transition-band gain, and maximum pole radius, can be designed with these methods.

The contents of Appendices A and B are largely unchanged except for some editorial changes.

Many of our past students at the University of Victoria have helped a great deal in improving the first edition and some of them, namely, Drs. M. L. R. de Campos, Sunder Kidambi, Rajeev C. Nongpiur, Ana Maria Sevcenco, and Ioana Sevcenco have provided meaningful help in the evolution of the second edition as well. We would also like to thank Drs. Z. Dong, T. Hinamoto, Y. Q. Hu, and W. Xu for useful discussions on optimization theory and its applications, Catherine Chang for typesetting the first draft of the second edition, and to Lynne Barrett for checking the entire second edition for typographical errors.

Victoria, Canada

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Preface to the First Edition

The rapid advancements in the efficiency of digital computers and the evolution of reliable software for numerical computation during the past three decades have led to an astonishing growth in the theory, methods, and algorithms of numerical optimization. This body of knowledge has, in turn, motivated widespread applications of optimization methods in many disciplines, e.g., engineering, business, and science, and led to problem solutions that were considered intractable not too long ago.

Although excellent books are available that treat the subject of optimization with great mathematical rigor and precision, there appears to be a need for a book that provides a practical treatment of the subject aimed at a broader audience ranging from college students to scientists and industry professionals. This book has been written to address this need. It treats unconstrained and constrained optimization in a unified manner and places special attention on the algorithmic aspects of optimization to enable readers to apply the various algorithms and methods to specific problems of interest. To facilitate this process, the book provides many solved examples that illustrate the principles involved, and includes, in addition, two chapters that deal exclusively with applications of unconstrained and constrained optimization methods to problems in the areas of pattern recognition, control systems, robotics, communication systems, and the design of digital filters. For each application, enough background information is provided to promote the understanding of the optimization algorithms used to obtain the desired solutions.

Chapter 1 gives a brief introduction to optimization and the general structure of optimization algorithms. Chapters 2 to 9 are concerned with unconstrained optimization methods. The basic principles of interest are introduced in Chapter 2. These include the first-order and second-order necessary conditions for a point to be a local minimizer, the second-order sufficient conditions, and the optimization of convex functions. Chapter 3 deals with general properties of algorithms such as the concepts of descent function, global convergence, and rate of convergence. Chapter 4 presents several methods for one-dimensional optimization, which are commonly referred to as line searches. The chapter also deals with inexact line-search methods that have been found to increase the efficiency in many optimization algorithms. Chapter 5 presents several basic gradient methods that include the steepest-descent, Newton, and Gauss-Newton methods. Chapter 6 presents a class of methods based on the concept of conjugate directions such as the conjugate-gradient, Fletcher-Reeves, Powell, and Partan methods. An important class of unconstrained optimization methods known as quasi-Newton methods is presented in Chapter 7. Representative methods of this class such as the Davidon-Fletcher-Powell and Broydon-Fletcher-Goldfarb-Shanno methods and their properties are investigated. The chapter also includes a practical, efficient, and reliable quasi-Newton algorithm that eliminates some problems associated with the basic quasi-Newton method. Chapter 8 presents minimax methods that are used in many applications including the design of digital filters. Chapter 9 presents three case studies in which several of the unconstrained optimization methods described in Chapters 4 to 8 are applied to point pattern matching, inverse kinematics for robotic manipulators, and the design of digital filters.

Chapters 10 to 16 are concerned with constrained optimization methods. Chapter 10 introduces the fundamentals of constrained optimization. The concept of Lagrange multipliers, the first-order necessary conditions known as Karush-Kuhn-Tucker conditions, and the duality principle of convex programming are addressed in detail and are illustrated by many examples. Chapters 11 and 12 are concerned with linear programming (LP) problems. The general properties of LP and the simplex method for standard LP problems are addressed in Chapter 11. Several interior-point methods including the primal affine-scaling, primal Newton-barrier, and primal-dual path-following methods are presented in Chapter 12. Chapter 13 deals with quadratic and general convex programming. The so-called active-set methods and several interior-point methods for convex quadratic programming are investigated. The chapter also includes the so-called cutting plane and ellipsoid algorithms for general convex programming problems. Chapter 14 presents two special classes of convex programming known as semidefinite and second-order cone programming, which have found interesting applications in a variety of disciplines. Chapter 15 treats general constrained optimization problems that do not belong to the class of convex programming; special emphasis is placed on several sequential quadratic programming methods that are enhanced through the use of efficient line searches and approximations of the Hessian matrix involved. Chapter 16, which concludes the book, examines several applications of constrained optimization for the design of digital filters, for the control of dynamic systems, for evaluating the force distribution in robotic systems, and in multiuser detection for wireless communication systems.

The book also includes two appendices, A and B, which provide additional support material. Appendix A deals in some detail with the relevant parts of linear algebra to consolidate the understanding of the underlying mathematical principles involved whereas Appendix B provides a concise treatment of the basics of digital filters to enhance the understanding of the design algorithms included in Chaps. 8, 9, and 16.

The book can be used as a text for a sequence of two one-semester courses on optimization. The first course comprising Chaps. 1 to 7, 9, and part of Chap. 10 may be offered to senior undergraduate or first-year graduate students. The prerequisite knowledge is an undergraduate mathematics background of calculus and linear algebra. The material in Chaps. 8 and 10 to 16 may be used as a text for an advanced graduate course on minimax and constrained optimization. The prerequisite knowledge for this course is the contents of the first optimization course.

The book is supported by online solutions of the end-of-chapter problems under password as well as by a collection of MATLAB programs for free access by the readers of the book, which can be used to solve a variety of optimization problems. These materials can be downloaded from book's website: https://www.ece.uvic.ca/optimization/.

We are grateful to many of our past students at the University of Victoria, in particular, Drs. M. L. R. de Campos, S. Netto, S. Nokleby, D. Peters, and Mr. J. Wong who took our optimization courses and have helped improve the manuscript in one way or another; to Chi-Tang Catherine Chang for typesetting the first draft of the manuscript and for producing most of the illustrations; to R. Nongpiur for checking a large part of the index; and to P. Ramachandran for proofreading the entire manuscript. We would also like to thank Professors M. Ahmadi, C. Charalambous, P. S. R. Diniz, Z. Dong, T. Hinamoto, and P. P. Vaidyanathan for useful discussions on optimization theory and practice; Tony Antoniou of Psicraft Studios for designing the book cover; the Natural Sciences and Engineering Research Council of Canada for supporting the research that led to some of the new results described in Chapters 8, 9, and 16; and last but not least the University of Victoria for supporting the writing of this book over a number of years.

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Wu-Sheng Lu

Contents

About the Authors

Andreas Antoniou received the B.Sc. and Ph.D. degrees in Electrical Engineering from the University of London, UK, in 1963 and 1966, respectively. He is a Life Member of the Association of Professional Engineers and Geoscientists of British Columbia, Canada, a Fellow of the Institution of Engineering and Technology, and a Life Fellow of the Institute of Electrical and Electronic Engineers. He served as the founding Chair of the Department of Electrical and Computer Engineering at the University of Victoria, BC, Canada and is now Professor Emeritus. He is the author of Digital Filters: Analysis, Design, and Signal Processing Applications published by McGraw-Hill in 2018 (previous editions of the book were published by McGraw-Hill under slightly different titles in 1979, 1993, and 2005). He served as Associate Editor/Editor of IEEE Transactions on Circuits and Systems from June 1983 to May 1987, as a Distinguished Lecturer of the IEEE Signal Processing Society in 2003, as General Chair of the 2004 International Symposium on Circuits and Systems, and as a Distinguished Lecturer of the IEEE Circuits and Systems Society during 2006–2007. He received the Ambrose Fleming Premium for 1964 from the IEE (best paper award), the CAS Golden Jubilee Medal from the IEEE Circuits and Systems Society in recognition of outstanding achievements in the area of circuits and systems, the BC Science Council Chairman's Award for Career Achievement both in 2000, the Doctor Honoris Causa degree by the Metsovio National Technical University, Athens, Greece, in 2002, the IEEE Circuits and Systems Society Technical Achievement Award for 2005, the IEEE Canada Outstanding Engineering Educator Silver Medal for 2008, the IEEE Circuits and Systems Society Education Award for 2009, the Craigdarroch Gold Medal for Career Achievement for 2011, and the Legacy Award for 2011 both from the University of Victoria.

Wu-Sheng Lu received the B.Sc. degree in Mathematics from Fudan University, Shanghai, China, in 1964, the M.S. degree in Electrical Engineering, and the Ph.D. degree in Control Science both from the University of Minnesota, Minneapolis, in 1983 and 1984, respectively. He is a Member of the Association of Professional Engineers and Geoscientists of British Columbia, Canada, a Fellow of the Engineering Institute of Canada, and a Fellow of the Institute of Electrical and Electronics Engineers. He has been teaching and carrying out research in the areas of digital signal processing and application of optimization methods at the

University of Victoria, BC, Canada, since 1987. He is the co-author with A. Antoniou of Two-Dimensional Digital Filters published by Marcel Dekker in 1992. He served as an Associate Editor of the Canadian Journal of Electrical and Computer Engineering in 1989, and Editor of the same journal from 1990 to 1992. He served as an Associate Editor for the IEEE Transactions on Circuits and Systems, Part II, from 1993 to 1995 and for Part I of the same journal from 1999 to 2001 and 2004 to 2005. He received two best paper awards from the IEEE Asia Pacific Conference on Circuits and Systems in 2006 and 2014, the Outstanding Teacher Award of the Engineering Institute of Canada, Vancouver Island Branch, for 1988 and 1990, and the University of Victoria Alumni Association Award for Excellence in Teaching for 1991.

Abbreviations

ADMM	Alternating direction methods of multipliers
AMA	Alternating minimization algorithms
AWGN	Additive white Gaussian noise
BER	Bit-error rate
BFGS	Broyden-Fletcher-Goldfarb-Shanno
CCP	Convex-concave procedure
CDMA	Code-division multiple access
CMBER	Constrained minimum BER
CP	Convex programming
DFP	Davidon-Fletcher-Powell
DH	Denavit-Hartenberg
DNB	Dual Newton barrier
DS-CDMA	Direct-sequence CDMA
FDMA	Frequency-division multiple access
FIR	Finite-duration impulse response
FISTA	Fast iterative shrinkage-thresholding algorithm
FR	Fletcher-Reeves
GCO	General constrained optimization
GN	Gauss-Newton
HOG	Histogram of oriented gradient
HWDR	Handwritten digits recognition
IIR	Infinite-duration impulse response
IP	Integer programming
KKT	Karush-Kuhn-Tucker
LMI	Linear matrix inequality
LP	Linear programming
LSQI	Least-squares minimization with quadratic inequality
LU	Lower-upper
MAI	Multiple access interference
ML	Maximum-likelihood
MLE	Maximum-likelihood estimation
MNIST	Modified National Institute for Standards and Technology
MPC	Model predictive control
NAG	Nesterov's accelerated gradient

PAS	Primal affine scaling
PCCP	Penalty convex-concave procedure
PCM	Predictor-corrector method
PNB	Primal Newton barrier
QP	Quadratic programming
SCP	Sequential convex programming
SD	Steepest-descent
SDP	Semidefinite programming
SDPR-D	SDP relaxation dual
SDPR-P	SDP relaxation primal
SNR	Signal-to-noise ratio
SOCP	Second-order cone programming
SQP	Sequential quadratic programming
SVD	Singular-value decomposition
TDMA	Time-division multiple access