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Lieven Vandenbergh

Convex Optimization

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Nisheeth K. Vishnoi



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Convex Optimization Stephen P. Boyd, Lieven Vandenberghe, 2004-03-08 Convex optimization problems arise frequently in many different fields This book provides a comprehensive introduction to the subject and shows in detail how such problems can be solved numerically with great efficiency The book begins with the basic elements of convex sets and functions and then describes various classes of convex optimization problems Duality and approximation techniques are then covered as are statistical estimation techniques Various geometrical problems are then presented and there is detailed discussion of unconstrained and constrained minimization problems and interior point methods The focus of the book is on recognizing convex optimization problems and then finding the most appropriate technique for solving them It contains many worked examples and homework exercises and will appeal to students researchers and practitioners in fields such as engineering computer science mathematics statistics finance and economics

Lectures on Convex Optimization Yurii Nesterov, 2018-11-19 This book provides a comprehensive modern introduction to convex optimization a field that is becoming increasingly important in applied mathematics economics and finance engineering and computer science notably in data science and machine learning Written by a leading expert in the field this book includes recent advances in the algorithmic theory of convex optimization naturally complementing the existing literature It contains a unified and rigorous presentation of the acceleration techniques for minimization schemes of first and second order It provides readers with a full treatment of the smoothing technique which has tremendously extended the abilities of gradient type methods Several powerful approaches in structural optimization including optimization in relative scale and polynomial time interior point methods are also discussed in detail Researchers in theoretical optimization as well as professionals working on optimization problems will find this book very useful It presents many successful examples of how to develop very fast specialized minimization algorithms Based on the author's lectures it can naturally serve as the basis for introductory and advanced courses in convex optimization for students in engineering economics computer science and mathematics

Convex Optimization Stephen Boyd, Lieven Vandenberghe, 2004-03-08 Convex optimization problems arise frequently in many different fields This book provides a comprehensive introduction to the subject and shows in detail how such problems can be solved numerically with great efficiency The book begins with the basic elements of convex sets and functions and then describes various classes of convex optimization problems Duality and approximation techniques are then covered as are statistical estimation techniques Various geometrical problems are then presented and there is detailed discussion of unconstrained and constrained minimization problems and interior point methods The focus of the book is on recognizing convex optimization problems and then finding the most appropriate technique for solving them It contains many worked examples and homework exercises and will appeal to students researchers and practitioners in fields such as engineering computer science mathematics statistics finance and economics

Convex Analysis for Optimization Jan

Brinkhuis,2020-05-05 This textbook offers graduate students a concise introduction to the classic notions of convex optimization Written in a highly accessible style and including numerous examples and illustrations it presents everything readers need to know about convexity and convex optimization The book introduces a systematic three step method for doing everything which can be summarized as conify work deconify It starts with the concept of convex sets their primal description constructions topological properties and dual description and then moves on to convex functions and the fundamental principles of convex optimization and their use in the complete analysis of convex optimization problems by means of a systematic four step method Lastly it includes chapters on alternative formulations of optimality conditions and on illustrations of their use The author deals with the delicate subjects in a precise yet light minded spirit For experts in the field this book not only offers a unifying view but also opens a door to new discoveries in convexity and optimization perfectly suited for classroom teaching Shuzhong Zhang Professor of Industrial and Systems Engineering University of Minnesota

Algorithms for Convex Optimization Nisheeth K. Vishnoi,2021-10-07 In the last few years Algorithms for Convex Optimization have revolutionized algorithm design both for discrete and continuous optimization problems For problems like maximum flow maximum matching and submodular function minimization the fastest algorithms involve essential methods such as gradient descent mirror descent interior point methods and ellipsoid methods The goal of this self contained book is to enable researchers and professionals in computer science data science and machine learning to gain an in depth understanding of these algorithms The text emphasizes how to derive key algorithms for convex optimization from first principles and how to establish precise running time bounds This modern text explains the success of these algorithms in problems of discrete optimization as well as how these methods have significantly pushed the state of the art of convex optimization itself

Introductory Lectures on Convex Optimization Y. Nesterov,2013-12-01 It was in the middle of the 1980s when the seminal paper by Kar markar opened a new epoch in nonlinear optimization The importance of this paper containing a new polynomial time algorithm for linear op timization problems was not only in its complexity bound At that time the most surprising feature of this algorithm was that the theoretical pre diction of its high efficiency was supported by excellent computational results This unusual fact dramatically changed the style and direc tions of the research in nonlinear optimization Thereafter it became more and more common that the new methods were provided with a complexity analysis which was considered a better justification of their efficiency than computational experiments In a new rapidly develop ing field which got the name polynomial time interior point methods such a justification was obligatory Afteralmost fifteen years of intensive research the main results of this development started to appear in monographs 12 14 16 17 18 19 Approximately at that time the author was asked to prepare a new course on nonlinear optimization for graduate students The idea was to create a course which would reflect the new developments in the field Actually this was a major challenge At the time only the theory of interior point methods for linear optimization was polished enough to be explained to students The general

theory of self concordant functions had appeared in print only once in the form of research monograph 12 *Linear and Convex Optimization* Michael H. Veatch, 2020-12-23 Discover the practical impacts of current methods of optimization with this approachable one stop resource *Linear and Convex Optimization A Mathematical Approach* delivers a concise and unified treatment of optimization with a focus on developing insights in problem structure modeling and algorithms Convex optimization problems are covered in detail because of their many applications and the fast algorithms that have been developed to solve them Experienced researcher and undergraduate teacher Mike Veatch presents the main algorithms used in linear integer and convex optimization in a mathematical style with an emphasis on what makes a class of problems practically solvable and developing insight into algorithms geometrically Principles of algorithm design and the speed of algorithms are discussed in detail requiring no background in algorithms The book offers a breadth of recent applications to demonstrate the many areas in which optimization is successfully and frequently used while the process of formulating optimization problems is addressed throughout *Linear and Convex Optimization* contains a wide variety of features including Coverage of current methods in optimization in a style and level that remains appealing and accessible for mathematically trained undergraduates Enhanced insights into a few algorithms instead of presenting many algorithms in cursory fashion An emphasis on the formulation of large data driven optimization problems Inclusion of linear integer and convex optimization covering many practically solvable problems using algorithms that share many of the same concepts Presentation of a broad range of applications to fields like online marketing disaster response humanitarian development public sector planning health delivery manufacturing and supply chain management Ideal for upper level undergraduate mathematics majors with an interest in practical applications of mathematics this book will also appeal to business economics computer science and operations research majors with at least two years of mathematics training Software to accompany the text can be found here <https://www.gordon.edu/michaelveatch/optimization> *Large-Scale Convex Optimization* Ernest K. Ryu, Wotao Yin, 2022-12 A unified analysis of first order optimization methods including parallel distributed algorithms using monotone operators *Convexity and Optimization in Banach Spaces* Viorel Barbu, Teodor Precupanu, 2012-01-03 An updated and revised edition of the 1986 title *Convexity and Optimization in Banach Spaces* this book provides a self contained presentation of basic results of the theory of convex sets and functions in infinite dimensional spaces The main emphasis is on applications to convex optimization and convex optimal control problems in Banach spaces A distinctive feature is a strong emphasis on the connection between theory and application This edition has been updated to include new results pertaining to advanced concepts of subdifferential for convex functions and new duality results in convex programming The last chapter concerned with convex control problems has been rewritten and completed with new research concerning boundary control systems the dynamic programming equations in optimal control theory and periodic optimal control problems Finally the structure of the book has been modified to highlight the most recent progression in the field including fundamental results on

the theory of infinite dimensional convex analysis and includes helpful bibliographical notes at the end of each chapter

Convex Optimization for Signal Processing and Communications Chong-Yung Chi, Wei-Chiang Li, Chia-Hsiang Lin, 2017-01-24 Convex Optimization for Signal Processing and Communications From Fundamentals to Applications provides fundamental background knowledge of convex optimization while striking a balance between mathematical theory and applications in signal processing and communications In addition to comprehensive proofs and perspective interpretations for core convex optimization theory this book also provides many insightful figures remarks illustrative examples and guided journeys from theory to cutting edge research explorations for efficient and in depth learning especially for engineering students and professionals With the powerful convex optimization theory and tools this book provides you with a new degree of freedom and the capability of solving challenging real world scientific and engineering problems *Introduction to Online Convex Optimization, second edition* Elad Hazan, 2022-09-06 New edition of a graduate level textbook on that focuses on online convex optimization a machine learning framework that views optimization as a process In many practical applications the environment is so complex that it is not feasible to lay out a comprehensive theoretical model and use classical algorithmic theory and or mathematical optimization Introduction to Online Convex Optimization presents a robust machine learning approach that contains elements of mathematical optimization game theory and learning theory an optimization method that learns from experience as more aspects of the problem are observed This view of optimization as a process has led to some spectacular successes in modeling and systems that have become part of our daily lives Based on the Theoretical Machine Learning course taught by the author at Princeton University the second edition of this widely used graduate level text features Thoroughly updated material throughout New chapters on boosting adaptive regret and approachability and expanded exposition on optimization Examples of applications including prediction from expert advice portfolio selection matrix completion and recommendation systems SVM training offered throughout Exercises that guide students in completing parts of proofs **Convex Optimization with Computational Errors** Alexander J. Zaslavski, 2020-01-31 The book is devoted to the study of approximate solutions of optimization problems in the presence of computational errors It contains a number of results on the convergence behavior of algorithms in a Hilbert space which are known as important tools for solving optimization problems The research presented in the book is the continuation and the further development of the author's c 2016 book Numerical Optimization with Computational Errors Springer 2016 Both books study the algorithms taking into account computational errors which are always present in practice The main goal is for a known computational error to find out what an approximate solution can be obtained and how many iterates one needs for this The main difference between this new book and the 2016 book is that in this present book the discussion takes into consideration the fact that for every algorithm its iteration consists of several steps and that computational errors for different steps are generally different This fact which was not taken into account in the previous book is indeed important in practice For

example the subgradient projection algorithm consists of two steps The first step is a calculation of a subgradient of the objective function while in the second one we calculate a projection on the feasible set In each of these two steps there is a computational error and these two computational errors are different in general It may happen that the feasible set is simple and the objective function is complicated As a result the computational error made when one calculates the projection is essentially smaller than the computational error of the calculation of the subgradient Clearly an opposite case is possible too Another feature of this book is a study of a number of important algorithms which appeared recently in the literature and which are not discussed in the previous book This monograph contains 12 chapters Chapter 1 is an introduction In Chapter 2 we study the subgradient projection algorithm for minimization of convex and nonsmooth functions We generalize the results of NOCE and establish results which has no prototype in NOCE In Chapter 3 we analyze the mirror descent algorithm for minimization of convex and nonsmooth functions under the presence of computational errors For this algorithm each iteration consists of two steps The first step is a calculation of a subgradient of the objective function while in the second one we solve an auxiliary minimization problem on the set of feasible points In each of these two steps there is a computational error We generalize the results of NOCE and establish results which has no prototype in NOCE In Chapter 4 we analyze the projected gradient algorithm with a smooth objective function under the presence of computational errors In Chapter 5 we consider an algorithm which is an extension of the projection gradient algorithm used for solving linear inverse problems arising in signal image processing In Chapter 6 we study continuous subgradient method and continuous subgradient projection algorithm for minimization of convex nonsmooth functions and for computing the saddle points of convex concave functions under the presence of computational errors All the results of this chapter has no prototype in NOCE In Chapters 7 12 we analyze several algorithms under the presence of computational errors which were not considered in NOCE Again each step of an iteration has a computational errors and we take into account that these errors are in general different An optimization problems with a composite objective function is studied in Chapter 7 A zero sum game with two players is considered in Chapter 8 A predicted decrease approximation based method is used in Chapter 9 for constrained convex optimization Chapter 10 is devoted to minimization of quasiconvex functions Minimization of sharp weakly convex functions is discussed in Chapter 11 Chapter 12 is devoted to a generalized projected subgradient method for minimization of a convex function over a set which is not necessarily convex The book is of interest for researchers and engineers working in optimization It also can be useful in preparation courses for graduate students The main feature of the book which appeals specifically to this audience is the study of the influence of computational errors for several important optimization algorithms The book is of interest for experts in applications of optimization to engineering and economics

Optimality Conditions in Convex Optimization Anulekha Dhara,Joydeep Dutta,2011-10-17 Optimality Conditions in Convex Optimization explores an important and central issue in the field of convex optimization optimality conditions It brings together the most

important and recent results in this area that have been scattered in the literature notably in the area of convex analysis essential in developing many of the important results

Introduction to Online Convex Optimization, second edition Elad Hazan, 2022-09-06 New edition of a graduate level textbook on that focuses on online convex optimization a machine learning framework that views optimization as a process In many practical applications the environment is so complex that it is not feasible to lay out a comprehensive theoretical model and use classical algorithmic theory and or mathematical optimization Introduction to Online Convex Optimization presents a robust machine learning approach that contains elements of mathematical optimization game theory and learning theory an optimization method that learns from experience as more aspects of the problem are observed This view of optimization as a process has led to some spectacular successes in modeling and systems that have become part of our daily lives Based on the Theoretical Machine Learning course taught by the author at Princeton University the second edition of this widely used graduate level text features Thoroughly updated material throughout New chapters on boosting adaptive regret and approachability and expanded exposition on optimization Examples of applications including prediction from expert advice portfolio selection matrix completion and recommendation systems SVM training offered throughout Exercises that guide students in completing parts of proofs

Convexity and Optimization in Finite Dimensions I Josef Stoer, Christoph Witzgall, 2012-12-06 Dantzig s development of linear programming into one of the most applicable optimization techniques has spread interest in the algebra of linear inequalities the geometry of polyhedra the topology of convex sets and the analysis of convex functions It is the goal of this volume to provide a synopsis of these topics and thereby the theoretical back ground for the arithmetic of convex optimization to be treated in a subsequent volume The exposition of each chapter is essentially independent and attempts to reflect a specific style of mathematical reasoning The emphasis lies on linear and convex duality theory as initiated by Gale Kuhn and Tucker Fenchel and v Neumann because it represents the theoretical development whose impact on modern optimization techniques has been the most pronounced Chapters 5 and 6 are devoted to two characteristic aspects of duality theory conjugate functions or polarity on the one hand and saddle points on the other The Farkas lemma on linear inequalities and its generalizations Motzkin s description of polyhedra Minkowski s supporting plane theorem are indispensable elementary tools which are contained in chapters 1 2 and 3 respectively The treatment of extremal properties of polyhedra as well as of general convex sets is based on the far reaching work of Klee Chapter 2 terminates with a description of Gale diagrams a recently developed successful technique for exploring polyhedral structures

Nonsmooth Mechanics and Convex Optimization Yoshihiro Kanno, 2011-04-05 This book concerns matter that is intrinsically difficult convex optimization complementarity and duality nonsmooth analysis linear and nonlinear programming etc The author has skillfully introduced these and many more concepts and woven them into a seamless whole by retaining an easy and consistent style throughout The book is not all the

Convex Optimization in Normed Spaces Juan Peypouquet, 2015-03-18 This work is intended to serve as a guide for

graduate students and researchers who wish to get acquainted with the main theoretical and practical tools for the numerical minimization of convex functions on Hilbert spaces. Therefore it contains the main tools that are necessary to conduct independent research on the topic. It is also a concise, easy to follow and self-contained textbook which may be useful for any researcher working on related fields as well as teachers giving graduate level courses on the topic. It will contain a thorough revision of the extant literature including both classical and state of the art references.

Convex Optimization Theory
Dimitri Bertsekas, 2009-06-01. An insightful, concise and rigorous treatment of the basic theory of convex sets and functions in finite dimensions and the analytical/geometrical foundations of convex optimization and duality theory. Convexity theory is first developed in a simple, accessible manner using easily visualized proofs. Then the focus shifts to a transparent geometrical line of analysis to develop the fundamental duality between descriptions of convex functions in terms of points and in terms of hyperplanes. Finally, convexity theory and abstract duality are applied to problems of constrained optimization. Fenchel and conic duality and game theory to develop the sharpest possible duality results within a highly visual geometric framework. This online version of the book includes an extensive set of theoretical problems with detailed, high quality solutions which significantly extend the range and value of the book. The book may be used as a text for a theoretical convex optimization course; the author has taught several variants of such a course at MIT and elsewhere over the last ten years. It may also be used as a supplementary source for nonlinear programming classes and as a theoretical foundation for classes focused on convex optimization models rather than theory. It is an excellent supplement to several of our books: *Convex Optimization Algorithms* (Athena Scientific, 2015), *Nonlinear Programming* (Athena Scientific, 2017), *Network Optimization* (Athena Scientific, 1998), *Introduction to Linear Optimization* (Athena Scientific, 1997) and *Network Flows and Monotropic Optimization* (Athena Scientific, 1998).

Convex Optimization & Euclidean Distance Geometry
Jon Dattorro, 2005. The study of Euclidean distance matrices (EDMs) fundamentally asks what can be known geometrically given only distance information between points in Euclidean space. Each point may represent simply a location or abstractly any entity expressible as a vector in finite dimensional Euclidean space. The answer to the question posed is that very much can be known about the points. The mathematics of this combined study of geometry and optimization is rich and deep. Throughout we cite beacons of historical accomplishment. The application of EDMs has already proven invaluable in discerning biological molecular conformation. The emerging practice of localization in wireless sensor networks, the global positioning system (GPS) and distance based pattern recognition will certainly simplify and benefit from this theory. We study the pervasive convex Euclidean bodies and their various representations. In particular we make convex polyhedra, cones and dual cones more visceral through illustration and we study the geometric relation of polyhedral cones to nonorthogonal bases, biorthogonal expansion. We explain conversion between halfspace and vertex descriptions of convex cones; we provide formulae for determining dual cones and we show how classic alternative systems of linear inequalities or linear matrix inequalities and optimality conditions can be

explained by generalized inequalities in terms of convex cones and their duals The conic analogue to linear independence called conic independence is introduced as a new tool in the study of classical cone theory the logical next step in the progression linear affine conic Any convex optimization problem has geometric interpretation This is a powerful attraction the ability to visualize geometry of an optimization problem We provide tools to make visualization easier The concept of faces extreme points and extreme directions of convex Euclidean bodies is explained here crucial to understanding convex optimization The convex cone of positive semidefinite matrices in particular is studied in depth We mathematically interpret for example its inverse image under affine transformation and we explain how higher rank subsets of its boundary united with its interior are convex The Chapter on Geometry of convex functions observes analogies between convex sets and functions The set of all vector valued convex functions is a closed convex cone Included among the examples in this chapter we show how the real affine function relates to convex functions as the hyperplane relates to convex sets Here also pertinent results for multidimensional convex functions are presented that are largely ignored in the literature tricks and tips for determining their convexity and discerning their geometry particularly with regard to matrix calculus which remains largely unsystematized when compared with the traditional practice of ordinary calculus Consequently we collect some results of matrix differentiation in the appendices The Euclidean distance matrix EDM is studied its properties and relationship to both positive semidefinite and Gram matrices We relate the EDM to the four classical axioms of the Euclidean metric thereby observing the existence of an infinity of axioms of the Euclidean metric beyond the triangle inequality We proceed by deriving the fifth Euclidean axiom and then explain why furthering this endeavor is inefficient because the ensuing criteria while describing polyhedra grow linearly in complexity and number Some geometrical problems solvable via EDMs EDM problems posed as convex optimization and methods of solution are presented eg we generate a recognizable isotonic map of the United States using only comparative distance information no distance information only distance inequalities We offer a new proof of the classic Schoenberg criterion that determines whether a candidate matrix is an EDM Our proof relies on fundamental geometry assuming any EDM must correspond to a list of points contained in some polyhedron possibly at its vertices and vice versa It is not widely known that the Schoenberg criterion implies nonnegativity of the EDM entries proved here We characterize the eigenvalues of an EDM matrix and then devise a polyhedral cone required for determining membership of a candidate matrix in Cayley Menger form to the convex cone of Euclidean distance matrices EDM cone ie a candidate is an EDM if and only if its eigenspectrum belongs to a spectral cone for EDM N We will see spectral cones are not unique In the chapter EDM cone we explain the geometric relationship between the EDM cone two positive semidefinite cones and the ellipsope We illustrate geometric requirements in particular for projection of a candidate matrix on a positive semidefinite cone that establish its membership to the EDM cone The faces of the EDM cone are described but still open is the question whether all its faces are exposed as they are for the positive semidefinite cone The classic Schoenberg criterion

relating EDM and positive semidefinite cones is revealed to be a discretized membership relation a generalized inequality a new Farkas like lemma between the EDM cone and its ordinary dual A matrix criterion for membership to the dual EDM cone is derived that is simpler than the Schoenberg criterion We derive a new concise expression for the EDM cone and its dual involving two subspaces and a positive semidefinite cone Semidefinite programming is reviewed with particular attention to optimality conditions of prototypical primal and dual conic programs their interplay and the perturbation method of rank reduction of optimal solutions extant but not well known We show how to solve a ubiquitous platonic combinatorial optimization problem from linear algebra the optimal Boolean solution x to $Ax \leq b$ via semidefinite program relaxation A three dimensional polyhedral analogue for the positive semidefinite cone of 3×3 symmetric matrices is introduced a tool for visualizing in 6 dimensions In EDM proximity we explore methods of solution to a few fundamental and prevalent Euclidean distance matrix proximity problems the problem of finding that Euclidean distance matrix closest to a given matrix in the Euclidean sense We pay particular attention to the problem when compounded with rank minimization We offer a new geometrical proof of a famous result discovered by Eckart Young in 1936 regarding Euclidean projection of a point on a subset of the positive semidefinite cone comprising all positive semidefinite matrices having rank not exceeding a prescribed limit ρ We explain how this problem is transformed to a convex optimization for any rank ρ

Lectures on Modern Convex Optimization Aharon Ben-Tal, Arkadi Nemirovski, 2001-01-01 Here is a book devoted to well structured and thus efficiently solvable convex optimization problems with emphasis on conic quadratic and semidefinite programming The authors present the basic theory underlying these problems as well as their numerous applications in engineering including synthesis of filters Lyapunov stability analysis and structural design The authors also discuss the complexity issues and provide an overview of the basic theory of state of the art polynomial time interior point methods for linear conic quadratic and semidefinite programming The book's focus on well structured convex problems in conic form allows for unified theoretical and algorithmical treatment of a wide spectrum of important optimization problems arising in applications

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