Additional Exercises for *Convex Optimization*

Stephen Boyd   Lieven Vandenberghe

May 26, 2017

This is a collection of additional exercises, meant to supplement those found in the book *Convex Optimization*, by Stephen Boyd and Lieven Vandenberghe. These exercises were used in several courses on convex optimization, EE364a (Stanford), EE236b (UCLA), or 6.975 (MIT), usually for homework, but sometimes as exam questions. Some of the exercises were originally written for the book, but were removed at some point. Many of them include a computational component using CVX, a Matlab package for convex optimization; files required for these exercises can be found at the book web site www.stanford.edu/~boyd/cvxbook/. We are in the process of adapting many of these problems to be compatible with two other packages for convex optimization: CVXPY (Python) and Convex.jl (Julia). Some of the exercises require a knowledge of elementary analysis.

You are free to use these exercises any way you like (for example in a course you teach), provided you acknowledge the source. In turn, we gratefully acknowledge the teaching assistants (and in some cases, students) who have helped us develop and debug these exercises. Pablo Parrilo helped develop some of the exercises that were originally used in 6.975, and the instructors of EE364a during summer quarters helped developed others.

Course instructors can obtain solutions by email to us. Please specify the course you are teaching and give its URL.

We'll update this document as new exercises become available, so the exercise numbers and sections will occasionally change. We have categorized the exercises into sections that follow the book chapters, as well as various additional application areas. Some exercises fit into more than one section, or don't fit well into any section, so we have just arbitrarily assigned these.

Stephen Boyd and Lieven Vandenberghe

Additional Exercises Convex Optimization Solution Boyd

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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 on line 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 **First-Order Methods in Optimization** Amir Beck,2017-10-02 The primary goal of this book is to provide a self contained comprehensive study of the main rst order methods that are frequently used in solving large scale problems First order methods exploit information on values and gradients subgradients but not Hessians of the functions composing the model under consideration With the increase in the number of applications that can be modeled as large or even huge scale optimization problems there has been a revived interest in using simple methods that require low iteration cost as well as low memory storage The author has gathered reorganized and synthesized in a unified manner many results that are currently scattered throughout the literature many of which cannot be typically found in optimization books First Order Methods in Optimization offers comprehensive study of first order methods with the theoretical foundations provides plentiful examples and illustrations emphasizes rates of convergence and complexity analysis of the main first order methods used to solve large scale problems and covers both variables and functional decomposition methods **Optimization Techniques and Applications with Examples** Xin-She Yang,2018-08-30 A guide to modern optimization applications and techniques in newly emerging areas spanning optimization data science machine intelligence engineering and computer sciences Optimization Techniques and Applications with Examples introduces the fundamentals of all the commonly used techniques in optimization that encompass the broadness and diversity of the methods traditional and new and algorithms The author a noted expert in the field covers a wide range of topics including mathematical foundations optimization formulation optimality conditions algorithmic complexity linear programming convex

optimization and integer programming In addition the book discusses artificial neural network clustering and classifications constraint handling queueing theory support vector machine and multi objective optimization evolutionary computation nature inspired algorithms and many other topics Designed as a practical resource all topics are explained in detail with step by step examples to show how each method works The book s exercises test the acquired knowledge that can be potentially applied to real problem solving By taking an informal approach to the subject the author helps readers to rapidly acquire the basic knowledge in optimization operational research and applied data mining This important resource Offers an accessible and state of the art introduction to the main optimization techniques Contains both traditional optimization techniques and the most current algorithms and swarm intelligence based techniques Presents a balance of theory algorithms and implementation Includes more than 100 worked examples with step by step explanations Written for upper undergraduates and graduates in a standard course on optimization operations research and data mining Optimization Techniques and Applications with Examples is a highly accessible guide to understanding the fundamentals of all the commonly used techniques in optimization **Set-Valued, Convex, and Nonsmooth Analysis in Dynamics and Control** Rafal K. Goebel,2024-06-26 Set valued analysis convex analysis and nonsmooth analysis are relatively modern branches of mathematical analysis that have become increasingly relevant in current control theory and control engineering literature This book serves as a broad introduction to analytical tools in these fields and to their applications in dynamical and control systems and is the first to cover these topics with this scope and at this level Both continuous time and discrete time mutlivalued dynamics modeled by differential and difference inclusions are considered Set Valued Convex and Nonsmooth Analysis in Dynamics and Control An Introduction is aimed at graduate students in control engineering and applied mathematics and researchers in control engineering who have no prior exposure to set valued convex and nonsmooth analysis The book will also be of interest to advanced undergraduate mathematics students and mathematicians with no prior exposure to the topic The expected mathematical background is a course on nonlinear differential equations dynamical systems and a course on real analysis Knowledge of some control theory is helpful but not essential Constructing Insurable Risk Portfolios Edward W. Frees,2025-04-09 Constructing Insurable Risk Portfolios offers a data driven approach to devising risk retention programs that safeguard firms from a multitude of risks Because firms face many risks including fire damage to their buildings liability from management misconduct and external threats like cyberattacks this book treats these potential liabilities as a portfolio Drawing inspiration from Markowitz portfolio theory the text leverages techniques from probability statistics and optimization to build algorithms that construct optimal risk insurable portfolios under budget constraints Features Through engaging case studies and supporting statistical R code readers will learn how to build optimal insurable risk portfolios This book illustrates a frontier that depicts the trade off between the uncertainty of a portfolio and the cost of risk transfer This visual representation mirroring familiar Markowitz investment tools enables informed decision

making and easy adoption by risk advisors This book lays the mathematical groundwork for constructing optimal insurable risk portfolios in an effective and aesthetically pleasing manner For those interested in the detailed mathematical aspects of insurable risk portfolio optimization comprehensive proofs and derivations are available in an online supplement This book equips students academics and practitioners with quantitative tools to analyze real world risk portfolios Additionally it empowers financial analysts to provide data driven insights that enhance their advisory roles for risk managers

Introduction to Machine Learning, fourth edition Ethem Alpaydin,2020-03-24 A substantially revised fourth edition of a comprehensive textbook including new coverage of recent advances in deep learning and neural networks The goal of machine learning is to program computers to use example data or past experience to solve a given problem Machine learning underlies such exciting new technologies as self driving cars speech recognition and translation applications This substantially revised fourth edition of a comprehensive widely used machine learning textbook offers new coverage of recent advances in the field in both theory and practice including developments in deep learning and neural networks The book covers a broad array of topics not usually included in introductory machine learning texts including supervised learning Bayesian decision theory parametric methods semiparametric methods nonparametric methods multivariate analysis hidden Markov models reinforcement learning kernel machines graphical models Bayesian estimation and statistical testing The fourth edition offers a new chapter on deep learning that discusses training regularizing and structuring deep neural networks such as convolutional and generative adversarial networks new material in the chapter on reinforcement learning that covers the use of deep networks the policy gradient methods and deep reinforcement learning new material in the chapter on multilayer perceptrons on autoencoders and the word2vec network and discussion of a popular method of dimensionality reduction t SNE New appendixes offer background material on linear algebra and optimization End of chapter exercises help readers to apply concepts learned Introduction to Machine Learning can be used in courses for advanced undergraduate and graduate students and as a reference for professionals **Introduction to Machine Learning, third edition** Ethem Alpaydin,2014-08-22 A substantially revised third edition of a comprehensive textbook that covers a broad range of topics not often included in introductory texts The goal of machine learning is to program computers to use example data or past experience to solve a given problem Many successful applications of machine learning exist already including systems that analyze past sales data to predict customer behavior optimize robot behavior so that a task can be completed using minimum resources and extract knowledge from bioinformatics data Introduction to Machine Learning is a comprehensive textbook on the subject covering a broad array of topics not usually included in introductory machine learning texts Subjects include supervised learning Bayesian decision theory parametric semi parametric and nonparametric methods multivariate analysis hidden Markov models reinforcement learning kernel machines graphical models Bayesian estimation and statistical testing Machine learning is rapidly becoming a skill that computer science students must master

before graduation The third edition of Introduction to Machine Learning reflects this shift with added support for beginners including selected solutions for exercises and additional example data sets with code available online Other substantial changes include discussions of outlier detection ranking algorithms for perceptrons and support vector machines matrix decomposition and spectral methods distance estimation new kernel algorithms deep learning in multilayered perceptrons and the nonparametric approach to Bayesian methods All learning algorithms are explained so that students can easily move from the equations in the book to a computer program The book can be used by both advanced undergraduates and graduate students It will also be of interest to professionals who are concerned with the application of machine learning methods

Introduction to Machine Learning Ethem Alpaydin,2014-08-22 Introduction Supervised learning Bayesian decision theory Parametric methods Multivariate methods Dimensionality reduction Clustering Nonparametric methods Decision trees Linear discrimination Multilayer perceptrons Local models Kernel machines Graphical models Brief contents Hidden markov models Bayesian estimation Combining multiple learners Reinforcement learning Design and analysis of machine learning experiments *Bulletin* Institute of Mathematics and Its Applications,1994 Linear Semi-Infinite Optimization Miguel A. Goberna,Marco A. López,1998-03-11 A linear semi infinite program is an optimization problem with linear objective functions and linear constraints in which either the number of unknowns or the number of constraints is finite The many direct applications of linear semi infinite optimization or programming have prompted considerable and increasing research effort in recent years The authors aim is to communicate the main theoretical ideas and applications techniques of this fascinating area from the perspective of convex analysis The four sections of the book cover Modelling with primal and dual problems the primal problem space of dual variables the dual problem Linear semi infinite systems existence theorems alternative theorems redundancy phenomena geometrical properties of the solution set Theory of linear semi infinite programming optimality duality boundedness perturbations well posedness Methods of linear semi infinite programming an overview of the main numerical methods for primal and dual problems Exercises and examples are provided to illustrate both theory and applications The reader is assumed to be familiar with elementary calculus linear algebra and general topology An appendix on convex analysis is provided to ensure that the book is self contained Graduate students and researchers wishing to gain a deeper understanding of the main ideas behind the theory of linear optimization will find this book to be an essential text

International Aerospace Abstracts ,1995 **Forthcoming Books** Rose Arny,2003-12 **Conference Record of the Thirty-Eighth Asilomar Conference on Signals, Systems & Computers, November 7-10, 2004, Pacific Grove, California** Michael B. Matthews,2004 **Books in Print Supplement** ,1984 Mathematical Reviews ,1970 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

Optimization on Solution Sets of Common Fixed Point Problems Alexander J. Zaslavski,2021 This book is devoted to a detailed study of the subgradient projection method and its variants for convex optimization problems over the solution sets of common fixed point problems and convex feasibility problems These optimization problems are investigated to determine good solutions obtained by different versions of the subgradient projection algorithm in the presence of sufficiently small computational errors The use of selected algorithms is highlighted including the Cimmino type subgradient the iterative subgradient and the dynamic string averaging subgradient All results presented are new Optimization problems where the underlying constraints are the solution sets of other problems frequently occur in applied mathematics The reader should not miss the section in Chapter 1 which considers some examples arising in the real world applications The problems discussed have an important impact in optimization theory as well The book will be useful for researches interested in the optimization theory and its applications *Convex Optimization & Euclidean Distance Geometry* Jon Dattorro,2005 The study of Euclidean distance matrices EDMs fundamentally asks what can be known geometrically given onlydistance information between points in Euclidean space Each point may represent simply locationor 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 recognitionwill 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 andwe 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 introducedas 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 bodiesis 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 explainhow 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 affinefunction relates to convex functions as the hyperplane relates to convex sets Here also pertinent results formultidimensional convex functions are presented that are largely ignored in the literature tricks and tips for determining their convexityand discerning their geometry particularly with regard to matrix calculus which remains largely unsystematizedwhen 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 beyondthe triangle inequality We proceed byderiving the fifth Euclidean axiom and then explain why furthering this endeavoris 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 arepresented eg we generate a recognizable isotonic map of the United States usingonly 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 proofrelies 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 devisea 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 betweenthe EDM cone two positive semidefinite cones and the elliptope We illustrate geometric requirements in particular for projection of a candidate matrixon 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 isrevealed 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 thatis simpler than the Schoenberg criterion We derive a new concise expression for the EDM cone and its dual involvingtwo subspaces and a positive semidefinite cone Semidefinite programming is reviewedwith particular attention to optimality conditionsof 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 b via semidefinite program relaxation A three dimensional polyhedral analogue for the positive semidefinite cone of 3X3 symmetricmatrices is introduced a tool for visualizing in 6 dimensions In EDM proximitywe explore methods of solution to a few fundamental and prevalentEuclidean distance matrix proximity problems the problem of finding that Euclidean distance matrix closestto 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 Euclideanprojection of a point on a subset of the positive semidefinite cone comprising all positive semidefinite matriceshaving rank not exceeding a prescribed limit rho We explain how this problem is transformed to a convex optimization for any rank rho   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 in this book and not usually found in conventional texts Unlike other books on convex optimization which usually discuss algorithms along with some basic theory the sole focus of this book is on fundamental and advanced convex optimization theory Although many results presented in the book can also be proved in infinite dimensions the authors focus on finite dimensions to allow for much deeper results and a better understanding of the structures involved in a convex optimization problem They address semi infinite optimization problems approximate solution concepts of convex optimization problems and some classes of non convex problems which can be studied using the tools of convex analysis They include examples wherever needed provide details of major results and discuss proofs of the main results   *Lectures on Convex Sets* Valeriu Soltan,2020 The exposition is self contained detailed and provides multiple cross references that makes the book accessible to a large audience An essential part of the text is adapted from various research articles never presented before in a textbook format The book has a multidisciplinary nature it can be useful to specialists in geometry convex analysis operations research and optimization The new edition contains new chapters and additional exercises with respective solutions Despite the presence of a large number of monographs on convex sets there are quite a few textbooks on this topic This book is to the level of graduate study with higher degree of complexity and essentially more research related results and references

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web step 1 spell out the problem always remember that a team building activity is essentially meant to solve a particular problem that is currently affecting the team s performance if you have been doing a needs assessment in past team building activities then this step should already be a habit on the other hand there is no point spelling

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