List of Figures

Fig. 0.1	NLALIB hierarchy.	XXV
Fig. 1.1	Matrix multiplication.	3
Fig. 1.2	Rotating the <i>xy</i> -plane.	7
Fig. 1.3	Rotated line	8
Fig. 1.4	Rotate three-dimensional coordinate system.	9
Fig. 1.5	Translate a point in two dimensions.	9
Fig. 1.6	Rotate a line about a point.	10
Fig. 1.7	Rotation about an arbitrary point.	11
Fig. 1.8	Undirected graph.	12
Fig. 2.1	Polynomial passing through four points.	26
Fig. 2.2	Inconsistent equations.	31
Fig. 2.3	Truss.	38
Fig. 2.4	Electrical circuit.	39
Fig. 2.5	Truss problem.	45
Fig. 2.6	Circuit problem.	45
Fig. 3.1	Subspace spanned by two vectors.	48
Fig. 4.1	Geometrical interpretation of the determinant.	75
Fig. 5.1	Direction of eigenvectors.	80
Fig. 5.2	Circuit with an inductor.	89
Fig. 5.3	Currents in the <i>RL</i> circuit.	92
Fig. 5.4	Digraph of an irreducible matrix.	93
Fig. 5.5	Hanowa matrix.	101
Fig. 6.1	Distance between points.	104
Fig. 6.2	Equality, addition, and subtraction of vectors.	104
Fig. 6.3	Scalar multiplication of vectors.	104
Fig. 6.4	Vector length.	106
Fig. 6.5	Geometric interpretation of the inner product.	106
Fig. 6.6	Law of cosines.	106
Fig. 6.7	Triangle inequality.	112
Fig. 6.8	Signal comparison.	112
Fig. 6.9	Projection of one vector onto another.	115
Fig. 7.1	Effect of an orthogonal transformation on a vector.	122
Fig. 7.2	Spherical coordinates.	123
Fig. 7.3	Orthonormal basis for spherical coordinates.	124
Fig. 7.4	Point in spherical coordinate basis and Cartesian coordinates.	125
Fig. 7.5	Function specified in spherical coordinates.	126
Fig. 7.6	Effect of a matrix on vectors.	128
Fig. 7.7	Unit spheres in three norms.	129
Fig. 7.8	Image of the unit circle.	133
Fig. 8.1	Floating-point number system.	149
Fig. 8.2	Map of IEEE double-precision floating-point.	150
Fig. 9.1	Matrix multiplication.	165
Fig. 10.1	Forward and backward errors.	184
Fig. 10.2	The Wilkinson polynomial.	187
Fig. 10.3 Fig. 10.4	Ill-conditioned Cauchy problem. Conditioning of a problem.	188 189
0	LU decomposition of a matrix.	206
Fig. 11.1 Fig. 11.2	$k \times k$ submatrix.	215
Fig. 11.2	Gaussian elimination flop count.	213
Fig. 11.3	Square wave with period 2π .	217
Fig. 12.1	Fourier series converging to a square wave.	244
Fig. 12.3	The heat equation: a thin rod insulated on its sides.	245
116. 14.3	The near equation, a tinn rou insurated on its sides.	243

Fig.	12.4	Numerical solution of the heat equation: subdivisions of the x and t axes.	245
Fig.	12.5	Numerical solution of the heat equation:locally related points in the grid.	246
	12.6	Grid for the numerical solution of the heat equation.	246
		1	
_	12.7	Graph of the solution for the heat equation problem.	247
Fig.	12.8	Linear least-squares approximation.	250
Fig.	12.9	Quadratic least-squares approximation.	251
	12.10	Estimating absolute zero.	252
		· · · · · · · · · · · · · · · · · · ·	
	12.11	Linear interpolation.	253
Fig.	12.12	Cubic splines.	253
Fig.	12.13	Cubic spline approximation.	256
	12.14	Sawtooth wave with period 2π .	258
		•	
-	13.1	Conductance matrix.	270
Fig.	14.1	Vector orthogonal projection.	282
Fig.	14.2	Removing the orthogonal projection.	282
	14.3	Result of the first three steps of Gram-Schmidt.	283
_		*	305
_	15.1	The four fundamental subspaces of a matrix.	
	15.2	SVD rotation and distortion.	308
Fig.	15.3	(a) Lena (512 \times 512) and (b) lena using 35 modes.	312
Fig.	15.4	Lena using 125 modes.	312
	15.5	Singular value graph of lena.	313
	15.6	SVD image capture.	314
Fig.	16.1	Geometric interpretation of the least-squares solution.	322
Fig.	16.2	An overdetermined system.	322
	16.3	Least-squares estimate for the power function.	329
	16.4	The reduced SVD for a full rank matrix.	330
Fig.	16.5	Velocity of an enzymatic reaction.	332
Fig.	16.6	Underdetermined system.	339
Fig.	17.1	Givens matrix.	353
_	17.2	Givens rotation.	354
_			
	17.3	Householder reflection.	363
Fig.	17.4	Linear combination associated with Householder reflection.	363
Fig.	17.5	Householder reflection to a multiple of e_1 .	366
_	17.6	Transforming an $m \times n$ matrix to upper triangular form using householder reflections.	369
	17.7	Householder reflections and submatrices.	369
Fig.	17.8	Householder reflection for a submatrix.	369
Fig.	18.1	Tacoma Narrows Bridge collapse.	380
_	18.2	Mass-spring system.	380
_			
_	18.3	Solution to a system of ordinary differential equations.	382
Fig.	18.4	Populations using the Leslie matrix.	387
Fig.	18.5	Column buckling.	387
Fig.	18.6	Deflection curves for critical loads P_1 , P_2 , and P_3 .	389
_	18.7	Reduced Hessenberg matrix.	401
		· · · · · · · · · · · · · · · · · · ·	
	18.8	Inductive step in Schur's triangularization.	407
Fig.	18.9	Schur's triangularization.	407
Fig.	18.10	Eigenvalues of a 2×2 matrix as shifts.	413
	18.11	Springs problem.	430
	19.1	Bisection.	454
_			
	19.2	Interlacing.	454
	19.3	Bisection method: λ_k located to the left.	456
Fig.	19.4	Bisection method: λ_k located to the right.	457
	19.5	Bisection and multiple eigenvalues.	458
_		Secular equation.	
_	19.6	•	460
	20.1	SOR spectral radius.	479
Fig.	20.2	Region in the plane.	479
	20.3	Five-point stencil.	480
	20.4	Poisson's equation. (a) Approximate solution and (b) analytical solution.	481
-		· · · · · · · · · · · · · · · · · · ·	
	20.5	One-dimensional Poisson equation grid.	484
	20.6	One-dimensional red-black GS.	486
	21.1	Examples of sparse matrices. (a) Positive definite: structural problem, (b) symmetric indefinite: quantum chemistry problem, and	
O.		(c) nonsymmetric: computational fluid dynamics problem.	492
E:~	21.2		
	21.2	Steepest descent. (a) Quadratic function in steepest descent and (b) gradient and contour lines.	495
	21.3	Steepest descent. (a) Deepest descent zigzag and (b) gradient contour lines.	495
Fig.	21.4	2-Norm and A-norm convergence.	498
Fig.	21.5	CG vs. steepest descent. (a) Density plot for symmetric positive definite sparse matrix CGDES and (b) residuals of CG and steepest	
0		descent.	502
			202

Fig. 21.6	Cholesky decomposition of a sparse symmetric positive definite matrix.	504
Fig. 21.7	CG vs. PRECG.	506
Fig. 21.8	Arnoldi projection from \mathbb{R}^n into \mathbb{R}^m , $m \ll n$.	509
Fig. 21.9	Arnoldi decomposition form 1.	511
Fig. 21.10	Arnoldi decomposition form 2.	512
Fig. 21.11	Large nonsymmetric matrix.	515
Fig. 21.12	Lanczos decomposition.	516
Fig. 21.13	Lanczos process with and without reorthogonalization. (a) Lanczos without reorthogonalization and (b) Lanczos with	
	reorthogonalization.	518
Fig. 21.14	Large sparse symmetric matrices.	520
Fig. 21.15	Iterative method decision tree.	521
Fig. 21.16	Poisson's equation grid for $n = 4$.	521
Fig. 21.17	Estimating the normal derivative.	523
Fig. 21.18	36×36 biharmonic matrix density plot.	524
Fig. 21.19	The biharmonic equation. (a) Biharmonic equation numerical solution and (b) biharmonic equation true solution.	525
Fig. 21.20	(a) Electrostatic potential fields induced by approximately 15 randomly placed point charges (b) contour plot of randomly placed	
	point charges.	532
Fig. 22.1	Nonsymmetric sparse matrix used in a chemical engineering model	534
Fig. 22.2	Eigenvalues and Ritz values of a random sparse matrix.	536
Fig. 23.1	Demmel and Kahan zero-shift <i>QR</i> downward sweep.	562
Fig. A.1	Complex addition and subtraction.	572
Fig. A.2	Complex conjugate.	572
Fig. A.3	Riemann zeta function.	577
Fig. C.1	The first five Chebyshev polynomials.	584