

$$v_i^* \frac{\partial h_i}{\partial x_k} + \sum_{j=1}^m u_j^* \frac{\partial g_j}{\partial x_k} = 0$$

$$\mathbf{x}^{(k+1)} = \mathbf{x}^{(k)} + \alpha_k$$

$$\Phi_{k+1,j} \leq \Phi_k - t_j \beta_k$$

$$(\mathbf{x}), r) = f(\mathbf{x}) + \sum_{i=1}^p \left[v_i h_i(\mathbf{x}) + \frac{1}{2} r h_i^2(\mathbf{x}) \right]$$

INTRODUCTION TO

OPTIMUM DESIGN

THIRD EDITION

JASBIR S. ARORA



Contents

Preface to Third Edition	xiii
Acknowledgments	xv
Key Symbols and Abbreviations	xvi

I

THE BASIC CONCEPTS

1 Introduction to Design Optimization	1
1.1 The Design Process	2
1.2 Engineering Design versus Engineering Analysis	4
1.3 Conventional versus Optimum Design Process	4
1.4 Optimum Design versus Optimal Control	6
1.5 Basic Terminology and Notation	6
1.5.1 Points and Sets	6
1.5.2 Notation for Constraints	8
1.5.3 Superscripts/Subscripts and Summation Notation	9
1.5.4 Norm/Length of a Vector	10
1.5.5 Functions	11
1.5.6 Derivatives of Functions	12
1.5.7 U.S.—British versus SI Units	13
2 Optimum Design Problem Formulation	17
2.1 The Problem Formulation Process	18
2.1.1 Step 1: Project/Problem Description	18
2.1.2 Step 2: Data and Information Collection	19
2.1.3 Step 3: Definition of Design Variables	20
2.1.4 Step 4: Optimization Criterion	21
2.1.5 Step 5: Formulation of Constraints	22
2.2 Design of a Can	25
2.3 Insulated Spherical Tank Design	26
2.4 Sawmill Operation	28
2.5 Design of a Two-Bar Bracket	30
2.6 Design of a Cabinet	37
2.6.1 Formulation 1 for Cabinet Design	37
2.6.2 Formulation 2 for Cabinet Design	38
2.6.3 Formulation 3 for Cabinet Design	39
2.7 Minimum-Weight Tubular Column Design	40
2.7.1 Formulation 1 for Column Design	41
2.7.2 Formulation 2 for Column Design	41
2.8 Minimum-Cost Cylindrical Tank Design	42
2.9 Design of Coil Springs	43
2.10 Minimum-Weight Design of a Symmetric Three-Bar Truss	46
2.11 A General Mathematical Model for Optimum Design	50
2.11.1 Standard Design Optimization Model	50
2.11.2 Maximization Problem Treatment	51
2.11.3 Treatment of "Greater Than Type" Constraints	51
2.11.4 Application to Different Engineering Fields	52
2.11.5 Important Observations about the Standard Model	52
2.11.6 Feasible Set	53
2.11.7 Active/Inactive/Violated Constraints	53
2.11.8 Discrete and Integer Design Variables	54
2.11.9 Types of Optimization Problems	55
Exercises for Chapter 2	56
3 Graphical Optimization and Basic Concepts	65
3.1 Graphical Solution Process	65
3.1.1 Profit Maximization Problem	65
3.1.2 Step-by-Step Graphical Solution Procedure	67

- 3.2 Use of *Mathematica* for Graphical Optimization 71
 - 3.2.1 Plotting Functions 72
 - 3.2.2 Identification and Shading of Infeasible Region for an Inequality 73
 - 3.2.3 Identification of Feasible Region 73
 - 3.2.4 Plotting of Objective Function Contours 74
 - 3.2.5 Identification of Optimum Solution 74
- 3.3 Use of MATLAB for Graphical Optimization 75
 - 3.3.1 Plotting of Function Contours 75
 - 3.3.2 Editing of Graph 77
- 3.4 Design Problem with Multiple Solutions 77
- 3.5 Problem with Unbounded Solution 79
- 3.6 Infeasible Problem 79
- 3.7 Graphical Solution for the Minimum-Weight Tubular Column 80
- 3.8 Graphical Solution for a Beam Design Problem 82
- Exercises for Chapter 3 83

- 4 Optimum Design Concepts: Optimality Conditions 95
 - 4.1 Definitions of Global and Local Minima 96
 - 4.1.1 Minimum 97
 - 4.1.2 Existence of a Minimum 102
 - 4.2 Review of Some Basic Calculus Concepts 103
 - 4.2.1 Gradient Vector: Partial Derivatives of a Function 103
 - 4.2.2 Hessian Matrix: Second-Order Partial Derivatives 105
 - 4.2.3 Taylor's Expansion 106
 - 4.2.4 Quadratic Forms and Definite Matrices 109
 - 4.3 Concept of Necessary and Sufficient Conditions 115
 - 4.4 Optimality Conditions: Unconstrained Problem 116
 - 4.4.1 Concepts Related to Optimality Conditions 116
 - 4.4.2 Optimality Conditions for Functions of a Single Variable 117
 - 4.4.3 Optimality Conditions for Functions of Several Variables 122
 - 4.5 Necessary Conditions: Equality-Constrained Problem 130
 - 4.5.1 Lagrange Multipliers 131
 - 4.5.2 Lagrange Multiplier Theorem 135
 - 4.6 Necessary Conditions for a General Constrained Problem 137
 - 4.6.1 The Role of Inequalities 137
 - 4.6.2 Karush-Kuhn-Tucker Necessary Conditions 139
 - 4.6.3 Summary of the KKT Solution Approach 152
 - 4.7 Postoptimality Analysis: The Physical Meaning of Lagrange Multipliers 153
 - 4.7.1 Effect of Changing Constraint Limits 153
 - 4.7.2 Effect of Cost Function Scaling on the Lagrange Multipliers 156
 - 4.7.3 Effect of Scaling a Constraint on Its Lagrange Multiplier 158
 - 4.7.4 Generalization of Constraint Variation Sensitivity Result 159
 - 4.8 Global Optimality 159
 - 4.8.1 Convex Sets 160
 - 4.8.2 Convex Functions 162
 - 4.8.3 Convex Programming Problem 164
 - 4.8.4 Transformation of a Constraint 168
 - 4.8.5 Sufficient Conditions for Convex Programming Problems 169
 - 4.9 Engineering Design Examples 171
 - 4.9.1 Design of a Wall Bracket 171
 - 4.9.2 Design of a Rectangular Beam 174
- Exercises for Chapter 4 178

- 5 More on Optimum Design Concepts: Optimality Conditions 189
 - 5.1 Alternate Form of KKT Necessary Conditions 189
 - 5.2 Irregular Points 192
 - 5.3 Second-Order Conditions for Constrained Optimization 194
 - 5.4 Second-Order Conditions for Rectangular Beam Design Problem 199
 - 5.5 Duality in Nonlinear Programming 201
 - 5.5.1 Local Duality: Equality Constraints Case 201
 - 5.5.2 Local Duality: The Inequality Constraints Case 206
- Exercises for Chapter 5 208

II

NUMERICAL METHODS FOR CONTINUOUS VARIABLE OPTIMIZATION

6 Optimum Design with Excel Solver 213

- 6.1 Introduction to Numerical Methods for Optimum Design 213
 - 6.1.1 Classification of Search Methods 214
 - 6.1.2 *What to Do If the Solution Process Fails* 215
 - 6.1.3 Simple Scaling of Variables 217
 - 6.2 Excel Solver: An Introduction 218
 - 6.2.1 Excel Solver 218
 - 6.2.2 Roots of a Nonlinear Equation 219
 - 6.2.3 Roots of a Set of Nonlinear Equations 222
 - 6.3 Excel Solver for Unconstrained Optimization Problems 224
 - 6.4 Excel Solver for Linear Programming Problems 225
 - 6.5 Excel Solver for Nonlinear Programming: Optimum Design of Springs 227
 - 6.6 Optimum Design of Plate Girders Using Excel Solver 231
 - 6.7 Optimum Design of Tension Members 238
 - 6.8 Optimum Design of Compression Members 243
 - 6.8.1 Formulation of the Problem 243
 - 6.8.2 Formulation of the Problem for Inelastic Buckling 247
 - 6.8.3 Formulation of the Problem for Elastic Buckling 249
 - 6.9 Optimum Design of Members for Flexure 250
 - 6.10 Optimum Design of Telecommunication Poles 263
- Exercises for Chapter 6 271
- ## 7 Optimum Design with MATLAB 275
- 7.1 Introduction to the Optimization Toolbox 275
 - 7.1.1 Variables and Expressions 275
 - 7.1.2 Scalar, Array, and Matrix Operations 276
 - 7.1.3 Optimization Toolbox 276

- 7.2 Unconstrained Optimum Design Problems 278
 - 7.3 Constrained Optimum Design Problems 281
 - 7.4 Optimum Design Examples with MATLAB 284
 - 7.4.1 Location of Maximum Shear Stress for Two Spherical Bodies in Contact 284
 - 7.4.2 Column Design for Minimum Mass 286
 - 7.4.3 Flywheel Design for Minimum Mass 290
- Exercises for Chapter 7 294

8 Linear Programming Methods for Optimum Design 299

- 8.1 Linear Functions 300
 - 8.2 Definition of a Standard Linear Programming Problem 300
 - 8.2.1 Standard LP Definition 300
 - 8.2.2 Transcription to Standard LP 302
 - 8.3 Basic Concepts Related to Linear Programming Problems 305
 - 8.3.1 Basic Concepts 305
 - 8.3.2 LP Terminology 310
 - 8.3.3 Optimum Solution to LP Problems 313
 - 8.4 Calculation of Basic Solutions 314
 - 8.4.1 The Tableau 314
 - 8.4.2 The Pivot Step 316
 - 8.4.3 Basic Solutions to $\mathbf{Ax} = \mathbf{b}$ 317
 - 8.5 The Simplex Method 321
 - 8.5.1 The Simplex 321
 - 8.5.2 Basic Steps in the Simplex Method 321
 - 8.5.3 Basic Theorems of Linear Programming 326
 - 8.6 The Two-Phase Simplex Method—Artificial Variables 334
 - 8.6.1 Artificial Variables 334
 - 8.6.2 Artificial Cost Function 336
 - 8.6.3 Definition of the Phase I Problem 336
 - 8.6.4 Phase I Algorithm 337
 - 8.6.5 Phase II Algorithm 339
 - 8.6.6 Degenerate Basic Feasible Solution 345
 - 8.7 Postoptimality Analysis 348
 - 8.7.1 Changes in Constraint Limits 348
 - 8.7.2 Ranging Right-Side Parameters 354
 - 8.7.3 Ranging Cost Coefficients 359
 - 8.7.4 Changes in the Coefficient Matrix 361
- Exercises for Chapter 8 363

9 More on Linear Programming Methods for Optimum Design	377
9.1 Derivation of the Simplex Method	377
9.1.1 General Solution to $\mathbf{Ax} = \mathbf{b}$	377
9.1.2 Selection of a Nonbasic Variable that Should Become Basic	379
9.1.3 Selection of a Basic Variable that Should Become Nonbasic	381
9.1.4 Artificial Cost Function	382
9.1.5 The Pivot Step	384
9.1.6 Simplex Algorithm	384
9.2 An Alternate Simplex Method	385
9.3 Duality in Linear Programming	387
9.3.1 Standard Primal LP Problem	387
9.3.2 Dual LP Problem	388
9.3.3 Treatment of Equality Constraints	389
9.3.4 Alternate Treatment of Equality Constraints	391
9.3.5 Determination of the Primal Solution from the Dual Solution	392
9.3.6 Use of the Dual Tableau to Recover the Primal Solution	395
9.3.7 Dual Variables as Lagrange Multipliers	398
9.4 KKT Conditions for the LP Problem	400
9.4.1 KKT Optimality Conditions	400
9.4.2 Solution to the KKT Conditions	400
9.5 Quadratic Programming Problems	402
9.5.1 Definition of a QP Problem	402
9.5.2 KKT Necessary Conditions for the QP Problem	403
9.5.3 Transformation of KKT Conditions	404
9.5.4 <i>The Simplex Method for Solving QP Problem</i>	405
Exercises for Chapter 9	409
10 Numerical Methods for Unconstrained Optimum Design	411
10.1 Gradient-Based and Direct Search Methods	411
10.2 General Concepts: Gradient-Based Methods	412
10.2.1 General Concepts	413
10.2.2 <i>A General Iterative Algorithm</i>	413
10.3 Descent Direction and Convergence of Algorithms	415
10.3.1 Descent Direction and Descent Step	415
10.3.2 Convergence of Algorithms	417
10.3.3 Rate of Convergence	417
10.4 Step Size Determination: Basic Ideas	418
10.4.1 Definition of the Step Size Determination Subproblem	418
10.4.2 Analytical Method to Compute Step Size	419
10.5 Numerical Methods to Compute Step Size	421
10.5.1 <i>General Concepts</i>	421
10.5.2 Equal-Interval Search	423
10.5.3 Alternate Equal-Interval Search	425
10.5.4 Golden Section Search	425
10.6 Search Direction Determination: The Steepest-Descent Method	431
10.7 Search Direction Determination: The Conjugate Gradient Method	434
10.8 Other Conjugate Gradient Methods	437
Exercises for Chapter 10	438
11 More on Numerical Methods for Unconstrained Optimum Design	443
11.1 More on Step Size Determination	444
11.1.1 Polynomial Interpolation	444
11.1.2 Inexact Line Search: Armijo's Rule	448
11.1.3 Inexact Line Search: Wolfe Conditions	449
11.1.4 Inexact Line Search: Goldstein Test	450
11.2 More on the Steepest-Descent Method	451
11.2.1 Properties of the Gradient Vector	451
11.2.2 Orthogonality of Steepest-Descent Directions	454
11.3 Scaling of Design Variables	456
11.4 Search Direction Determination: Newton's Method	459
11.4.1 Classical Newton's Method	460
11.4.2 Modified Newton's Method	461
11.4.3 Marquardt Modification	465
11.5 Search Direction Determination: Quasi-Newton Methods	466
11.5.1 Inverse Hessian Updating: The DFP Method	467
11.5.2 Direct Hessian Updating: The BFGS Method	470
11.6 Engineering Applications of Unconstrained Methods	472
11.6.1 Data Interpolation	472
11.6.2 Minimization of Total Potential Energy	473

11.6.3 Solutions of Nonlinear Equations	475
11.7 Solutions to Constrained Problems Using Unconstrained Optimization Methods	477
11.7.1 Sequential Unconstrained Minimization Techniques	478
11.7.2 Augmented Lagrangian (Multiplier) Methods	479
11.8 Rate of Convergence of Algorithms	481
11.8.1 Definitions	481
11.8.2 Steepest-Descent Method	482
11.8.3 Newton's Method	483
11.8.4 Conjugate Gradient Method	484
11.8.5 Quasi-Newton Methods	484
11.9 Direct Search Methods	485
11.9.1 Univariate Search	485
11.9.2 Hooke-Jeeves Method	486
Exercises for Chapter 11	487

12 Numerical Methods for Constrained Optimum Design 491

12.1 Basic Concepts Related to Numerical Methods	492
12.1.1 Basic Concepts Related to Algorithms for Constrained Problems	492
12.1.2 Constraint Status at a Design Point	495
12.1.3 Constraint Normalization	496
12.1.4 The Descent Function	498
12.1.5 Convergence of an Algorithm	498
12.2 Linearization of the Constrained Problem	499
12.3 The Sequential Linear Programming Algorithm	506
12.3.1 Move Limits in SLP	506
12.3.2 An SLP Algorithm	508
12.3.3 The SLP Algorithm: Some Observations	512
12.4 Sequential Quadratic Programming	513
12.5 Search Direction Calculation: The QP Subproblem	514
12.5.1 Definition of the QP Subproblem	514
12.5.2 Solving of the QP Subproblem	518
12.6 The Step Size Calculation Subproblem	520
12.6.1 The Descent Function	520
12.6.2 Step Size Calculation: Line Search	522
12.7 The Constrained Steepest-Descent Method	525
12.7.1 The CSD Algorithm	526

12.7.2 The CSD Algorithm: Some Observations	527
Exercises for Chapter 12	527

13 More on Numerical Methods for Constrained Optimum Design 533

13.1 Potential Constraint Strategy	534
13.2 Inexact Step Size Calculation	537
13.2.1 Basic Concept	537
13.2.2 Descent Condition	538
13.2.3 CSD Algorithm with Inexact Step Size	542
13.3 Bound-Constrained Optimization	549
13.3.1 Optimality Conditions	549
13.3.2 Projection Methods	550
13.3.3 Step Size Calculation	552
13.4 Sequential Quadratic Programming: SQP Methods	553
13.4.1 Derivation of the Quadratic Programming Subproblem	554
13.4.2 Quasi-Newton Hessian Approximation	557
13.4.3 SQP Algorithm	558
13.4.4 Observations on SQP Methods	561
13.4.5 Descent Functions	563
13.5 Other Numerical Optimization Methods	564
13.5.1 Method of Feasible Directions	564
13.5.2 Gradient Projection Method	566
13.5.3 Generalized Reduced Gradient Method	567
13.6 Solution to the Quadratic Programming Subproblem	569
13.6.1 Solving the KKT Necessary Conditions	570
13.6.2 Direct Solution to the QP Subproblem	571
Exercises for Chapter 13	572

14 Practical Applications of Optimization 575

14.1 Formulation of Practical Design Optimization Problems	576
14.1.1 General Guidelines	576
14.1.2 Example of a Practical Design Optimization Problem	577

14.2 Gradient Evaluation of Implicit Functions	582	15.1.3 Overview of Solution Concepts	622
14.3 Issues in Practical Design Optimization	587	15.2 Branch-and-Bound Methods	623
14.3.1 Selection of an Algorithm	587	15.2.1 Basic BBM	623
14.3.2 Attributes of a Good Optimization Algorithm	588	15.2.2 BBM with Local Minimization	625
14.4 Use of General-Purpose Software	589	15.2.3 BBM for General MV-OPT	627
14.4.1 Software Selection	589	15.3 Integer Programming	628
14.4.2 Integration of an Application into General-Purpose Software	589	15.4 Sequential Linearization Methods	629
14.5 Optimum Design of Two-Member Frame with Out-of-Plane Loads	590	15.5 Simulated Annealing	630
14.6 Optimum Design of a Three-Bar Structure for Multiple Performance Requirements	592	15.6 Dynamic Rounding-Off Method	632
14.6.1 Symmetric Three-Bar Structure	592	15.7 Neighborhood Search Method	633
14.6.2 Asymmetric Three-Bar Structure	594	15.8 Methods for Linked Discrete Variables	633
14.6.3 Comparison of Solutions	598	15.9 Selection of a Method	635
14.7 Optimal Control of Systems by Nonlinear Programming	598	15.10 Adaptive Numerical Method for Discrete Variable Optimization	636
14.7.1 A Prototype Optimal Control Problem	598	15.10.1 Continuous Variable Optimization	636
14.7.2 Minimization of Error in State Variable	602	15.10.2 Discrete Variable Optimization	637
14.7.3 Minimum Control Effort Problem	608	Exercises for Chapter 15	639
14.7.4 Minimum Time Control Problem	609		
14.7.5 Comparison of Three Formulations for the Optimal Control of System Motion	611		
14.8 Alternative Formulations for Structural Optimization Problems	612		
14.9 Alternative Formulations for Time-Dependent Problems	613		
Exercises for Chapter 14	615		

III

ADVANCED AND MODERN TOPICS ON OPTIMUM DESIGN

15 Discrete Variable Optimum Design Concepts and Methods	619	16 Genetic Algorithms for Optimum Design	643
15.1 Basic Concepts and Definitions	620	16.1 Basic Concepts and Definitions	644
15.1.1 Definition of Mixed Variable Optimum Design Problem: MV-OPT	620	16.2 Fundamentals of Genetic Algorithms	646
15.1.2 Classification of Mixed Variable Optimum Design Problems	621	16.3 Genetic Algorithm for Sequencing-Type Problems	651
		16.4 Applications	653
		Exercises for Chapter 16	653
		17 Multi-objective Optimum Design Concepts and Methods	657
		17.1 Problem Definition	658
		17.2 Terminology and Basic Concepts	660
		17.2.1 Criterion Space and Design Space	660
		17.2.2 Solution Concepts	662
		17.2.3 Preferences and Utility Functions	665
		17.2.4 Vector Methods and Scalarization Methods	666
		17.2.5 Generation of Pareto Optimal Set	666
		17.2.6 Normalization of Objective Functions	667
		17.2.7 Optimization Engine	667
		17.3 Multi-objective Genetic Algorithms	667
		17.4 Weighted Sum Method	671
		17.5 Weighted Min-Max Method	672
		17.6 Weighted Global Criterion Method	673
		17.7 Lexicographic Method	674

- 17.8 Bounded Objective Function Method 675
- 17.9 Goal Programming 676
- 17.10 Selection of Methods 677
- Exercises for Chapter 17 678

18 Global Optimization Concepts and Methods 681

- 18.1 Basic Concepts of Solution Methods 682
 - 18.1.1 Basic Solution Concepts 682
 - 18.1.2 Overview of Methods 683
- 18.2 Overview of Deterministic Methods 684
 - 18.2.1 Covering Methods 684
 - 18.2.2 Zooming Method 685
 - 18.2.3 Methods of Generalized Descent 686
 - 18.2.4 Tunneling Method 688
- 18.3 Overview of Stochastic Methods 689
 - 18.3.1 Pure Random Search Method 690
 - 18.3.2 Multistart Method 691
 - 18.3.3 Clustering Methods 691
 - 18.3.4 Controlled Random Search: Nelder-Mead Method 694
 - 18.3.5 Acceptance-Rejection Methods 697
 - 18.3.6 Stochastic Integration 698
- 18.4 Two Local-Global Stochastic Methods 699
 - 18.4.1 Conceptual Local-Global Algorithm 699
 - 18.4.2 Domain Elimination Method 700
 - 18.4.3 Stochastic Zooming Method 702
 - 18.4.4 Operations Analysis of Methods 702
- 18.5 Numerical Performance of Methods 705
 - 18.5.1 Summary of Features of Methods 705
 - 18.5.2 Performance of Some Methods with Unconstrained Problems 706
 - 18.5.3 Performance of Stochastic Zooming and Domain Elimination Methods 707
 - 18.5.4 Global Optimization of Structural Design Problems 708
- Exercises for Chapter 18 710

19 Nature-Inspired Search Methods 713

- 19.1 Differential Evolution Algorithm 714
 - 19.1.1 Generation of an Initial Population 715
 - 19.1.2 Generation of a Donor Design 716

- 19.1.3 Crossover Operation to Generate the Trial Design 716
- 19.1.4 Acceptance/Rejection of the Trial Design 717
- 19.1.5 DE Algorithm 717
- 19.2 Ant Colony Optimization 718
 - 19.2.1 Ant Behavior 718
 - 19.2.2 ACO Algorithm for the Traveling Salesman Problem 721
 - 19.2.3 ACO Algorithm for Design Optimization 724
- 19.3 Particle Swarm Optimization 727
 - 19.3.1 Swarm Behavior and Terminology 727
 - 19.3.2 Particle Swarm Optimization Algorithm 728
- Exercises for Chapter 19 729

20 Additional Topics on Optimum Design 731

- 20.1 Meta-Models for Design Optimization 731
 - 20.1.1 Meta-Model 731
 - 20.1.2 Response Surface Method 733
 - 20.1.3 Normalization of Variables 737
- 20.2 Design of Experiments for Response Surface Generation 741
- 20.3 Discrete Design with Orthogonal Arrays 749
- 20.4 Robust Design Approach 754
 - 20.4.1 Robust Optimization 754
 - 20.4.2 The Taguchi Method 761
- 20.5 Reliability-Based Design Optimization—Design under Uncertainty 767
 - 20.5.1 Review of Background Material for RBDO 768
 - 20.5.2 Calculation of the Reliability Index 774
 - 20.5.3 Formulation of Reliability-Based Design Optimization 784

Appendix A: Vector and Matrix Algebra 785

- A.1 Definition of Matrices 785
- A.2 Types of Matrices and Their Operations 787
 - A.2.1 Null Matrix 787
 - A.2.2 Vector 787
 - A.2.3 Addition of Matrices 787

A.2.4	Multiplication of Matrices	788	A.5.1	Linear Independence of a Set of Vectors	810
A.2.5	Transpose of a Matrix	790	A.5.2	Vector Spaces	814
A.2.6	Elementary Row—Column Operations	790	A.6	Eigenvalues and Eigenvectors	816
A.2.7	Equivalence of Matrices	790	A.7	Norm and Condition Number of a Matrix	818
A.2.8	Scalar Product—Dot Product of Vectors	790	A.7.1	Norm of Vectors and Matrices	818
A.2.9	Square Matrices	791	A.7.2	Condition Number of a Matrix	819
A.2.10	Partitioning of Matrices	791	Exercises for Appendix A	819	
A.3	Solving n Linear Equations in n Unknowns	792	Appendix B: Sample Computer Programs	823	
A.3.1	Linear Systems	792	B.1	Equal Interval Search	823
A.3.2	Determinants	793	B.2	Golden Section Search	826
A.3.3	Gaussian Elimination Procedure	796	B.3	Steepest-Descent Method	829
A.3.4	Inverse of a Matrix: Gauss-Jordan Elimination	800	B.4	Modified Newton's Method	829
A.4	Solution to m Linear Equations in n Unknowns	803	Bibliography	841	
A.4.1	Rank of a Matrix	803	Answers to Selected Exercises	851	
A.4.2	General Solution of $m \times n$ Linear Equations	804	Index	861	
A.5	Concepts Related to a Set of Vectors	810			