



minimize  $f(x)$   
subject to  $g_i(x) = 0, i \in \mathcal{S}$   
 $g_i(x) \geq 0, i \in \mathcal{I}$ .

$$x_{k+1} = x_k + \alpha_P \Delta x_k$$
$$\lambda_{k+1} = \lambda_k + \alpha_D \Delta \lambda_k$$

# Linear and Nonlinear Optimization

SECOND EDITION

Igor Griva ■ Stephen G. Nash ■ Ariela Sofer

# Contents

<b>Preface</b>	xiii
<b>I Basics</b>	<b>1</b>
<b>1 Optimization Models</b>	<b>3</b>
1.1 Introduction . . . . .	3
1.2 Optimization: An Informal Introduction . . . . .	4
1.3 Linear Equations . . . . .	7
1.4 Linear Optimization . . . . .	10
Exercises . . . . .	12
1.5 Least-Squares Data Fitting . . . . .	12
Exercises . . . . .	14
1.6 Nonlinear Optimization . . . . .	14
1.7 Optimization Applications . . . . .	18
1.7.1 Crew Scheduling and Fleet Scheduling . . . . .	18
Exercises . . . . .	22
1.7.2 Support Vector Machines . . . . .	22
Exercises . . . . .	24
1.7.3 Portfolio Optimization . . . . .	25
Exercises . . . . .	27
1.7.4 Intensity Modulated Radiation Treatment Planning . . . . .	28
Exercises . . . . .	31
1.7.5 Positron Emission Tomography Image Reconstruction . . . . .	32
Exercises . . . . .	34
1.7.6 Shape Optimization . . . . .	35
1.8 Notes . . . . .	40
<b>2 Fundamentals of Optimization</b>	<b>43</b>
2.1 Introduction . . . . .	43
2.2 Feasibility and Optimality . . . . .	43
Exercises . . . . .	47
2.3 Convexity . . . . .	48
2.3.1 Derivatives and Convexity . . . . .	50

Exercises . . . . .	52
2.4 The General Optimization Algorithm . . . . .	54
Exercises . . . . .	58
2.5 Rates of Convergence . . . . .	58
Exercises . . . . .	61
2.6 Taylor Series . . . . .	62
Exercises . . . . .	65
2.7 Newton's Method for Nonlinear Equations . . . . .	67
2.7.1 Systems of Nonlinear Equations . . . . .	72
Exercises . . . . .	74
2.8 Notes . . . . .	76
<b>3 Representation of Linear Constraints</b>	<b>77</b>
3.1 Basic Concepts . . . . .	77
Exercises . . . . .	82
3.2 Null and Range Spaces . . . . .	82
Exercises . . . . .	84
3.3 Generating Null-Space Matrices . . . . .	86
3.3.1 Variable Reduction Method . . . . .	86
3.3.2 Orthogonal Projection Matrix . . . . .	89
3.3.3 Other Projections . . . . .	90
3.3.4 The QR Factorization . . . . .	90
Exercises . . . . .	91
3.4 Notes . . . . .	93
<b>II Linear Programming</b>	<b>95</b>
<b>4 Geometry of Linear Programming</b>	<b>97</b>
4.1 Introduction . . . . .	97
Exercises . . . . .	98
4.2 Standard Form . . . . .	100
Exercises . . . . .	105
4.3 Basic Solutions and Extreme Points . . . . .	106
Exercises . . . . .	114
4.4 Representation of Solutions; Optimality . . . . .	117
Exercises . . . . .	123
4.5 Notes . . . . .	124
<b>5 The Simplex Method</b>	<b>125</b>
5.1 Introduction . . . . .	125
5.2 The Simplex Method . . . . .	126
5.2.1 General Formulas . . . . .	129
5.2.2 Unbounded Problems . . . . .	134
5.2.3 Notation for the Simplex Method (Tableaus) . . . . .	135
5.2.4 Deficiencies of the Tableau . . . . .	139

Exercises . . . . .	141
5.3     The Simplex Method (Details) . . . . .	144
5.3.1     Multiple Solutions . . . . .	144
5.3.2     Feasible Directions and Edge Directions . . . . .	145
Exercises . . . . .	148
5.4     Getting Started—Artificial Variables . . . . .	149
5.4.1     The Two-Phase Method . . . . .	150
5.4.2     The Big-M Method . . . . .	156
Exercises . . . . .	159
5.5     Degeneracy and Termination . . . . .	162
5.5.1     Resolving Degeneracy Using Perturbation . . . . .	167
Exercises . . . . .	170
5.6     Notes . . . . .	171
<b>6     Duality and Sensitivity</b>	<b>173</b>
6.1     The Dual Problem . . . . .	173
Exercises . . . . .	177
6.2     Duality Theory . . . . .	179
6.2.1     Complementary Slackness . . . . .	182
6.2.2     Interpretation of the Dual . . . . .	184
Exercises . . . . .	185
6.3     The Dual Simplex Method . . . . .	189
Exercises . . . . .	194
6.4     Sensitivity . . . . .	195
Exercises . . . . .	201
6.5     Parametric Linear Programming . . . . .	204
Exercises . . . . .	210
6.6     Notes . . . . .	211
<b>7     Enhancements of the Simplex Method</b>	<b>213</b>
7.1     Introduction . . . . .	213
7.2     Problems with Upper Bounds . . . . .	214
Exercises . . . . .	221
7.3     Column Generation . . . . .	222
Exercises . . . . .	227
7.4     The Decomposition Principle . . . . .	227
Exercises . . . . .	238
7.5     Representation of the Basis . . . . .	240
7.5.1     The Product Form of the Inverse . . . . .	240
7.5.2     Representation of the Basis—The <i>LU</i> Factorization . . . . .	248
Exercises . . . . .	256
7.6     Numerical Stability and Computational Efficiency . . . . .	259
7.6.1     Pricing . . . . .	260
7.6.2     The Initial Basis . . . . .	264
7.6.3     Tolerances; Degeneracy . . . . .	265
7.6.4     Scaling . . . . .	266

7.6.5	Preprocessing . . . . .	267
7.6.6	Model Formats . . . . .	268
Exercises . . . . .		269
7.7	Notes . . . . .	270
<b>8</b>	<b>Network Problems</b>	<b>271</b>
8.1	Introduction . . . . .	271
8.2	Basic Concepts and Examples . . . . .	271
Exercises . . . . .		280
8.3	Representation of the Basis . . . . .	280
Exercises . . . . .		287
8.4	The Network Simplex Method . . . . .	287
Exercises . . . . .		294
8.5	Resolving Degeneracy . . . . .	295
Exercises . . . . .		299
8.6	Notes . . . . .	299
<b>9</b>	<b>Computational Complexity of Linear Programming</b>	<b>301</b>
9.1	Introduction . . . . .	301
9.2	Computational Complexity . . . . .	302
Exercises . . . . .		304
9.3	Worst-Case Behavior of the Simplex Method . . . . .	305
Exercises . . . . .		308
9.4	The Ellipsoid Method . . . . .	308
Exercises . . . . .		313
9.5	The Average-Case Behavior of the Simplex Method . . . . .	314
9.6	Notes . . . . .	316
<b>10</b>	<b>Interior-Point Methods for Linear Programming</b>	<b>319</b>
10.1	Introduction . . . . .	319
10.2	The Primal-Dual Interior-Point Method . . . . .	321
10.2.1	Computational Aspects of Interior-Point Methods . . . . .	328
10.2.2	The Predictor-Corrector Algorithm . . . . .	329
Exercises . . . . .		330
10.3	Feasibility and Self-Dual Formulations . . . . .	331
Exercises . . . . .		334
10.4	Some Concepts from Nonlinear Optimization . . . . .	334
10.5	Affine-Scaling Methods . . . . .	336
Exercises . . . . .		343
10.6	Path-Following Methods . . . . .	344
Exercises . . . . .		352
10.7	Notes . . . . .	353

<b>III Unconstrained Optimization</b>	<b>355</b>
<b>11 Basics of Unconstrained Optimization</b>	<b>357</b>
11.1 Introduction . . . . .	357
11.2 Optimality Conditions . . . . .	357
Exercises . . . . .	361
11.3 Newton's Method for Minimization . . . . .	364
Exercises . . . . .	369
11.4 Guaranteeing Descent . . . . .	371
Exercises . . . . .	374
11.5 Guaranteeing Convergence: Line Search Methods . . . . .	375
11.5.1 Other Line Searches . . . . .	381
Exercises . . . . .	385
11.6 Guaranteeing Convergence: Trust-Region Methods . . . . .	391
Exercises . . . . .	398
11.7 Notes . . . . .	399
<b>12 Methods for Unconstrained Optimization</b>	<b>401</b>
12.1 Introduction . . . . .	401
12.2 Steepest-Descent Method . . . . .	402
Exercises . . . . .	408
12.3 Quasi-Newton Methods . . . . .	411
Exercises . . . . .	420
12.4 Automating Derivative Calculations . . . . .	422
12.4.1 Finite-Difference Derivative Estimates . . . . .	422
12.4.2 Automatic Differentiation . . . . .	426
Exercises . . . . .	429
12.5 Methods That Do Not Require Derivatives . . . . .	431
12.5.1 Simulation-Based Optimization . . . . .	432
12.5.2 Compass Search: A Derivative-Free Method . . . . .	434
12.5.3 Convergence of Compass Search . . . . .	437
Exercises . . . . .	440
12.6 Termination Rules . . . . .	441
Exercises . . . . .	445
12.7 Historical Background . . . . .	446
12.8 Notes . . . . .	448
<b>13 Low-Storage Methods for Unconstrained Problems</b>	<b>451</b>
13.1 Introduction . . . . .	451
13.2 The Conjugate-Gradient Method for Solving Linear Equations . . . . .	452
Exercises . . . . .	459
13.3 Truncated-Newton Methods . . . . .	460
Exercises . . . . .	465
13.4 Nonlinear Conjugate-Gradient Methods . . . . .	466
Exercises . . . . .	469
13.5 Limited-Memory Quasi-Newton Methods . . . . .	470

Exercises . . . . .	473
13.6 Preconditioning . . . . .	474
Exercises . . . . .	477
13.7 Notes . . . . .	478
<b>IV Nonlinear Optimization</b>	<b>481</b>
<b>14 Optimality Conditions for Constrained Problems</b>	<b>483</b>
14.1 Introduction . . . . .	483
14.2 Optimality Conditions for Linear Equality Constraints . . . . .	484
Exercises . . . . .	489
14.3 The Lagrange Multipliers and the Lagrangian Function . . . . .	491
Exercises . . . . .	493
14.4 Optimality Conditions for Linear Inequality Constraints . . . . .	494
Exercises . . . . .	501
14.5 Optimality Conditions for Nonlinear Constraints . . . . .	502
14.5.1 Statement of Optimality Conditions . . . . .	503
Exercises . . . . .	508
14.6 Preview of Methods . . . . .	510
Exercises . . . . .	514
14.7 Derivation of Optimality Conditions for Nonlinear Constraints . . . . .	515
Exercises . . . . .	520
14.8 Duality . . . . .	522
14.8.1 Games and Min-Max Duality . . . . .	523
14.8.2 Lagrangian Duality . . . . .	526
14.8.3 Wolfe Duality . . . . .	532
14.8.4 More on the Dual Function . . . . .	534
14.8.5 Duality in Support Vector Machines . . . . .	538
Exercises . . . . .	542
14.9 Historical Background . . . . .	543
14.10 Notes . . . . .	546
<b>15 Feasible-Point Methods</b>	<b>549</b>
15.1 Introduction . . . . .	549
15.2 Linear Equality Constraints . . . . .	549
Exercises . . . . .	555
15.3 Computing the Lagrange Multipliers . . . . .	556
Exercises . . . . .	561
15.4 Linear Inequality Constraints . . . . .	563
15.4.1 Linear Programming . . . . .	570
Exercises . . . . .	572
15.5 Sequential Quadratic Programming . . . . .	573
Exercises . . . . .	580
15.6 Reduced-Gradient Methods . . . . .	581
Exercises . . . . .	588

---

15.7	Filter Methods . . . . .	588
	Exercises . . . . .	597
15.8	Notes . . . . .	598
<b>16</b>	<b>Penalty and Barrier Methods</b>	<b>601</b>
16.1	Introduction . . . . .	601
16.2	Classical Penalty and Barrier Methods . . . . .	602
16.2.1	Barrier Methods . . . . .	603
16.2.2	Penalty Methods . . . . .	610
16.2.3	Convergence . . . . .	613
	Exercises . . . . .	617
16.3	Ill-Conditioning . . . . .	618
16.4	Stabilized Penalty and Barrier Methods . . . . .	619
	Exercises . . . . .	623
16.5	Exact Penalty Methods . . . . .	623
	Exercises . . . . .	626
16.6	Multiplier-Based Methods . . . . .	626
16.6.1	Dual Interpretation . . . . .	635
	Exercises . . . . .	638
16.7	Nonlinear Primal-Dual Methods . . . . .	640
16.7.1	Primal-Dual Interior-Point Methods . . . . .	641
16.7.2	Convergence of the Primal-Dual Interior-Point Method .	645
	Exercises . . . . .	647
16.8	Semidefinite Programming . . . . .	649
	Exercises . . . . .	654
16.9	Notes . . . . .	656
<b>V</b>	<b>Appendices</b>	<b>659</b>
<b>A</b>	<b>Topics from Linear Algebra</b>	<b>661</b>
A.1	Introduction . . . . .	661
A.2	Eigenvalues . . . . .	661
A.3	Vector and Matrix Norms . . . . .	662
A.4	Systems of Linear Equations . . . . .	664
A.5	Solving Systems of Linear Equations by Elimination . . . . .	666
A.6	Gaussian Elimination as a Matrix Factorization . . . . .	669
A.6.1	Sparse Matrix Storage . . . . .	675
A.7	Other Matrix Factorizations . . . . .	676
A.7.1	Positive-Definite Matrices . . . . .	677
A.7.2	The $LDL^T$ and Cholesky Factorizations . . . . .	678
A.7.3	An Orthogonal Matrix Factorization . . . . .	681
A.8	Sensitivity (Conditioning) . . . . .	683
A.9	The Sherman–Morrison Formula . . . . .	686
A.10	Notes . . . . .	688

<b>B Other Fundamentals</b>	<b>691</b>
B.1 Introduction . . . . .	691
B.2 Computer Arithmetic . . . . .	691
B.3 Big-O Notation, $O(\cdot)$ . . . . .	693
B.4 The Gradient, Hessian, and Jacobian . . . . .	694
B.5 Gradient and Hessian of a Quadratic Function . . . . .	696
B.6 Derivatives of a Product . . . . .	697
B.7 The Chain Rule . . . . .	698
B.8 Continuous Functions; Closed and Bounded Sets . . . . .	699
B.9 The Implicit Function Theorem . . . . .	700
<b>C Software</b>	<b>703</b>
C.1 Software . . . . .	703
<b>Bibliography</b>	<b>707</b>
<b>Index</b>	<b>727</b>