

General Index

- A**ccelerated convergence of series 166ff.
Accuracy 28f.
 achievable in minimization 398, 404, 410
 achievable in root finding 353
 contrasted with fidelity 841, 849
 CPU different from memory 186
 vs. stability 710, 736, 839, 853
Acknowledgments xii
Adams-Bashford-Moulton method 749
Adams' stopping criterion 373
Adaptive integration 129, 141, 709, 714ff.,
 725ff., 733f., 737, 744, 749f., 797
Adaptive Monte Carlo integration 316ff.,
 319ff.
Addition, multiple precision 916
Addition theorem, elliptic integrals 262
ADI (alternating direction implicit) method
 856, 870f., 915
Adjoint operator 876
Adobe Illustrator xiii, xvii
Advective equation 835
AGM (arithmetic geometric mean) 915
Airy function 210, 240, 250
 routine for 250f.
Aitken's delta squared process 166
Aitken's interpolation algorithm 108
Algorithms, non-numerical 889ff.
Aliasing 501, 576
 see also Fourier transform
All-poles model 573
 see also Maximum entropy method (MEM)
All-zeros model 573
 see also Periodogram
Allocation of storage 19, 21f., 940ff.
Alternating-direction implicit method (ADI)
 856, 870f., 915
Alternating series 166f.
Alternative extended Simpson's rule 134
Amoeba 410
 see also Simplex, method of Nelder and
 Mead
Amplification factor 837, 839, 841, 849, 854f.
Amplitude error 840
Analog-to-digital converter 821, 894
Analyticity 201
Analyze/factorize/operate package 71f., 833
Anderson-Darling statistic 626f.
Andrew's sine 702
Annealing, method of simulated 394f., 444ff.
 assessment 454f.
 for continuous variables 444, 451f.
 schedule 445
 thermodynamic analogy 444f.
 traveling salesman problem 445ff.
ANSI C standard 2f., 14, 25, 930, 941
ANSI macro 17, 930
Antonov-Saleev variant of Sobol' sequence
 310ff.
Apple xvii
 Macintosh 894
Approximate inverse of matrix 57
Approximation of functions 105f.
 by Chebyshev polynomials 191f., 519
 Padé approximant 200ff.
 by rational functions 204ff.
 by wavelets 601f., 791
 see also Fitting
Arguments, conversion of data types 24f.,
 930
Arithmetic
 arbitrary precision 889, 915ff.
 complex 23f., 948ff.
 floating point 889
 IEEE standard 285, 890f.
 rounding 890
Arithmetic coding 889, 910ff.
Arithmetic-geometric mean (AGM) method
 915
Array
 centered subarray of 119
 how to allocate 19
 index range 18
 one-dimensional 18
 relation to C pointer 18
 three-dimensional 23
 two-dimensional 20f.
 unit-offset 18, 940f.
 variable dimension 20
 zero-offset 18
Artificial viscosity 840, 846
Ascending transformation, elliptic integrals
 262
ASCII character set 5, 896, 903, 910
Assembly language 278
Associated Legendre polynomials 252f., 773
 recurrence relation for 253
 relation to Legendre polynomials 252
Association, measures of 610, 628ff.
Asymptotic series 167
 exponential integral 224
Attenuation factors 590

- Autocorrelation
 in linear prediction 565
 use of FFT 545
 Wiener-Khinchin theorem 498, 574
- AUTODIN-II polynomial 898
- Autonomous differential equations 735f.
- Autoregressive model (AR) *see* Maximum entropy method (MEM)
- Average deviation of distribution 611
- Averaging kernel, in Backus-Gilbert method 816
- B**acksubstitution 42, 47, 50, 98
 in band diagonal matrix 54
 in Cholesky decomposition 97
 complex equations 49
 direct for computing $\mathbf{A}^{-1} \cdot \mathbf{B}$ 48
 relaxation solution of boundary value problems 764
 in singular value decomposition 64
- Backtracking 427
 in quasi-Newton methods 384
- Backus-Gilbert method 815ff.
- Backward deflation 370
- Bader-Deuffhard method 737, 742f.
- Bairstow's method 371, 376f.
- Balancing 483
- Band diagonal matrix 50, 51ff.
 backsubstitution 54
 LU decomposition 53f.
 multiply by vector 52f.
 storage 52
- Band-pass filter 558, 562
 wavelets 592, 599f.
- Bandwidth limited function 501
- Bank accounts, checksum for 902
- Bar codes, checksum for 902
- Bartlett window 554
- Base of representation 28, 890
- BASIC, Numerical Recipes in xv, 1
- Basis functions in general linear least squares 671
- Bayes' Theorem 819
- Bayesian
 approach to inverse problems 808, 820, 825f.
 contrasted with frequentist 819
 vs. historic maximum entropy method 825f.
 views on straight line fitting 670
- Bays' shuffle 280
- Bernoulli number 138
- Bessel functions 230ff., 240ff.
 asymptotic form 230, 236
 complex 210
 continued fraction 240f., 246f.
 double precision 230
 fractional order 230, 240ff.
 Miller's algorithm 181, 234
 modified 236ff.
 modified, fractional order 246ff.
 modified, normalization formula 239, 246
 modified, routines for 237ff.
 normalization formula 181
 recurrence relation 178, 231, 239, 241f.
 reflection formulas 242
 reflection formulas, modified functions 247
 routines for 232ff., 243ff.
 routines for modified functions 248f.
 series for 166, 230
 series for K_ν 247
 series for Y_ν 242
 spherical 240, 251
 turning point 241
 Wronskian 240, 246
- Best-fit parameters 656, 662, 666, 703
see also Fitting
- Beta function 213
 incomplete *see* Incomplete beta function
- BFGS algorithm *see* Broyden-Fletcher-Goldfarb-Shanno algorithm
- Bias, of exponent 28
- Bias, removal in linear prediction 570
- Biconjugacy 84
- Biconjugate gradient method
 elliptic partial differential equations 833
 preconditioning 85f., 833
 for sparse system 84f., 606
- Bicubic interpolation 125f.
- Bicubic spline 127f.
- Big-endian 302
- Bilinear interpolation 123f.
- Binomial coefficients 213
 recurrences for 215
- Binomial probability function 215
 cumulative 229
 deviates from 290, 295f.
- Binormal distribution 637, 695
- Biorthogonality 84
- Bisection 117, 366
 compared to minimum bracketing 397f., 399f.
 minimum finding with derivatives 406
 root finding 350, 353f., 359ff., 397, 476
- BISYNCH 898
- Bit 28
 reversal in fast Fourier transform (FFT) 505f., 532
- Bitwise logical functions 296ff., 898f.
- Block-by-block method 797
- Block of statements 6
- Bode's rule 132
- Boltzmann probability distribution 445
- Boltzmann's constant 445
- Bootstrap method 691f.
- Bordering method for Toeplitz matrix 92f.
- Borwein and Borwein method for π 915
- Boundary 161f., 432f., 753
- Boundary conditions
 for differential equations 707f.
 initial value problems 708
 in multigrid method 877f.
 partial differential equations 514, 828ff., 857ff.
 for spheroidal harmonics 774
 two-point boundary value problems 708, 753ff.
- Boundary value problems *see* Differential equations; Elliptic partial differential

- equations; Two-point boundary value problems
 - Box-Muller algorithm for normal deviate 289
 - Bracketing
 - of function minimum 350, 397ff., 409
 - of roots 348, 350ff., 360, 369, 371, 376, 397
 - Branch cut, for hypergeometric function 209f.
 - Branching 8
 - Break iteration 12f.
 - Brenner, N.M. 506, 522
 - Brent's method
 - minimization 395f., 402ff., 666
 - minimization, using derivative 396, 406
 - root finding 348, 356, 666
 - Broyden-Fletcher-Goldfarb-Shanno algorithm 397, 426ff.
 - Broyden's method 380, 389ff., 393
 - singular Jacobian 393
 - Bubble sort 330
 - Bugs
 - in compilers xiii
 - how to report iv, xviii
 - Bulirsch-Stoer
 - algorithm for rational function interpolation 111f.
 - method (differential equations) 209, 272, 708f., 712, 722, 724ff., 733, 747
 - method (differential equations), stepsize control 725, 733f.
 - for second order equations 733
 - Burg's LP algorithm 568
 - Byte 28
- C++** 7, 24
- C (programming language) 11
 - ANSI 2f., 14, 25, 930, 941
 - C++ 7, 24
 - compilers 3
 - control structures 5
 - deficiencies 16, 24f., 26f.
 - external functions 25
 - features 15f.
 - function declaration 17
 - function definition 17
 - header (.h) file 17
 - implicit conversions 24f., 930
 - Kernighan and Ritchie 2, 16, 24, 930
 - nature of 15f.
 - Numerical Recipes in xv, 1
 - operator associativity 25f.
 - operator precedence 25f.
 - prototypes 2, 25, 930
 - vectors in 18
 - Calendar algorithms 1f., 11ff.
 - Calibration 659
 - Cards, sorting a hand of 330
 - Carlson's elliptic integrals 261f.
 - Cash-Karp parameters 716f.
 - Cauchy probability distribution *see* Lorentzian probability distribution
 - Cauchy problem for partial differential equations 827f.
 - Cayley's representation of $\exp(-iHt)$ 853
 - CCITT (Comité Consultatif International Télégraphique et Téléphonique) 897f., 909
 - CCITT polynomial 897f.
 - Center of mass 305ff.
 - Central limit theorem 658f.
 - Central tendency, measures of 610ff.
 - Change of variable
 - in integration 144ff., 797
 - in Monte Carlo integration 307f.
 - in probability distribution 287f.
 - Characteristic polynomial
 - digital filter 561
 - eigensystems 456, 475f.
 - linear prediction 567
 - matrix with a specified 375
 - of recurrence relation 180
 - Characteristics of partial differential equations 827
 - Chebyshev acceleration in successive over-relaxation (SOR) 868f.
 - Chebyshev approximation 91, 130, 189, 190ff.
 - Clenshaw-Curtis quadrature 196
 - Clenshaw's recurrence formula 193
 - coefficients for 191
 - contrasted with Padé approximation 201
 - derivative of approximated function 189, 195
 - economization of series 198ff., 201
 - for error function 220f.
 - even function 194
 - and fast cosine transform 519
 - gamma functions 242
 - integral of approximated function 195
 - odd function 194
 - polynomial fits derived from 197
 - rational function 204ff.
 - Remez exchange algorithm for filter 560
 - Chebyshev polynomials 190ff.
 - continuous orthonormality 190f.
 - discrete orthonormality 191
 - explicit formulas for 190
 - formula for x^k in terms of 199
 - Check digit 901
 - Checksum 889, 896
 - cyclic redundancy (CRC) 896ff.
 - Cherry, sundae without a 818
 - Chi-by-eye 657
 - Chi-square fitting *see* Fitting; Least squares fitting
 - Chi-square probability function 216, 221, 621, 660, 806
 - as boundary of confidence region 693f.
 - related to incomplete gamma function 221
 - Chi-square test 620f.
 - for binned data 620f.
 - chi-by-eye 657
 - and confidence limit estimation 693f.
 - for contingency table 630ff.
 - degrees of freedom 621f.
 - for inverse problems 806
 - least squares fitting 659ff.
 - nonlinear models 681ff.
 - rule of thumb 661
 - for straight line fitting 661ff.

- for straight line fitting, errors in both coordinates 666
- for two binned data sets 622
- unequal size samples 623
- Chip rate 300
- Chirp signal 563
- Cholesky decomposition 96ff., 430, 462
 - backsubstitution 97
 - operation count 97
 - pivoting 97
 - solution of normal equations 674
- Circulant 592
- Class, data type 7
- Clenshaw-Curtis quadrature 130, 196, 518, 519
- Clenshaw's recurrence formula 181ff., 196
 - for Chebyshev polynomials 193
 - stability 181ff.
- Clocking errors 899
- cn function 269
- Coarse-to-fine operator 873
- Coarse-grid correction 873f.
- Coding
 - arithmetic 910ff.
 - checksums 896
 - decoding a Huffman-encoded message 905
 - Huffman 903ff.
 - run-length 909
 - variable length code 903
 - Ziv-Lempel 903
 - see also* Arithmetic coding; Huffman coding
- Coefficients
 - binomial 215
 - for Gaussian quadrature 147ff.
 - for Gaussian quadrature, nonclassical weight function 157ff., 797
 - for quadrature formulas 131ff., 797
- Column degeneracy 32
- Column operations on matrix 37, 40f.
- Column totals 630
- Combinatorial minimization *see* Annealing
- Comité Consultatif International Télégraphique et Téléphonique (CCITT) 897f., 909
- Communication theory, use in adaptive integration 727
- Communications protocol 896
- Comparison function for rejection method 290f.
- Complementary error function
 - see* Error function
- Complete elliptic integral *see* Elliptic integrals
- Complex arithmetic 23f., 176ff., 948ff.
 - avoidance of in path integration 209
 - cubic equations 185
 - for linear equations 49f.
 - quadratic equations 184
- Complex error function 259
- Complex plane
 - fractal structure for Newton's rule 367f.
 - path integration for function evaluation 208ff., 271
 - poles in 111, 166, 208f., 213, 561, 573, 724f.
- Complex systems of linear equations 49f.
- complex.c utility functions 23f., 948ff.
- Compression of data 603, 889, 903ff., 910ff.
- Concordant pair for Kendall's tau 642f.
- Condition number 61, 85
- Confidence level 692f., 696ff.
- Confidence limits
 - bootstrap method 692f.
 - and chi-square 693f.
 - confidence region, confidence interval 692
 - on estimated model parameters 689ff.
 - by Monte Carlo simulation 689ff.
 - from singular value decomposition (SVD) 698
- Confluent hypergeometric function 210, 246
- Conjugate directions 414f., 421ff.
- Conjugate gradient method
 - biconjugate 84
 - compared to variable metric method 425f.
 - elliptic partial differential equations 833
 - for minimization 396f., 420ff., 812f., 824
 - minimum residual method 85
 - preconditioner 85f.
 - for sparse system 83ff., 606
 - and wavelets 606
- Conservative differential equations 732f.
- Constrained linear inversion method 808ff.
- Constrained linear optimization *see* Linear programming
- Constrained optimization 394
- Constraints, deterministic 813ff.
- Constraints, linear 431
- Contingency coefficient C 631
- Contingency table 628ff., 644
 - statistics based on chi-square 630ff.
 - statistics based on entropy 632ff.
- continue construction 14
- Continued fraction 169ff.
 - Bessel functions 240f.
 - convergence criterion 171
 - equivalence transformation 172
 - evaluation 169ff.
 - evaluation along with normalization condition 247
 - even and odd parts 172, 217, 222
 - even part 255, 257
 - exponential integral 222
 - Fresnel integral 255
 - incomplete beta function 227
 - incomplete gamma function 217
 - Lentz's method 171, 219
 - modified Lentz's method 171
 - Pincherle's theorem 181
 - ratio of Bessel functions 246
 - rational function approximation 170, 217, 227
 - recurrence for evaluating 170f.
 - and recurrence relation 181
 - sine and cosine integrals 257
 - Steed's method 170f.
 - tangent function 169
 - typography for 169
- Continuous variable (statistics) 628
- Control structures 6, 8ff.
 - bad 14

- Conventions in C programs 25ff.
- Convergence
- accelerated, for series 166ff.
 - of algorithm for π 915
 - criteria for 353, 398f., 410, 489f., 495, 684f., 767
 - eigenvalues accelerated by shifting 477f.
 - golden ratio 354, 406
 - of golden section search 398f.
 - of Levenberg-Marquardt method 684f.
 - linear 353, 400
 - of QL method 477f.
 - quadratic 57, 358, 364f., 415f., 427, 915
 - rate 353, 359f., 364f.
 - recurrence relation 181
 - of Ridders' method 358
 - series vs. continued fraction 169f.
 - and spectral radius 865ff., 871
- `convert_matrix()` utility 945
- Convex sets, use in inverse problems 813f.
- Convolution
- denoted by asterisk 498
 - finite impulse response (FIR) 538
 - of functions 498, 509
 - of large data sets 543f.
 - for multiple precision arithmetic 918
 - multiplication as 918
 - necessity for optimal filtering 542
 - overlap-add method 544
 - overlap-save method 543f.
 - and polynomial interpolation 120
 - relation to wavelet transform 592
 - theorem 498, 538ff., 553
 - theorem, discrete 538ff.
 - treatment of end effects 540
 - use of FFT 530, 538ff.
 - wraparound problem 540
- Cooley-Tukey FFT algorithm 509
- Co-processor, floating point 894
- Copyright rules xvi
- Cornwell-Evans algorithm 825
- Corporate promotion ladder 336f.
- Corrected two-pass algorithm 613
- Correction, in multigrid method 872
- Correlation coefficient (linear) 636ff.
- Correlation function 498
- autocorrelation 498, 546, 565
 - and Fourier transforms 498
 - theorem 498, 545
 - treatment of end effects 546
 - using FFT 545f.
 - Wiener-Khinchin theorem 498, 574
- Correlation, statistical 609f., 628
- Kendall's tau 640, 642ff.
 - linear correlation coefficient 636ff., 664
 - linear related to least square fitting 636, 664
 - nonparametric or rank statistical 639ff.
 - among parameters in a fit 663, 673, 676
 - in random number generators 277
 - Spearman rank-order coefficient 640f.
 - sum squared difference of ranks 640
- Cosine function, recurrence 178
- Cosine integral 255, 257ff.
- continued fraction 257
 - routine for 258f.
 - series 257
- Cosine transform *see* Fast Fourier transform (FFT); Fourier transform
- Coulomb wave function 210, 240
- Courant condition 838, 841, 843, 845
- multidimensional 855
- Courant-Friedrichs-Lewy stability criterion *see* Courant condition
- Covariance
- a priori 705
 - in general linear least squares 673, 677
 - matrix, by Cholesky decomposition 98, 673
 - matrix, of errors 805, 817
 - matrix, is inverse of Hessian matrix 685
 - matrix, when it is meaningful 695ff.
 - in nonlinear models 685, 687
 - relation to chi-square 695ff.
 - from singular value decomposition (SVD) 698
 - in straight line fitting 663
- CR method *see* Cyclic reduction (CR)
- Cramer's V 631
- Crank-Nicholson method 848, 853, 855
- CRC (cyclic redundancy check) 896ff.
- CRC-12 898
- CRC-16 polynomial 898
- CRC-CCITT 898
- Creativity, essay on 8
- Critical (Nyquist) sampling 500, 550
- Cross (denotes matrix outer product) 73
- Crosstabulation analysis 629
- see also* Contingency table
- Crout's algorithm 44ff., 53
- Cubic equations 183ff., 367
- Cubic spline interpolation 113ff.
- see also* Spline
- Cumulative binomial distribution 226, 229
- Cumulative Poisson function 221
- related to incomplete gamma function 221
- Curvature matrix *see* Hessian matrix
- `cvector()` utility 943
- Cycle, in multigrid method 874
- Cyclic Jacobi method 466
- Cyclic reduction (CR) 857f., 861f.
- Cyclic redundancy check (CRC) 896ff.
- Cyclic tridiagonal systems 74f.
- D**anielson-Lanczos lemma 504f., 532
- Data
- assigning keys to 897
 - continuous vs. binned 620
 - entropy 632ff., 903f.
 - essay on 609
 - fitting 656ff.
 - fraudulent 661
 - glitches in 659
 - iid (independent and identically distributed) 691
 - modeling 656ff.
 - serial port 899
 - smoothing 610, 650ff.
 - statistical tests 609ff.

- unevenly or irregularly sampled 576, 581f., 654
 - use of CRCs in manipulating 897
 - windowing 553ff.
 - see also* Statistical tests
- Data compression 603, 889
 - arithmetic coding 910ff.
 - cosine transform 519
 - Huffman coding 903ff., 910
 - linear predictive coding (LPC) 571f.
 - lossless 903
- Data Encryption Standard (DES) 300ff.
- Data type 28
- DAUB4 592ff., 595, 598f., 601
- DAUB6 593
- DAUB12 605
- DAUB20 598f.
- Daubechies wavelet coefficients 592ff., 596, 598f., 601, 605
- Davidon-Fletcher-Powell algorithm 397, 426f.
- Dawson's integral 259f., 606
 - approximation for 259
 - routine for 260
- D.C. (direct current) 498
- Debugging 7
- DEC (Digital Equipment Corp.) xvii, 3, 894
- Declarations 930ff.
- Decomposition *see* Cholesky decomposition; LU decomposition; QR decomposition; Singular value decomposition (SVD)
- Deconvolution 542, 549
 - see also* Convolution; Fast Fourier transform (FFT); Fourier transform
- Defect, in multigrid method 872
- Deferred approach to the limit *see* Richardson's deferred approach to the limit
- Deflation
 - of matrix 478
 - of polynomials 369ff., 377, 378
- Degeneracy of linear algebraic equations 32, 61, 65, 676
- Degenerate kernel 794
- Degenerate minimization principle 804
- Degrees of freedom 621f., 660, 695f.
- Demonstration programs 3
- Derivatives
 - computation via Chebyshev approximation 189, 195
 - computation via Savitzky-Golay filters 189, 651
 - matrix of first partial *see* Jacobian determinant
 - matrix of second partial *see* Hessian matrix
 - numerical computation 186ff., 386, 651, 738, 758, 779
 - of polynomial 173f.
 - use in optimization 395f., 406
- DES *see* Data Encryption Standard
- Descending transformation, elliptic integrals 262
- Descent direction 383, 390, 427
- Descriptive statistics 609ff.
 - see also* Statistical tests
- Design matrix 651, 671, 804, 809
- Determinant 34, 49
- Deviates, random *see* Random deviates
- DFP algorithm *see* Davidon-Fletcher-Powell algorithm
- Diagonal dominance 51, 684, 789, 865
- Difference equations, finite *see* Finite difference equations (FDEs)
- Difference operator 167
- Differential equations 707ff.
 - accuracy vs. stability 710, 736
 - Adams-Bashforth-Moulton schemes 749
 - adaptive stepsize control 709, 714ff., 725, 733f., 738, 744, 749f., 751
 - algebraically difficult sets 772
 - backward Euler's method 735
 - Bader-Deuffhard method for stiff 737, 742f.
 - boundary conditions 707f., 753ff., 757, 760, 779f.
 - Bulirsch-Stoer method 209, 272, 708f., 712, 722, 724ff., 747
 - Bulirsch-Stoer method for conservative equations 733
 - comparison of methods 708f., 747, 751
 - conservative 732f.
 - danger of too small stepsize 720
 - eigenvalue problem 756, 772ff., 779f., 781
 - embedded Runge-Kutta method 715f., 738
 - equivalence of multistep and multivalued methods 751
 - Euler's method 708, 710, 735
 - forward Euler's method 735
 - free boundary problem 756, 785
 - high-order implicit methods 737ff.
 - implicit differencing 735f., 749
 - initial value problems 708
 - internal boundary conditions 784ff.
 - internal singular points 784ff.
 - interpolation on right-hand sides 117
 - Kaps-Rentrop method for stiff 737
 - local extrapolation 715
 - modified midpoint method 722f., 726
 - multistep methods 747ff.
 - multivalued methods 747
 - order of method 710f., 725
 - path integration for function evaluation 208ff., 271
 - predictor-corrector methods 708, 737, 747ff.
 - reduction to first-order sets 707, 753
 - relaxation method 754f., 762ff.
 - relaxation method, example of 772ff.
 - r.h.s. independent of x 735
 - Rosenbrock methods for stiff 737
 - Runge-Kutta method 708f., 710ff., 714ff., 738, 747
 - Runge-Kutta method, high-order 711
 - Runge-Kutta-Fehlberg method 715f.
 - scaling stepsize to required accuracy 716f.
 - second order 732f.
 - semi-implicit differencing 737
 - semi-implicit Euler method 737, 743
 - semi-implicit extrapolation method 737, 743

- semi-implicit midpoint rule 743
 shooting method 754, 757ff.
 shooting method, example 779f., 781
 similarity to Volterra integral equations 794f.
 singular points 724f., 760, 784ff.
 step doubling 715
 stepsize control 709, 714ff., 724, 733f., 738, 744, 749f., 751
 stiff 709, 734ff.
 stiff methods compared 747
 Stoermer's rule 732f.
see also Partial differential equations; Two-point boundary value problems
 Diffusion equation 827, 847ff., 864
 Crank-Nicholson method 848, 853, 855
 Forward Time Centered Space (FTCS) 847ff., 850f., 864
 implicit differencing 848
 multidimensional 855f.
 Digamma function 222
 Digital filtering *see* Filter
 Dihedral group D_5 902
 Dimensions (units) 683f.
 Diminishing increment sort 331
 Dirac delta function 293, 789
 Direct method *see* Periodogram
 Direct methods for linear algebraic equations 35
 Direct product *see* Outer product of matrices
 Direction of largest decrease 416f.
 Direction numbers, Sobol's sequence 311
 Direction-set methods for minimization 396, 412ff.
 Dirichlet boundary conditions 829, 849, 859, 865, 867
 Disclaimer of warranty xvi
 Discordant pair for Kendall's tau 643
 Discrete convolution theorem 538ff.
 Discrete Fourier transform (DFT) 500ff.
 as approximate continuous transform 503
 see also Fast Fourier transform (FFT)
 Discrete optimization 444ff.
 Discriminant 184, 464
 Diskettes, how to order xvi, 996f.
 Dispersion 840
 DISPO *see* Savitzky-Golay filters
 Dissipation, numerical 839
 Divergent series 167
 Division
 complex 177
 multiple precision 919f.
 of polynomials 175, 369, 377
`dmatrix()` utility 944
`dn` function 269
 Do-while iteration 12
 Dogleg step methods 393
 Domain of integration 161f.
 Dominant solution of recurrence relation 179
 Dot (denotes matrix multiplication) 33
 Double exponential error distribution 701
 Double precision
 as refuge of scoundrels 890
 use in iterative improvement 56
 Double root 348
 Downhill simplex method *see* Simplex, method of Nelder and Mead
 Driver programs 3
 Dual viewpoint, in multigrid method 883
 Duplication theorem, elliptic integrals 262f.
`dvector()` utility 943
 DWT (discrete wavelet transform) *see* Wavelet transform

Eardley, D.M. 346
 EBCDIC 898
 Economization of power series 198ff., 201
 Eigensystems 456ff.
 balancing matrix 483
 bounds on eigenvalues 58
 calculation of few eigenvectors or eigenvalues 461, 494
 canned routines 461
 characteristic polynomial 456, 475f.
 completeness 457
 defective 457, 482, 494
 deflation 478
 degenerate eigenvalues 456, 458
 elimination method 460, 485
 factorization method 460
 fast Givens reduction 470
 generalized eigenproblem 462
 Givens reduction 469f.
 Hermitian matrix 481f.
 Hessenberg matrix 460, 477, 482ff., 494
 Householder transformation 460, 469ff., 476, 480, 481, 484f.
 ill-conditioned eigenvalues 483
 implicit shifts 478ff.
 and integral equations 788ff., 794
 invariance under similarity transform 459
 inverse iteration 462, 476, 483, 493ff.
 Jacobi transformation 460, 463ff., 469, 481, 495
 left eigenvalues 458
 list of tasks 461
 multiple eigenvalues 495
 nonlinear 462
 nonsymmetric matrix 482ff.
 operation count of balancing 483
 operation count of Givens reduction 470
 operation count of Householder reduction 474
 operation count of inverse iteration 494
 operation count of Jacobi method 467
 operation count of QL method 477, 480
 operation count of QR method for Hessenberg matrices 490
 operation count of reduction to Hessenberg form 485
 orthogonality 457
 polynomial roots and 375
 QL method 476ff., 481, 494f.
 QL method with implicit shifts 478ff.
 QR method 60, 460, 463, 476ff.
 QR method for Hessenberg matrices 486ff.
 real, symmetric matrix 156, 474, 794
 reduction to Hessenberg form 484f.
 right eigenvalues 458
 shifting eigenvalues 456, 477f., 486f.

- special matrices 461
- termination criterion 489f., 495
- tridiagonal matrix 460, 475ff., 494
- Eigenvalue and eigenvector, defined 456
- Eigenvalue problem for differential equations 756, 772ff., 779, 781
- Eigenvalues and polynomial root finding 375
- EISPACK 461, 482
- Electromagnetic potential 525
- Elimination *see* Gaussian elimination
- Ellipse in confidence limit estimation 693
- Elliptic integrals 261ff., 915
 - addition theorem 262
 - Carlson's forms and algorithms 261ff.
 - Cauchy principal value 263
 - duplication theorem 262f.
 - Legendre 261ff., 267ff.
 - routines for 264ff.
 - symmetric form 261f.
 - Weierstrass 262
- Elliptic partial differential equations 827
 - alternating-direction implicit method (ADI) 870f., 915
 - analyze/factorize/operate package 833
 - biconjugate gradient method 833
 - boundary conditions 828f.
 - comparison of rapid methods 863
 - conjugate gradient method 833
 - cyclic reduction 857f., 861f.
 - Fourier analysis and cyclic reduction (FACR) 857ff., 863
 - Gauss-Seidel method 864, 873, 874f., 884
 - incomplete Cholesky conjugate gradient method (ICCG) 833
 - Jacobi's method 864f., 873
 - matrix methods 833
 - multigrid method 833, 871ff.
 - rapid (Fourier) method 833, 857ff.
 - relaxation method 832, 863ff.
 - strongly implicit procedure 833
 - successive over-relaxation (SOR) 866ff., 871, 875
- Emacs, GNU xiii
- Embedded Runge-Kutta method 715f., 738
- Encapsulation, in programs 6f.
- Encryption 300
- Entropy 903f.
 - of data 632ff., 820
- EOM (end of message) 910
- Equality constraints 431
- Equations
 - cubic 183ff., 367
 - normal (fitting) 651, 672ff., 809f.
 - quadratic 29, 183ff.
 - see also* Differential equations; Partial differential equations; Root finding
- Equivalence classes 345f.
- Equivalence transformation 172
- Error
 - checksums for preventing 899
 - clocking 899
 - double exponential distribution 701
 - local truncation 883
 - Lorentzian distribution 701f.
 - in multigrid method 872
 - nonnormal 659, 695, 699ff.
 - relative truncation 883
 - roundoff 185, 889f.
 - series, advantage of an even 138f., 723
 - systematic vs. statistical 659
 - truncation 30, 186, 406, 715, 889f.
 - varieties found by check digits 902
 - varieties of, in PDEs 840ff.
 - see also* Roundoff error
- Error function 220f., 607
 - approximation via sampling theorem 607f.
 - Chebyshev approximation 220f.
 - complex 259
 - for Fisher's z-transformation 638
 - relation to Dawson's integral 259
 - relation to Fresnel integrals 255
 - relation to incomplete gamma function 220
 - routine for 220f.
 - for significance of correlation 636
 - for sum squared difference of ranks 641
- Error handling in programs 2, 940
- Estimation of parameters *see* Fitting; Maximum likelihood estimate
- Estimation of power spectrum 549ff., 572ff.
- Euler equation (fluid flow) 840
- Euler-Maclaurin summation formula 138, 142
- Euler's constant 223f., 257
- Euler's method for differential equations 708, 710, 735
- Euler's transformation 166ff.
 - generalized form 168f.
- Evaluation of functions *see* Function
- Even and odd parts, of continued fraction 172, 217, 222
- Even parity 896
- Exception handling in programs 2, 940
- exit() function 2
- Explicit differencing 836
- Exponent in floating point format 28, 890
- Exponential deviate 287f.
- Exponential integral 222ff.
 - asymptotic expansion 224
 - continued fraction 222
 - recurrence relation 178
 - related to incomplete gamma function 222
 - relation to cosine integral 257
 - routine for $E_n(x)$ 223f.
 - routine for $Ei(x)$ 225
 - series 222
- Exponential probability distribution 577
- Extended midpoint rule 130f., 135, 141f.
- Extended Simpson's rule 134, 796, 799
- Extended Simpson's three-eighths rule 797
- Extended trapezoidal rule 131f., 133, 136ff., 141, 795
 - roundoff error 138
- extern storage class 25
- Extrapolation (so-called) 581f.
- Extrapolation 105ff.
 - in Bulirsch-Stoer method 724ff., 731
 - differential equations 708
 - by linear prediction 564ff.
 - local 715
 - maximum entropy method as type of 574

- polynomial 728, 730f., 748
 - rational function 724ff., 731
 - relation to interpolation 105
 - for Romberg integration 140
 - see also* Interpolation
 - Extremization *see* Minimization
- F**-distribution probability function 226, 229
- F-test for differences of variances 617, 619
- FACR *see* Fourier analysis and cyclic reduction (FACR)
- Facsimile standard 909
- Factorial
 - double (denoted “!!”) 253
 - evaluation of 165
 - relation to gamma function 213
 - routine for 214f.
- False position 354ff.
- Family tree 345
- FAS (full approximation storage algorithm) 882ff.
- Fast Fourier transform (FFT) 504ff., 889
 - alternative algorithms 509f.
 - applications 537ff.
 - as approximation to continuous transform 503
 - Bartlett window 554
 - bit reversal 505f., 532
 - and Clenshaw-Curtis quadrature 196
 - convolution 509, 530, 538ff., 918
 - convolution of large data sets 543f.
 - Cooley-Tukey algorithm 509
 - correlation 545f.
 - cosine transform 196, 517ff., 860f.
 - cosine transform, second form 519, 861
 - Danielson-Lanczos lemma 504f., 532
 - data sets not a power of 2 509
 - data smoothing 650
 - data windowing 553ff.
 - decimation-in-frequency algorithm 509
 - decimation-in-time algorithm 509
 - discrete autocorrelation 546
 - discrete convolution theorem 538ff.
 - discrete correlation theorem 545
 - at double frequency 582
 - endpoint corrections 585f.
 - external storage 532
 - figures of merit for data windows 554
 - filtering 558ff.
 - FIR filter 559f.
 - Fourier integrals 584ff.
 - Fourier integrals, infinite range 590f.
 - Hamming window 554
 - Hann window 554
 - history 504
 - IIR filter 559
 - image processing 812, 814
 - integrals using 130
 - inverse of cosine transform 518f.
 - inverse of sine transform 517
 - large data sets 532
 - leakage 551
 - memory-local algorithm 535f.
 - multidimensional 521ff.
 - for multiple precision arithmetic 915
 - for multiple precision multiplication 918
 - number-theoretic transforms 509f.
 - operation count 504
 - optimal (Wiener) filtering 547ff., 565f.
 - order of storage in 507
 - partial differential equations 833, 857ff.
 - Parzen window 554
 - periodicity of 503
 - periodogram 550ff., 574
 - power spectrum estimation 549ff.
 - for quadrature 130
 - of real data in 2D and 3D 525ff.
 - of real functions 510ff., 525ff.
 - related algorithms 509f.
 - Sande-Tukey algorithm 509
 - sine transform 514ff., 859
 - Singleton’s algorithm 532
 - square window 553
 - treatment of end effects in convolution 540
 - treatment of end effects in correlation 546
 - Tukey’s trick for frequency doubling 582
 - use in smoothing data 650
 - used for Lomb periodogram 581f.
 - variance of power spectrum estimate 552, 556
 - virtual memory machine 535f.
 - Welch window 554
 - Winograd algorithms 509- see also* Discrete Fourier transform (DFT); Fourier transform; Spectral density

Faure sequence 310

Fax (facsimile) Group 3 standard 909

`fcomplex` (data type) 24, 948

Feasible vector 431

FFT *see* Fast Fourier transform (FFT)

Field, in data record 338

Figure-of-merit function 656

Filon’s method 590

Filter 558ff.

 - acausal 559
 - bilinear transformation method 561
 - causal 559, 650
 - characteristic polynomial 561
 - data smoothing 650
 - digital 558ff.
 - DISPO 650
 - by fast Fourier transform (FFT) 530, 558ff.
 - finite impulse response (FIR) 538, 559f.
 - homogeneous modes of 561
 - infinite impulse response (IIR) 559, 573
 - Kalman 705
 - linear 559ff.
 - low-pass for smoothing 650
 - nonrecursive 559f.
 - optimal (Wiener) 542, 547ff., 565f., 650
 - quadrature mirror 592, 600
 - realizable 559, 561
 - recursive 559, 573
 - Remes exchange algorithm 560
 - Savitzky-Golay 189, 650ff.
 - stability of 561
 - in the time domain 558ff.

Fine-to-coarse operator 873

- Finite difference equations (FDEs) 762, 772, 783
 alternating-direction implicit method (ADI) 856, 870f.
 art, not science 838
 Cayley's form for unitary operator 853
 Courant condition 838, 841, 845
 Courant condition (multidimensional) 855
 Crank-Nicholson method 848, 853, 855
 eigenmodes of 836f.
 explicit vs. implicit schemes 836
 forward Euler 835f.
 Forward Time Centered Space (FTCS) 836ff., 847ff., 852, 864
 implicit scheme 848
 Lax method 837ff., 845
 Lax method (multidimensional) 854f.
 mesh drifting instability 843f.
 numerical derivatives 186
 partial differential equations 830ff.
 in relaxation methods 762ff.
 staggered leapfrog method 842f.
 two-step Lax-Wendroff method 844ff.
 upwind differencing 841f., 846
see also Partial differential equations
- Finite element methods, partial differential equations 833f.
- Finite impulse response (FIR) 538
- Finkelstein, S. xii
- FIR (finite impulse response) filter 559f.
- Fisher's z-transformation 637f.
- Fitting 656ff.
 basis functions 671
 by Chebyshev approximation 191f.
 chi-square 659ff.
 confidence levels related to chi-square values 696ff.
 confidence levels from singular value decomposition (SVD) 698
 confidence limits on fitted parameters 689ff.
 covariance matrix not always meaningful 657, 695
 degeneracy of parameters 679
 an exponential 679
 freezing parameters in 674, 705
 Gaussians, a sum of 687f.
 general linear least squares 671ff.
 Kalman filter 705
 K-S test, caution regarding 627
 least squares 657ff.
 Legendre polynomials 680
 Levenberg-Marquardt method 683ff., 825
 linear regression 661ff.
 maximum likelihood estimation 658, 699ff.
 Monte Carlo simulation 627, 660, 689ff.
 multidimensional 680
 nonlinear models 681ff.
 nonlinear models, advanced methods 688
 nonlinear problems that are linear 679
 nonnormal errors 662, 695, 699ff.
 polynomial 90, 120, 197, 650f., 671, 679f.
 by rational Chebyshev approximation 204ff.
 robust methods 699ff.
 of sharp spectral features 573
 standard (probable) errors on fitted parameters 663, 667f., 673, 677, 689ff.
 straight line 661ff., 673f., 703
 straight line, errors in both coordinates 666ff.
see also Error; Least squares fitting; Maximum likelihood estimate; Robust estimation
- Five-point difference star 876
- Fixed point format 28
- Fletcher-Powell algorithm *see* Davidon-Fletcher-Powell algorithm
- Fletcher-Reeves algorithm 396f., 421ff.
- float to double conversion 24f.
- Floating point co-processor 894
- Floating point format 28, 890
 care in numerical derivatives 186
 IEEE 285, 890f.
- Flux-conservative initial value problems 834ff.
- FMG (full multigrid method) 872, 877f.
- for iteration 8, 11
- Formats of numbers 28, 890
- FORTRAN 16, 20
 Numerical Recipes in xv, 1
- Forward deflation 370
- Forward difference operator 167
- Forward Euler differencing 835f.
- Forward Time Centered Space *see* FTCS
- Fourier analysis and cyclic reduction (FACR) 858, 863
- Fourier and spectral applications 537ff.
- Fourier integrals
 attenuation factors 590
 endpoint corrections 585f.
 tail integration by parts 591
 use of fast Fourier transform (FFT) 584ff.
- Fourier transform 105, 496ff.
 aliasing 501, 576
 approximation of Dawson's integral 259
 autocorrelation 498
 basis functions compared 514f.
 contrasted with wavelet transform 591f., 601
 convolution 498, 509, 538ff., 918
 correlation 498, 545f.
 cosine transform 196, 517ff., 860f.
 cosine transform, second form 519, 861
 critical sampling 500, 550, 552
 definition 496
 discrete Fourier transform (DFT) 190, 500ff.
 Gaussian function 607
 image processing 812, 814
 infinite range 590f.
 inverse of discrete Fourier transform 503
 method for partial differential equations 857ff.
 missing data 576
 missing data, fast algorithm 581f.
 Nyquist frequency 500ff., 526, 550, 552, 576, 579
 optimal (Wiener) filtering 547ff., 565f.
 Parseval's theorem 498, 504, 551
 power spectral density (PSD) 498f.
 power spectrum estimation by FFT 549ff.

- power spectrum estimation by maximum entropy method 572ff.
 - properties of 497f.
 - sampling theorem 501, 550, 552, 606f.
 - scalings of 497
 - significance of a peak in 577f.
 - sine transform 514ff., 859
 - symmetries of 497
 - uneven sampling, fast algorithm 581f.
 - unevenly sampled data 575ff., 581f. and wavelets 599f.
 - Wiener-Khinchin theorem 498, 566, 574
see also Fast Fourier transform (FFT); Spectral density
 - Fractal region 367f.
 - Fractional step methods 856f.
 - Fredholm alternative 789
 - Fredholm equations 788f.
 - eigenvalue problems 789, 794
 - error estimate in solution 793
 - first kind 788
 - Fredholm alternative 789
 - homogeneous, second kind 793f.
 - homogeneous vs. inhomogeneous 789
 - ill-conditioned 789
 - infinite range 797f.
 - inverse problems 789, 804ff.
 - kernel 788f.
 - nonlinear 790
 - Nystrom method 791ff., 797f.
 - product Nystrom method 797
 - second kind 789, 791f.
 - with singularities 797
 - with singularities, worked example 801
 - subtraction of singularity 798
 - symmetric kernel 794
 - see also* Inverse problems
 - Freeing of storage 19, 21f., 940ff.
 - `free_matrix()` utility 946
 - `free_vector()` utility 946
 - Frequency domain 496
 - Frequency spectrum *see* Fast Fourier transform (FFT)
 - Frequentist, contrasted with Bayesian 819
 - Fresnel integrals 255ff.
 - asymptotic form 255
 - continued fraction 255
 - routine for 256f.
 - series 255
 - Friday the Thirteenth 13f.
 - FTCS (forward time centered space) 836ff., 847ff., 852
 - stability of 836ff., 847ff., 864
 - Full approximation storage (FAS) algorithm 882ff.
 - Full moon 13f.
 - Full multigrid method (FMG) 872, 877f.
 - Full Newton methods, nonlinear least squares 688
 - Full pivoting 38
 - Full weighting 876
 - Function
 - Airy 210, 240, 250
 - approximation 105f., 190ff.
 - associated Legendre polynomial 252f., 773
 - autocorrelation of 498
 - bandwidth limited 501
 - Bessel 178, 210, 230ff., 240ff.
 - beta 215f.
 - branch cuts of 209f.
 - chi-square probability 221, 806
 - complex 208
 - confluent hypergeometric 210, 246
 - convolution of 498
 - correlation of 498
 - Coulomb wave 210, 240
 - cumulative binomial probability 226, 229
 - cumulative Poisson 216
 - Dawson's integral 259f., 606
 - declaration 17
 - definition 17
 - digamma 222
 - elliptic integrals 261ff., 915
 - error 220f., 255, 259, 607, 636, 641
 - evaluation 165ff.
 - evaluation by path integration 208ff., 271
 - exponential integral 178, 222ff., 257
 - external 25
 - F-distribution probability 226, 229
 - Fresnel integral 255ff.
 - gamma 213f.
 - hypergeometric 208ff., 271ff.
 - incomplete beta 226ff., 616
 - incomplete gamma 216ff., 621, 660, 663f.
 - inverse hyperbolic 184, 262
 - inverse trigonometric 262
 - Jacobian elliptic 261, 269f.
 - Kolmogorov-Smirnov probability 624f., 646f.
 - Legendre polynomial 178, 252f., 680
 - logarithm 262
 - modified Bessel 236ff.
 - modified Bessel, fractional order 246ff.
 - path integration to evaluate 208ff.
 - pathological 105f., 350f.
 - Poisson cumulant 221
 - prototypes 16f., 25, 930
 - representations of 496
 - routine for plotting a 349f.
 - sine and cosine integrals 255, 257ff.
 - sn, dn, cn 269
 - spherical Bessel 240
 - spherical harmonics 252f.
 - spheroidal harmonic 772ff., 779f., 781
 - Student's probability 226, 228
 - Weber 210
 - Functional iteration, for implicit equations 748
 - FWHM (full width at half maximum) 555
- G**
- Gamma deviate 290ff.
 - Gamma function 213ff.
 - incomplete *see* Incomplete gamma function
 - Gauss-Chebyshev integration 147, 151, 518f.
 - Gauss-Hermite integration 151, 798
 - abscissas and weights 153
 - normalization 153

- Gauss-Jacobi integration 151
 abscissas and weights 154
- Gauss-Jordan elimination 36ff., 41, 71
 operation count 42, 48
 solution of normal equations 673
 storage requirements 38f.
- Gauss-Kronrod quadrature 160
- Gauss-Laguerre integration 151, 798
- Gauss-Legendre integration 151
see also Gaussian integration
- Gauss-Lobatto quadrature 160, 196, 518
- Gauss-Radau quadrature 160
- Gauss-Seidel method (relaxation) 864, 866, 873, 874f.
 nonlinear 884
- Gauss transformation 262
- Gaussian (normal) distribution 275, 658, 807
 central limit theorem 658f.
 deviates from 288f., 578
 kurtosis of 612
 multivariate 695
 semi-invariants of 614
 tails compared to Poisson 659
 two-dimensional (binormal) 637
 variance of skewness of 612
- Gaussian elimination 41f., 59, 63
 fill-in 53, 71
 integral equations 795
 operation count 42
 in reduction to Hessenberg form 485
 relaxation solution of boundary value problems 762ff., 785
- Gaussian function
 Hardy's theorem on Fourier transforms 607
see also Gaussian (normal) distribution
- Gaussian integration 133, 147ff., 798
 calculation of abscissas and weights 150ff.
 error estimate in solution 793
 extensions of 160
 Golub-Welsch algorithm for weights and abscissas 156f.
 for integral equations 790, 792
 from known recurrence relation 156f.
 nonclassical weight function 157ff., 797
 and orthogonal polynomials 148
 preassigned nodes 160
 weight function $\log x$ 159
 weight functions 147ff., 797
- Gear's method (stiff ODEs) 737
- Geiger counter 274
- Generalized eigenvalue problems 462
- Generalized minimum residual method (GMRES) 85
- Geophysics, use of Backus-Gilbert method 818
- Gerchberg-Saxton algorithm 814f.
- Gilbert and Sullivan 720
- Givens reduction 469f., 480
 fast 470
 operation count 470
- Glassman, A.J. 185
- Global optimization 394f., 444ff., 656
 continuous variables 451f.
- Globally convergent
 minimization 425ff.
 root finding 380, 383ff., 390, 757f., 761
- GMRES (generalized minimum residual method) 85
- GNU Emacs xiii
- Godunov's method 846
- Golden mean (golden ratio) 30, 354, 399, 406
- Golden section search 348, 396, 397ff., 403
- Golub-Welsch algorithm, for Gaussian quadrature 156f.
- Goodness-of-fit 656, 660, 663f., 668, 695
- goto statements, danger of 8
- Gram-Schmidt
 biorthogonalization 421f.
 orthogonalization 100, 457, 458
 SVD as alternative to 66
- Graphics, function plotting 349f.
- Gravitational potential 525
- Gray code 311, 889, 894ff.
- Greenbaum, A. 86
- Gregorian calendar 12, 15
- Grid square 123f.
- Group, dihedral 902
- Guard digits 890
- H**alf weighting 876
- Halton's quasi-random sequence 309f.
- Hamming window 554
- Hamming's motto 348
- Hann window 554
- Harmonic analysis *see* Fourier transform
- Hashing 303
- HDLC checksum 898
- Header (.h) files 16f.
- Heap (data structure) 336f., 344, 905
- Heapsort 329, 336f., 344
- Helmholtz equation 861
- Hermite polynomials 151, 153
- Hermitian matrix 457ff., 481f.
- Hertz (unit of frequency) 496
- Hessenberg matrix 100, 460, 477, 482, 494
see also Matrix
- Hessian matrix 389, 414, 422, 427, 681ff., 812, 824
 is inverse of covariance matrix 673, 685
 second derivatives in 683
- Hexadecimal constants 285, 303
- Hierarchically band diagonal matrix 606
- Hierarchy of program structure 5f.
- High-order not same as high-accuracy 106f., 130, 396, 406, 711, 715, 748f.
- High-pass filter 558
- Hilbert matrix 90
- Historic maximum entropy method 825f.
- Homogeneous linear equations 61
- Hook step methods 393
- Hotelling's method for matrix inverse 57, 606
- Householder transformation 60, 460, 469ff., 476, 480, 481, 484f., 488ff.
 operation count 474
 in QR decomposition 99
- Huffman coding 571, 889, 903ff., 910
- Hyperbolic functions, explicit formulas for inverse 184

- Hyperbolic partial differential equations 827
 advective equation 835
 flux-conservative initial value problems 834ff.
- Hypergeometric function 208ff., 271ff.
 routine for 272f.
- Hypothesis, null 609
- I**
IBM xvii
 bad random number generator 277
 PC 3, 285, 303, 894
 radix base for floating point arithmetic 483
- IBM checksum 901f.
- ICCG (incomplete Cholesky conjugate gradient method) 833
- ICF (intrinsic correlation function) model 826
- Identity (unit) matrix 34
- IEEE floating point format 285, 890f.
- if structure 11
 warning about nesting 11
- IIR (infinite impulse response) filter 559, 573
- ill-conditioned integral equations 789
- Image processing 525, 812
 cosine transform 519
 fast Fourier transform (FFT) 525, 530, 812
 as an inverse problem 812
 maximum entropy method (MEM) 818ff.
 from modulus of Fourier transform 814
 wavelet transform 603
- imatrix() utility 944
- Implicit
 conversion of data types 24f., 930
 function theorem 347
 pivoting 38
 shifts in QL method 478ff.
- Implicit differencing 836
 for diffusion equation 848
 for stiff equations 735f., 749
- Importance sampling, in Monte Carlo 316f.
- Improper integrals 141ff.
- Impulse response function 538, 549, 559
- IMSL xvii, 35, 72, 212, 371, 376, 461
- In-place selection 342
- Include files 17, 930
- Incomplete beta function 226ff.
 for F-test 619
 routine for 227f.
 for Student's t 616, 618
- Incomplete Cholesky conjugate gradient method (ICCG) 833
- Incomplete gamma function 216
 for chi-square 621, 660, 663f.
 deviates from 290ff.
 in mode estimation 616
 routine for 218f.
- Increment of linear congruential generator 276
- Indentation of blocks 11
- Index 965ff.
 this entry 977
- Index table 329, 338
- Inequality constraints 431
- Inheritance 7
- Initial value problems 708, 827f.
 see also Differential equations;
 Partial differential equations
- Injection operator 873
- Instability *see* Stability
- Integer programming 443
- Integral equations 788ff.
 adaptive stepsize control 797
 block-by-block method 797
 correspondence with linear algebraic equations 788ff.
 degenerate kernel 794
 eigenvalue problems 789, 794
 error estimate in solution 793
 Fredholm 788f., 791f.
 Fredholm alternative 789
 homogeneous, second kind 793f.
 ill-conditioned 789
 infinite range 797f.
 inverse problems 789, 804ff.
 kernel 788f.
 nonlinear 790, 796
 Nystrom method 791f., 797
 product Nystrom method 797
 with singularities 797ff.
 with singularities, worked example 801
 subtraction of singularity 798
 symmetric kernel 794
 unstable quadrature 796
 Volterra 789f., 794f.
 wavelets 791
 see also Inverse problems
- Integral operator, wavelet approximation of 603f., 791
- Integration of functions 129ff.
 cosine integrals 257
 Fourier integrals 584ff.
 Fourier integrals, infinite range 590f.
 Fresnel integrals 255
 Gauss-Hermite 153
 Gauss-Jacobi 154
 Gauss-Laguerre 152
 Gauss-Legendre 151
 integrals that are elliptic integrals 261
 path integration 208ff.
 sine integrals 257
 see also Quadrature
- Integro-differential equations 791
- Interface, in programs 7
- Intermediate value theorem 350
- Internet xvii
- Interpolation 105ff.
 Aitken's algorithm 108
 avoid 2-stage method 106
 avoid in Fourier analysis 576
 bicubic 125f.
 bilinear 123f.
 caution on high-order 106f.
 coefficients of polynomial 106, 120ff., 197, 582
 for computing Fourier integrals 586
 error estimates for 106
 of functions with poles 111ff.
 inverse quadratic 360, 402ff.

- multidimensional 107f., 123ff.
- in multigrid method 876
- Neville's algorithm 108f., 188
- Nystrom 792
- offset arrays 110, 119
- operation count for 106
- operator 873
- order of 106
- and ordinary differential equations 107
- oscillations of polynomial 106, 120, 396, 406
- parabolic, for minimum finding 402
- polynomial 105, 108ff., 188
- rational Chebyshev approximation 204ff.
- rational function 105, 111ff., 200ff., 231f., 724ff., 731
- reverse (extrapolation) 581f.
- spline 106, 113ff., 127f.
- trigonometric 105
- see also* Fitting
- Interval variable (statistics) 628
- Intrinsic correlation function (ICF) model 826
- Inverse hyperbolic function 184, 262
- Inverse iteration *see* Eigensystems
- Inverse problems 789, 804ff.
 - Backus-Gilbert method 815ff.
 - Bayesian approach 808, 820, 825f.
 - central idea 808
 - constrained linear inversion method 808ff.
 - data inversion 816
 - deterministic constraints 813ff.
 - in geophysics 818
 - Gerchberg-Saxton algorithm 814f.
 - incomplete Fourier coefficients 822
 - and integral equations 789
 - linear regularization 808ff.
 - maximum entropy method (MEM) 818ff., 824f.
 - MEM demystified 823
 - Phillips-Twomey method 808ff.
 - principal solution 806
 - regularization 805ff.
 - regularizing operator 807
 - stabilizing functional 807
 - Tikhonov-Miller regularization 808ff.
 - trade-off curve 804
 - trade-off curve, Backus-Gilbert method 818
 - two-dimensional regularization 812
 - use of conjugate gradient minimization 812f., 824
 - use of convex sets 813f.
 - use of Fourier transform 812, 814
 - Van Cittert's method 813
- Inverse quadratic interpolation 360, 402ff.
- Inverse response kernel, in Backus-Gilbert method 816f.
- Inverse trigonometric function 262
- ISBN (International Standard Book Number)
 - checksum 901
- Iterated integrals 161
- Iteration 8
 - functional 748
 - to improve solution of linear algebraic equations 55ff., 201
 - for linear algebraic equations 35
 - required for two-point boundary value problems 753
 - in root finding 347f.
- Iteration matrix 865
- ITPACK 78
- ivector() utility 943
- J**acobi matrix, for Gaussian quadrature 156
- Jacobi transformation (or rotation) 100, 460, 463ff., 469, 481, 495
- Jacobian determinant 288f., 783
- Jacobian elliptic functions 261, 269f.
- Jacobian matrix 381, 383, 386, 389, 738
 - singular in Newton's rule 393
- Jacobi's method (relaxation) 864f., 866, 873
- Jenkins-Traub method 376
- Julian Day 1, 12, 14
- Jump transposition errors 902
- K**-S test *see* Kolmogorov-Smirnov test
- Kalman filter 705
- Kaps-Rentrop method 737
- Kendall's tau 640, 642ff.
- Kermit checksum 897
- Kernel 788f.
 - averaging, in Backus-Gilbert method 816f.
 - degenerate 794
 - finite rank 794
 - inverse response 816f.
 - separable 794
 - singular 797f.
 - symmetric 793f.
- Kernighan & Ritchie C (K&R C) 2, 16, 24, 930
- Keys used in sorting 338, 897
- Kolmogorov-Smirnov test 620, 623ff., 699
 - two-dimensional 645ff.
 - variants 626ff., 645ff.
- Kuiper's statistic 627
- Kurtosis 612, 614
- L**-estimate 699
- Labels, statement 8
- Lag 498, 545f., 560
- Lagrange multiplier 804
- Lagrange's formula for polynomial interpolation 91, 108, 582, 585
- Laguerre's method 348, 371ff.
- Lanczos lemma 504f.
- Lanczos method for gamma function 213
- Landen transformation 262
- LAPACK 35
- Laplace's equation 252, 827
 - see also* Poisson equation
- Las Vegas 631
- Latin square or hypercube 315
- Laurent series 573
- Lax method 837ff., 845, 854f.
 - multidimensional 854f.
- Lax-Wendroff method 844ff.
- Leakage in power spectrum estimation 551, 554f.

- Leakage width 554f.
- Leapfrog method 842f.
- Least squares filters *see* Savitzky-Golay filters
- Least squares fitting 650f., 657ff., 661ff., 666ff., 671ff.
- contrasted to general minimization problems 689
 - degeneracies in 677, 679
 - Fourier components 577
 - freezing parameters in 674, 705
 - general linear case 671ff.
 - Levenberg-Marquardt method 683ff., 825
 - Lomb periodogram 577
 - as M-estimate for normal errors 701
 - as maximum likelihood estimator 658
 - as method for smoothing data 650f.
 - multidimensional 680
 - nonlinear 393, 681ff., 825
 - nonlinear, advanced methods 688
 - normal equations 651, 672ff., 809f.
 - normal equations often singular 676, 679
 - optimal (Wiener) filtering 547
 - QR method in 100, 674
 - for rational Chebyshev approximation 205
 - relation to linear correlation 636, 664
 - Savitzky-Golay filter as 650f.
 - singular value decomposition (SVD) 34f., 59ff., 205, 676ff.
 - skewed by outliers 659
 - for spectral analysis 577
 - standard (probable) errors on fitted parameters 673, 677
 - weighted 658
 - see also* Fitting
- L'Ecuyer's long period random generator 280ff.
- Left eigenvalues or eigenvectors 458
- Legal matters xvi
- Legendre elliptic integral *see* Elliptic integrals
- Legendre polynomials 252f.
- fitting data to 680
 - recurrence relation 178
 - shifted monic 159
 - see also* Associated Legendre polynomials; Spherical harmonics
- Lehmer-Schur algorithm 376
- Lemarie's wavelet 600
- Lentz's method for continued fraction 171, 219
- Lepage, P. 319
- Leptokurtic distribution 612
- Levenberg-Marquardt algorithm 393, 683ff., 825
- advanced implementation 688
 - Levinson's method 92f.
- Lewis, H.W. 284
- License information xvi
- Limbo 362
- Limit cycle, in Laguerre's method 372
- Line minimization *see* Minimization, along a ray
- Line search *see* Minimization, along a ray
- Linear algebraic equations 32f.
- band diagonal 51ff.
 - biconjugate gradient method 84f.
 - Cholesky decomposition 96ff., 430, 462, 674
 - complex 49f.
 - computing $\mathbf{A}^{-1} \cdot \mathbf{B}$ 48
 - conjugate gradient method 83ff., 606
 - cyclic tridiagonal 74f.
 - direct methods 35, 71
 - Gauss-Jordan elimination 36ff.
 - Gaussian elimination 41f.
 - Hilbert matrix 90
 - Hotelling's method 57, 606
 - and integral equations 788ff., 792
 - iterative improvement 55ff., 201
 - iterative methods 35, 83ff.
 - large sets of 33
 - least squares solution 62, 65f., 205, 676
 - LU decomposition 43ff., 201, 393, 739, 792, 795, 810
 - nonsingular 33
 - overdetermined 34f., 205, 676, 806
 - partitioned 77f.
 - QR decomposition 98f., 389, 393, 674
 - row vs. column elimination 40f.
 - Schultz's method 57, 606
 - Sherman-Morrison formula 73ff., 90
 - singular 32, 61, 66, 205, 676
 - singular value decomposition (SVD) 59ff., 205, 676ff., 806
 - sparse 33, 51ff., 71ff., 739, 813
 - summary of tasks 34
 - Toeplitz 90, 92ff., 201
 - Vandermonde 90ff., 120
 - wavelet solution 603ff., 791
 - Woodbury formula 75ff., 90
 - see also* Eigensystems
- Linear congruential random number generator 276f.
- choice of constants for 284f.
- Linear constraints 431
- Linear convergence 353, 400
- Linear correlation (statistics) 636ff.
- Linear dependency
- constructing orthonormal basis 66, 100
 - of directions in N -dimensional space 415
 - in linear algebraic equations 32f.
- Linear equations *see* Differential equations; Integral equations; Linear algebraic equations
- Linear inversion method, constrained 808ff.
- Linear prediction 564ff.
- characteristic polynomial 567
 - coefficients 564ff.
 - compared with regularization 810
 - contrasted to polynomial extrapolation 567
 - related to optimal filtering 565f.
 - removal of bias in 570
 - stability 567
- Linear predictive coding (LPC) 571f.
- Linear programming 394, 430ff.
- artificial variables 437
 - auxiliary objective function 437
 - basic variables 434
 - composite simplex algorithm 443
 - constraints 431

- convergence criteria 439
- degenerate feasible vector 436
- dual problem 443
- equality constraints 431
- feasible basis vector 433f.
- feasible vector 431
- fundamental theorem 432f.
- inequality constraints 431
- left-hand variables 434
- nonbasic variables 434
- normal form 433
- objective function 431
- optimal feasible vector 431
- pivot element 435f.
- primal-dual algorithm 443
- primal problem 443
- reduction to normal form 436ff.
- restricted normal form 433ff.
- revised simplex method 443
- right-hand variables 434
- simplex method 408f., 430, 433ff., 439ff.
- slack variables 436
- tableau 434
- vertex of simplex 433
- Linear regression 661ff., 666ff.
 - see also* Fitting
- Linear regularization 808ff.
- LINPACK 35
- Little-endian 302
- Local extrapolation 715
- Local extremum 394, 445
- Localization of roots *see* Bracketing
- Logarithmic function 262
- Lomb periodogram method of spectral analysis 576f.
 - fast algorithm 581f.
- Loops 8
- Lorentzian probability distribution 292, 701f.
- Low-pass filter 558, 650
- LP coefficients *see* Linear prediction
- LPC (linear predictive coding) 571f.
- LU decomposition 43ff., 56f., 59, 63, 71, 104, 381, 673, 739
 - for $\mathbf{A}^{-1} \cdot \mathbf{B}$ 48
 - band diagonal matrix 51ff., 53f.
 - complex equations 49f.
 - Crout's algorithm 44ff., 53
 - for integral equations 792, 795
 - for inverse iteration of eigenvectors 494
 - for inverse problems 810
 - for matrix determinant 49
 - for matrix inverse 48
 - for nonlinear sets of equations 381, 393
 - operation count 44, 48
 - for Padé approximant 201
 - pivoting 45f.
 - repeated backsubstitution 48, 54
 - solution of linear algebraic equations 48
 - solution of normal equations 673
 - for Toeplitz matrix 94
- Lucifer (encryption algorithm) 300
- `lvector()` utility 943
- how to compute 702f.
 - local 700ff.
 - see also* Maximum likelihood estimate
- Machine accuracy 28f., 890
- Macintosh, *see* Apple Macintosh
- Maehly's procedure 370, 378
- Magic
 - in MEM image restoration 823
 - in Padé approximation 201
- Mantissa in floating point format 28, 890, 918
- Marginals 630
- Marquardt method (least squares fitting) 683ff., 825
- Mass, center of 305ff.
- MasterCard checksum 901f.
- Mathematical Center (Amsterdam) 360
- Matrix 33ff.
 - allocating and freeing 21f., 940ff.
 - approximation of 66f., 605f.
 - band diagonal 50, 51ff., 71
 - band triangular 71
 - banded 35, 461
 - bidagonal 60
 - block diagonal 71, 762
 - block triangular 71
 - block tridiagonal 71
 - bordered 71
 - characteristic polynomial 456, 475f.
 - Cholesky decomposition 96ff., 430, 462, 674
 - column augmented 37
 - compatibility 940
 - complex 49f.
 - condition number 61, 85
 - curvature 682
 - cyclic banded 71
 - cyclic tridiagonal 74f.
 - defective 457, 482, 494
 - of derivatives *see* Hessian matrix; Jacobian determinant
 - design (fitting) 651, 671, 809
 - determinant of 34, 49
 - diagonalization 459ff.
 - elementary row and column operations 37
 - finite differencing of partial differential equations 830ff.
 - freeing a submatrix 23
 - Hermitian 457, 461, 481f.
 - Hermitian conjugate 457
 - Hessenberg 100, 460, 477, 482, 484f., 494
 - Hessian *see* Hessian matrix
 - hierarchically band diagonal 606
 - Hilbert 90
 - identity 34
 - ill-conditioned 61, 63, 120
 - indexed storage of 78f.
 - and integral equations 788, 792
 - inverse 34, 36, 42, 48f., 73ff., 77f., 102ff.
 - inverse, approximate 57
 - inverse by Hotelling's method 57, 606
 - inverse by Schultz's method 57, 606
 - inverse multiplied by a matrix 49
 - iteration for inverse 57, 606
 - Jacobi transformation 460, 463ff., 469

M-estimates 699ff.

- Jacobian 738
 lower triangular 43f., 96, 790
 multiplication denoted by dot 33
 norm 58
 normal 457, 458
 nullity 61
 nullspace 34, 61, 63, 456, 804
 orthogonal 98, 457, 470, 594
 orthogonal transformation 459, 470ff., 477
 orthonormal basis 66, 100
 outer product denoted by \otimes 73, 427
 partitioning for determinant 78
 partitioning for inverse 77f.
 pattern multiply of sparse 81f.
 positive definite 35, 96, 674
 QR decomposition 98f., 389, 393, 674
 range 61
 rank 61
 residual 57
 row and column indices 33
 row vs. column operations 40f.
 self-adjoint 457
 similarity transform 459ff., 463, 483, 485, 488
 singular 61, 63, 66, 456
 singular value decomposition 34f., 59ff., 806
 sparse 33, 71ff., 78, 606, 739, 762, 813
 special forms 35
 splitting in relaxation method 865f.
 spread 817
 square root of 430, 462
 storage schemes in C 20f., 33f., 940ff.
 submatrix of 22, 945
 symmetric 35, 96, 457, 461, 469ff., 674, 793f.
 threshold multiply of sparse 81ff.
 Toeplitz 90, 92ff., 201
 transpose of sparse 80f.
 triangular 460
 tridiagonal 35, 50f., 71, 115, 156, 460, 461, 469ff., 475ff., 494, 848f., 862, 870f.
 tridiagonal with fringes 831
 unitary 457
 updating 100, 389f.
 upper triangular 43f., 98
 Vandermonde 90ff., 120
see also Eigensystems
- Matrix equations *see* Linear algebraic equations
- `matrix()` utility 943f.
- Matterhorn 612
- Maximization *see* Minimization
- Maximum entropy method (MEM) 572ff.
 algorithms for image restoration 824f.
 Bayesian 825f.
 Cornwell-Evans algorithm 825
 demystified 823
 historic vs. Bayesian 825f.
 image restoration 818ff.
 intrinsic correlation function (ICF) model 826
 for inverse problems 818ff.
 operation count 574
- see also* Linear prediction
- Maximum likelihood estimate (M-estimates) 695, 699ff.
 and Bayes' Theorem 820
 chi-square test 695
 defined 658
 how to compute 702f.
 mean absolute deviation 701, 703
 relation to least squares 658
- Maxwell's equations 835
- Mean(s)
 of distribution 610f., 614
 statistical differences between two 615ff.
- Mean absolute deviation of distribution 611, 701
 related to median 703
- Measurement errors 656
- Median 329
 calculating 341
 of distribution 611, 614f.
 as L-estimate 699
 role in robust straight line fitting 703
 by selection 703
- Median-of-three, in Quicksort 333
- MEM *see* Maximum entropy method (MEM)
- Memory, allocating and freeing 19, 21f., 940ff.
- Merit function 656
 in general linear least squares 671
 for inverse problems 806
 nonlinear models 681
 for straight line fitting 662, 703
 for straight line fitting, errors in both coordinates 666
- Mesh-drift instability 843f.
- Mesokurtic distribution 612
- Method of regularization 808ff.
- Metropolis algorithm 445f.
- Microsoft xvii
- Midpoint method *see* Modified midpoint method;
 Semi-implicit midpoint rule
- Mikado, or Town of Titipu 720
- Miller's algorithm 181, 234
- Minimal solution of recurrence relation 179
- Minimax polynomial 192, 204
- Minimax rational function 204
- Minimization 394ff.
 along a ray 84, 384f., 396, 412f., 418f., 424, 425
 annealing, method of simulated 394f., 444ff.
 bracketing of minimum 397ff., 409
 Brent's method 396, 402ff., 406, 666
 Broyden-Fletcher-Goldfarb-Shanno algorithm 397, 426ff.
 chi-square 659ff., 681ff.
 choice of methods 395ff.
 combinatorial 444
 conjugate gradient method 396f., 420ff., 812f., 824
 convergence rate 400, 415f.
 Davidon-Fletcher-Powell algorithm 397, 426f.
 degenerate 804
 direction-set methods 396, 412ff.

- downhill simplex method 396, 408ff., 451f., 702f.
 finding best-fit parameters 656
 Fletcher-Reeves algorithm 396f., 421ff.
 functional 804
 global 394f., 451f., 656
 globally convergent multidimensional 425ff.
 golden section search 397ff., 403
 multidimensional 395f., 408ff.
 in nonlinear model fitting 681f.
 Polak-Ribiere algorithm 396f., 422f.
 Powell's method 396, 408, 412ff.
 quasi-Newton methods 383, 397, 425ff.
 and root finding 382
 scaling of variables 428
 by searching smaller subspaces 824
 steepest descent method 421, 813
 termination criterion 398f., 410
 use in finding double roots 348
 use for sparse linear systems 84ff.
 using derivatives 396f., 405ff.
 variable metric methods 397, 425ff.
see also Linear programming
- Minimum residual method, for sparse system 85
- MINPACK 688
- MIPS 894
- Missing data problem 576
- Mississippi River 446, 455
- Mode of distribution 611, 615
- Modeling of data *see* Fitting
- Model-trust region 393, 688
- Modes, homogeneous, of recursive filters 561
- Modified Bessel functions *see* Bessel functions
- Modified Lentz's method, for continued fractions 171
- Modified midpoint method 722f., 726
- Modified moments 158
- Modula-2 7
- Modular arithmetic, without overflow 278, 281, 284
- Modularization, in programs 6f.
- Modulus of linear congruential generator 276
- Moments
 - of distribution 610ff.
 - filter that preserves 650
 - modified problem of 158
 - problem of 90f.
 - and quadrature formulas 799
 - semi-invariants 614
- Monic polynomial 149
- Monotonicity constraint, in upwind differencing 846
- Monte Carlo 162, 275
 - adaptive 316ff., 319ff.
 - bootstrap method 691f.
 - comparison of sampling methods 318f.
 - exploration of binary tree 300
 - importance sampling 316f.
 - integration 130, 162, 304ff., 316ff.
 - integration, recursive 323ff.
 - integration, using Sobol' sequence 313ff.
 - integration, VEGAS algorithm 319ff.
- and Kolmogorov-Smirnov statistic 627, 646f.
- partial differential equations 833
- quasi-random sequences in 309ff.
- quick and dirty 691f.
- recursive 316ff., 323ff.
- significance of Lomb periodogram 578
- simulation of data 660, 689ff., 695
- stratified sampling 317f., 323
- Moon, calculate phases of 1f., 13f.
- Mother functions 591
- Mother Nature 689, 691
- Moving average (MA) model 573
- Moving window averaging 650
- Mozart 8
- MS xvii
- MS-DOS xii, 3
- Muller's method 371, 379
- Multidimensional
 - confidence levels of fitting 694
 - data, use of binning 629
 - Fourier transform 521ff.
 - Fourier transform, real data 525ff.
 - initial value problems 853ff.
 - integrals 130, 161ff., 304ff., 316ff.
 - interpolation 123ff.
 - Kolmogorov-Smirnov test 645ff.
 - least squares fitting 680
 - minimization 408ff., 412ff., 420ff.
 - Monte Carlo integration 304ff., 316ff.
 - normal (Gaussian) distribution 695
 - optimization 395f.
 - partial differential equations 853ff.
 - root finding 347ff., 365, 377, 379ff., 382, 754, 757f., 761, 762
 - search using quasi-random sequence 309
 - secant method 380, 389ff.
 - wavelet transform 602
- Multigrid method 833, 871ff.
 - avoid SOR 875
 - boundary conditions 877f.
 - choice of operators 877
 - coarse-to-fine operator 873
 - coarse-grid correction 873f.
 - cycle 874
 - dual viewpoint 883
 - fine-to-coarse operator 873
 - full approximation storage (FAS) algorithm 882ff.
 - full multigrid method (FMG) 872, 877f.
 - full weighting 876
 - Gauss-Seidel relaxation 874f.
 - half weighting 876
 - importance of adjoint operator 876
 - injection operator 873
 - interpolation operator 873
 - line relaxation 875
 - local truncation error 883
 - Newton's rule 882, 884
 - nonlinear equations 882ff.
 - nonlinear Gauss-Seidel relaxation 884
 - odd-even ordering 875, 878
 - operation count 871
 - prolongation operator 873
 - recursive nature 874

- relative truncation error 883
- relaxation as smoothing operator 874
- restriction operator 873
- speeding up FMG algorithm 881f.
- stopping criterion 884
- straight injection 876
- symbol of operator 875f.
- use of Richardson extrapolation 878
- V-cycle 874
- W-cycle 874
- zebra relaxation 875
- Multiple precision arithmetic 915ff.
- Multiple roots 348, 369
- Multiplication, complex 177
- Multiplication, multiple precision 916, 918
- Multiplier of linear congruential generator 276
- Multistep and multivalued methods (ODEs) 747ff.
 - see also* Differential Equations; Predictor-corrector methods
- Multivariate normal distribution 695
- Murphy's Law 413
- Musical scores 5

- NAG** xvii, 35, 72, 212, 461
- National Science Foundation (U.S.) xiii, xv
- Natural cubic spline 115
- Navier-Stokes equation 839, 840
- Needle, eye of (minimization) 410
- Negation, multiple precision 916
- Negentropy 820, 904
- Nelder-Mead minimization method 396, 408ff.
- Nested iteration 877
- Neumann boundary conditions 829, 849, 860, 867
- Neutrino 645
- Neville's algorithm 108f., 111, 140, 188
- Newton-Cotes formulas 131ff., 147
 - open 132
- Newton-Raphson method *see* Newton's rule
- Newton's rule 149f., 185, 348, 362ff., 369, 371, 476
 - with backtracking 384f.
 - caution on use of numerical derivatives 365
 - fractal domain of convergence 367f.
 - globally convergent multidimensional 380, 383ff., 389, 757f., 761
 - for matrix inverse 57, 606
 - in multidimensions 377, 379ff., 757f., 761, 762
 - in nonlinear multigrid 882, 884
 - nonlinear Volterra equations 796
 - for reciprocal of number 919
 - safe 366
 - scaling of variables 389
 - singular Jacobian 393
 - solving stiff ODEs 748
 - for square root of number 921
- Niederreiter sequence 310
- NL2SOL 688
- Noise
 - bursty 897
 - effect on maximum entropy method 574
 - equivalent bandwidth 554
 - fitting data which contains 653, 656
 - model, for optimal filtering 548
- Nominal variable (statistics) 628
- Nonexpansive projection operator 814
- Non-interfering directions *see* Conjugate directions
- Nonlinear eigenvalue problems 462
- Nonlinear equations
 - finding roots of 347ff.
 - integral equations 790, 796
 - in MEM inverse problems 822f.
 - multigrid method for elliptic PDEs 882ff.
- Nonlinear instability 840
- Nonlinear programming 443
- Nonnegativity constraints 430f.
- Nonparametric statistics 639ff.
- Nonpolynomial complete (NP-complete) 445
- Norm, of matrix 58
- Normal (Gaussian) distribution 275, 658, 687f., 807
 - central limit theorem 658f.
 - deviates from 288f., 578
 - kurtosis of 612
 - multivariate 695
 - semi-invariants of 614
 - tails compared to Poisson 659
 - two-dimensional (binormal) 637
 - variance of skewness of 612
- Normal equations (fitting) 34f., 651, 672ff., 804, 809f.
 - often are singular 676
- Normalization
 - of Bessel functions 181
 - of floating-point representation 28, 890
 - of functions 149, 774
 - of modified Bessel functions 239
- Notch filter 558, 562f.
- NP-complete problem 445
- nr.h prototypes for Numerical Recipes 17, 930
- NRANSI macro 17, 930
- NR_END macro, for offset arrays 941
- nrerror() utility 2, 942f.
- nrutil.c utility functions 2, 19, 21f., 940, 942ff.
- nrutil.h prototypes for utilities 17, 27, 940ff.
- Null hypothesis 609
- Nullity 61
- Nullspace 34, 61, 63, 456, 804
- Number-theoretic transforms 509f.
- Numerical derivatives 186ff., 651
- Numerical integration *see* Quadrature
- Numerical Recipes
 - compatibility with First Edition 3f.
 - compilers tested 3
 - Example Book 3
 - how to get diskettes xvi, 996f.
 - how to report bugs iv
 - license information xvi
 - list of all 951ff.
 - machines tested 3
 - OEM information xvii
 - no warranty on xvi

- programming conventions 25ff.
 - programs by chapter and section xix
 - prototypes (nr.h) 17, 930
 - table of dependencies 951ff.
 - table of prototypes 930
 - as trademark xvii
 - utility functions 2, 940ff.
 - utility prototypes (nrutil.h) 17, 27, 940ff.
 - Numerical Recipes Software xi, xvii
 - address and fax number xvii
 - Nyquist frequency 500ff., 526, 550, 552, 576, 578f.
 - Nystrom method 791f., 797f.
 - product version 797
- O**bject extensibility 7
- Objective function 431
 - Object-oriented programming 7
 - Oblateness parameter 773
 - Odd parity 896
 - Odd-even ordering
 - in Gauss-Seidel relaxation 875, 878
 - in successive over-relaxation (SOR) 868
 - OEM information xvii
 - One-sided power spectral density 498
 - Operation count
 - balancing 483
 - Bessel function evaluation 234f.
 - bisection method 353
 - Cholesky decomposition 97
 - coefficients of interpolating polynomial 120f.
 - complex multiplication 104
 - cubic spline interpolation 115
 - evaluating polynomial 174f.
 - fast Fourier transform (FFT) 504
 - Gauss-Jordan elimination 42, 48
 - Gaussian elimination 42
 - Givens reduction 470
 - Householder reduction 474
 - interpolation 106
 - inverse iteration 494
 - iterative improvement 56
 - Jacobi transformation 467
 - Kendall's tau 643f.
 - linear congruential generator 277
 - LU decomposition 44, 48
 - matrix inversion 104
 - matrix multiplication 103
 - maximum entropy method 574
 - multidimensional minimization 420
 - multigrid method 871
 - multiplication 918
 - polynomial evaluation 104, 174f.
 - QL method 477, 480
 - QR decomposition 98
 - QR method for Hessenberg matrices 490
 - reduction to Hessenberg form 485
 - selection by partitioning 341
 - sorting 329ff.
 - Toeplitz matrix 90
 - Vandermonde matrix 90
 - Operator
 - associativity, in C 25f.
 - overloading 7
 - precedence, in C 25f.
 - splitting 832, 856f., 870
 - Optimal feasible vector 431
 - Optimal (Wiener) filtering 542, 547ff., 565f., 650
 - compared with regularization 810
 - Optimization *see* Minimization
 - Ordinal variable (statistics) 628
 - Ordinary differential equations *see* Differential equations
 - Orthogonal *see* Orthonormal functions; Orthonormal polynomials
 - Orthogonal transformation 459, 470ff., 477, 591
 - Orthonormal basis, constructing 66, 100
 - Orthonormal functions 149, 252
 - Orthonormal polynomials
 - Chebyshev 151, 190ff.
 - construct for arbitrary weight 157ff.
 - in Gauss-Hermite integration 153
 - and Gaussian quadrature 149
 - Gaussian weights from recurrence 156
 - Hermite 151
 - Jacobi 151
 - Laguerre 151
 - Legendre 151
 - weight function $\log x$ 159
 - Orthonormality 59f., 149, 470
 - Outer product of matrices (denoted by \otimes) 73, 427
 - Outgoing wave boundary conditions 829
 - Outlier 611, 659, 662, 699, 702
 - see also* Robust estimation
 - Overcorrection 866
 - Overflow 890
 - how to avoid in modulo multiplication 278
 - in complex arithmetic 177
 - Overlap-add and overlap-save methods 543f.
 - Overrelaxation parameter 866
 - choice of 866f.
- P**adé approximant 111, 200ff.
- Parabolic interpolation 403
 - Parabolic partial differential equations 827, 847ff.
 - Parallel axis theorem 318
 - Parameters in fitting function 657f., 689ff.
 - Parity bit 896
 - Park and Miller minimal standard random generator 278f.
 - Parseval's Theorem 498, 551
 - discrete form 504
 - Partial differential equations 827ff.
 - advective equation 835
 - alternating-direction implicit method (ADI) 856, 870f.
 - amplification factor 837, 843
 - analyze/factorize/operate package 833
 - artificial viscosity 840, 846
 - biconjugate gradient method 833
 - boundary conditions 828ff.

- boundary value problems 828ff., 857f.
 Cauchy problem 827f.
 caution on high-order methods 853f.
 Cayley's form 853
 characteristics 827
 Chebyshev acceleration 868f.
 classification of 827ff.
 comparison of rapid methods 863
 conjugate gradient method 833
 Courant condition 838, 841, 843, 845
 Courant condition (multidimensional) 855
 Crank-Nicholson method 848, 851, 853, 855
 cyclic reduction (CR) method 857f., 861f.
 diffusion equation 827, 847ff., 855, 864
 Dirichlet boundary conditions 829, 848, 859, 865, 867
 elliptic, defined 827
 error, varieties of 840ff.
 explicit vs. implicit differencing 836
 FACR method 863
 finite difference method 830ff.
 finite element methods 833f.
 flux-conservative initial value problems 834ff.
 forward Euler differencing 835f.
 Forward Time Centered Space (FTCS) 836ff., 847ff., 852, 864
 Fourier analysis and cyclic reduction (FACR) 857ff., 863
 Gauss-Seidel method (relaxation) 864, 873ff., 884
 Godunov's method 846
 Helmholtz equation 861
 hyperbolic 827, 834f.
 implicit differencing 848
 incomplete Cholesky conjugate gradient method (ICCG) 833
 inhomogeneous boundary conditions 859f.
 initial value problems 827f.
 initial value problems, recommendations on 847ff.
 Jacobi's method (relaxation) 864f., 873
 Laplace's equation 827
 Lax method 837ff., 845, 854f.
 Lax method (multidimensional) 854f.
 matrix methods 833
 mesh-drift instability 843f.
 Monte Carlo methods 833
 multidimensional initial value problems 853ff.
 multigrid method 833, 871ff.
 Neumann boundary conditions 829, 849, 860, 867
 nonlinear diffusion equation 851
 nonlinear instability 840
 numerical dissipation or viscosity 839
 operator splitting 832, 856f., 870
 outgoing wave boundary conditions 829
 parabolic 827, 847ff.
 periodic boundary conditions 859, 867
 piecewise parabolic method (PPM) 846
 Poisson equation 827, 861
 rapid (Fourier) methods 514ff., 833, 857ff.
 relaxation methods 832, 863ff.
 Schrödinger equation 851ff.
 second-order accuracy 842ff., 848f.
 shock 840, 846
 sparse matrices from 71
 spectral methods 833f.
 spectral radius 865ff., 871
 stability vs. accuracy 839
 stability vs. efficiency 830
 staggered grids 519, 861
 staggered leapfrog method 842f.
 strongly implicit procedure 833
 successive over-relaxation (SOR) 866ff., 871, 875
 time splitting 856f., 870
 two-step Lax-Wendroff method 844ff.
 upwind differencing 841f., 846
 variational methods 833
 varieties of error 840ff.
 von Neumann stability analysis 836f., 839, 842, 849
 wave equation 827, 834f.
see also Elliptic partial differential equations; Finite difference equations (FDEs)
- Partial pivoting 38
 Partition-exchange 332, 341
 Partitioned matrix, inverse of 77f.
 Party tricks 102ff., 174f.
 Parzen window 554
 Pascal 16, 18, 20
 Pascal, Numerical Recipes in xv, 1
 Path integration, for function evaluation 208ff., 271
 Pattern multiply of sparse matrices 81f.
 PBCG (preconditioned biconjugate gradient method) 85f., 833
 PC methods *see* Predictor-corrector methods
 PCGPACK 78
 PDEs *see* Partial differential equations
 Pearson's r 636ff.
 PECE method 749
 Pentagon, symmetries of 902
 Percentile 329
 Period of linear congruential generator 276
 Periodic boundary conditions 859, 867
 Periodogram 550ff., 574
 Lomb's normalized 576f., 581f.
 variance of 552
 Perl (programming language) xiii
 Perron's theorems, for convergence of recurrence relations 180f.
 Perturbation methods for matrix inversion 73ff.
 Peter Principle 337
 Phase error 840
 Phase-locked loop 705
 Phi statistic 631
 Phillips-Twomey method 808ff.
 Pi, computation of 915ff.
 Piecewise parabolic method (PPM) 846
 Pincherle's theorem 181
 Pivot element 38, 41, 764
 in linear programming 435f.
 Pivoting 36, 38ff., 54, 73, 97
 full 38
 implicit 38, 46

- in LU decomposition 45f.
 - partial 38, 41, 46
 - and QR decomposition 99
 - in reduction to Hessenberg form 485
 - in relaxation method 764
 - for tridiagonal systems 51
- Pixel 525, 603, 812, 820
- Planck's constant 851
- Plane rotation *see* Givens reduction; Jacobi transformation (or rotation)
- Platykurtic distribution 612
- Plotting of functions 349f.
- POCS (method of projection onto convex sets) 814
- Poetry 5
- Pointer
 - to array 18
 - use for matrices 20, 33f., 940ff.
- Poisson equation 525, 827, 861
- Poisson probability function
 - cumulative 221
 - deviates from 290, 293ff., 579
 - semi-invariants of 614
 - tails compared to Gaussian 659
- Poisson process 287, 291, 293
- Polak-Ribiere algorithm 396f., 422f.
- Poles *see* Complex plane, poles in
- Polishing of roots 365, 370f., 376f.
- Polymorphism 7
- Polynomial interpolation 105, 108ff.
 - Aitken's algorithm 108
 - in Bulirsch-Stoer method 728, 730f.
 - coefficients for 120ff.
 - Lagrange's formula 91, 108f.
 - multidimensional 123ff.
 - Neville's algorithm 108f., 111, 140, 188
 - pathology in determining coefficients for 120
 - in predictor-corrector method 748
 - smoothing filters 650f.
 - see also* Interpolation
- Polynomials 173ff.
 - algebraic manipulations 175
 - approximating modified Bessel functions 236
 - approximation from Chebyshev coefficients 197
 - AUTODIN-II 898
 - CCITT 897f.
 - characteristic 375
 - characteristic, for digital filters 561, 567
 - characteristic, for eigenvalues of matrix 456, 475f.
 - Chebyshev 190ff.
 - CRC-16 898
 - deflation 369ff., 377
 - derivatives of 173f.
 - division 91, 175, 369, 377
 - evaluation of 173
 - evaluation of derivatives 173f.
 - extrapolation in Bulirsch-Stoer method 728, 730f.
 - extrapolation in Romberg integration 140
 - fitting 90, 120, 197, 650f., 671, 679f.
 - generator for CRC 897f.
 - ill-conditioned 369
 - matrix method for roots 375
 - minimax 192, 204
 - monic 149
 - multiplication 175
 - operation count for 174f.
 - orthonormal 149, 190f.
 - primitive modulo 2 296ff., 311f., 897
 - roots of 183ff., 369ff., 375
 - shifting of 198f.
 - stopping criterion in root finding 373
- Port, serial data 899
- Portability 2f., 16
- Portable random number generator *see* Random number generator
- Positive definite matrix, testing for 97
- Positivity constraints 431
- Postal Service (U.S.), barcode 902
- PostScript xiii, xvii
- Powell's method 396, 408, 412ff.
- Power (in a signal) 498f.
- Power series 165ff., 173f., 201
 - economization of 198ff.
 - Padé approximant of 200ff.
- Power spectral density *see* Fourier transform; Spectral density
- Power spectrum estimation *see* Fourier transform; Spectral density
- PPM (piecewise parabolic method) 846
- Precedence of operators, in C 25f.
- Precision, floating point 890
- Precision, multiple 915ff.
- Preconditioned biconjugate gradient method (PBCG) 85f.
- Preconditioning, in conjugate gradient methods 833
- Predictor-corrector methods 708, 737, 747ff.
 - Adams-Bashforth-Moulton schemes 749
 - adaptive order methods 751
 - compared to other methods 747f.
 - fallacy of multiple correction 748f.
 - with fixed number of iterations 749
 - functional iteration vs. Newton's rule 749
 - multivalued compared with multistep 749f.
 - starting and stopping 750, 751
 - stepsize control 749f.
- Prime numbers 924f.
- Primitive polynomials modulo 2 296ff., 311f., 897
- Principal directions 414f.
- Principal solution, of inverse problem 806
- Prize, \$1000 offered 281
- Probability *see* Random number generator; Statistical tests
- Probability density, change of variables in 287ff.
- Process loss 554
- Product Nystrom method 797
- Program(s)
 - as black boxes xiv, 5, 35, 60, 212, 348, 413
 - dependencies 951ff.
 - encapsulation 6f.
 - interfaces 7
 - modularization 6f.

- organization 5ff.
 - recipes by chapter and section xix
 - typography of 11
 - validation 2f.
 - Projection onto convex sets (POCS) 814
 - Projection operator, nonexpansive 814
 - Prolongation operator 873
 - Protocol, for communications 896
 - Prototypes in C 16f., 25, 930
 - PSD (power spectral density) *see* Fourier transform; Spectral density
 - Pseudo-random numbers 274ff.
 - Puns, particularly bad 173, 752, 755
 - Pyramidal algorithm 594
 - Pythagoreans 399
- Q**
- QL** *see* Eigensystems
 - QR** *see* Eigensystems
 - QR decomposition 98f., 389, 393
 - backsubstitution 98
 - and least squares 674
 - operation count 98
 - pivoting 99
 - updating 100, 389
 - use for orthonormal basis 66, 100
 - Quadratic
 - convergence 57, 262, 358, 364f., 415f., 427, 915
 - equations 29, 183ff., 398, 464
 - interpolation 360, 371
 - programming 443
 - Quadrature 129ff.
 - adaptive 129, 196, 797
 - alternative extended Simpson's rule 134
 - arbitrary weight function 157ff., 797
 - automatic 160
 - Bode's rule 132
 - change of variable in 144ff., 797
 - by Chebyshev fitting 130, 195
 - classical formulas for 130ff.
 - Clenshaw-Curtis 130, 196, 518f.
 - closed formulas 131, 133f.
 - and computer science 889
 - by cubic splines 130
 - error estimate in solution 793
 - extended midpoint rule 135, 141f.
 - extended rules 133ff., 140, 795, 797, 799
 - extended Simpson's rule 134
 - Fourier integrals 584ff.
 - Fourier integrals, infinite range 590f.
 - Gauss-Chebyshev 151, 518f.
 - Gauss-Hermite 151, 798
 - Gauss-Jacobi 151
 - Gauss-Kronrod 160
 - Gauss-Laguerre 151, 798
 - Gauss-Legendre 151, 792, 797
 - Gauss-Lobatto 160, 196, 518
 - Gauss-Radau 160
 - Gaussian integration 133, 147ff., 790, 792, 797
 - Gaussian integration, nonclassical weight function 157ff., 797
 - for improper integrals 141ff., 797f.
 - for integral equations 790f., 795
 - Monte Carlo 130, 162, 304ff., 316ff.
 - multidimensional 130, 161ff.
 - Newton-Cotes formulas 131ff., 147
 - Newton-Cotes open formulas 132
 - open formulas 131, 132f., 135f., 141
 - related to differential equations 129
 - related to predictor-corrector methods 747f.
 - Romberg integration 130, 140f., 143, 188, 723, 797
 - semi-open formulas 135f.
 - Simpson's rule 132, 139, 143, 590, 791f., 797, 799
 - Simpson's three-eighths rule 132, 797, 799
 - singularity removal 144ff., 797f.
 - singularity removal, worked example 801
 - trapezoidal rule 131, 133, 136ff., 140, 586, 590, 791f., 795
 - using FFTs 130
 - weight function $\log x$ 159
 - see also* Integration of functions
 - Quadrature mirror filter 592, 600
 - Quantum mechanics, Uncertainty Principle 607
 - Quartile value 329
 - Quasi-Newton methods for minimization 397, 425ff.
 - Quasi-random sequence 309ff., 327, 889, 896
 - Halton's 309f.
 - for Monte Carlo integration 313ff., 319, 327
 - Sobol's 311
 - see also* Random number generator
 - Quicksort 329, 332ff., 338, 341
 - Quotient-difference algorithm 170
- R**
- R**-estimates 699f.
 - Radioactive decay 287
 - Radix base for floating point arithmetic 483, 890, 916, 922
 - Radix conversion 910, 914, 922
 - Ramanujan's identity for π 924
 - RAND_MAX macro 275f., 277
 - Random bits, generation of 296ff.
 - Random deviates 274ff.
 - binomial 295f.
 - exponential 287f.
 - gamma distribution 290ff.
 - Gaussian 275, 288f., 578, 807
 - normal 275, 288f., 578
 - Poisson 293ff., 579
 - quasi-random sequences 309ff., 889, 896
 - uniform 275ff.
 - uniform integer 280, 283ff.
 - Random number generator 274ff.
 - bitwise operations 296ff.
 - Box-Muller algorithm 289
 - Data Encryption Standard 300ff.
 - good choices for modulus, multiplier and increment 284f.
 - for integer-valued probability distribution 293
 - integer vs. real implementation 283
 - L'Ecuyer's long period 280f.

- linear congruential generator 276f.
- machine language 278
- Minimal Standard, Park and Miller's 278f.
- nonrandomness of low-order bits 277
- perfect 281
- planes, numbers lie on 277
- portable 278ff.
- primitive polynomials modulo 2 296ff.
- pseudo-DES 300
- quasi-random sequences 309ff., 889, 896
- quick and dirty 283ff.
- quicker and dirtier 284f.
- in Quicksort 333
- random access to n th number 303
- random bits 296ff.
- recommendations 285f.
- rejection method 290ff.
- shuffling procedure 280, 281
- in simulated annealing method 445
- spectral test 284
- subtractive method 282
- system-supplied 275ff.
- timings 285f.
- transformation method 287ff.
- trick for trigonometric functions 289
- Random numbers *see* Monte Carlo; Random deviates
- Random walk 29
- RANDU, infamous routine 277
- Range 61, 63
- Rank (matrix) 61
 - kernel of finite 794
- Rank (sorting) 329, 340f.
- Rank (statistics) 639ff., 699f.
 - Kendall's tau 642ff.
 - Spearman correlation coefficient 640f.
 - sum squared differences of 640
- Ratio variable (statistics) 628
- Rational Chebyshev approximation 204ff.
- Rational function 105, 173ff., 200ff., 204ff.
 - approximation for Bessel functions 231f.
 - approximation for continued fraction 170, 217, 227
 - Chebyshev approximation 204ff.
 - evaluation of 176
 - extrapolation in Bulirsch-Stoer method 724ff., 731
 - interpolation and extrapolation using 105, 111ff., 200ff., 204ff., 724ff., 731
 - minimax 204
 - as power spectrum estimate 573
- Realizable (causal) 559, 561
- Rearranging *see* Sorting
- Reciprocal, multiple precision 919
- Record, in data file 338
- Recurrence relation 178ff.
 - associated Legendre polynomials 253
 - Bessel function 178, 231, 241f.
 - binomial coefficients 215
 - Bulirsch-Stoer 111f.
 - characteristic polynomial of tridiagonal matrix 475
 - Clenshaw's recurrence formula 181ff. and continued fraction 181
 - continued fraction evaluation 170f.
 - convergence 181
 - cosine function 178, 506
 - dominant solution 179
 - exponential integrals 178
 - gamma function 213
 - generation of random bits 297f.
 - Golden Mean 30
 - Legendre polynomials 178
 - minimal vs. dominant solution 179
 - modified Bessel function 239
 - Neville's 109, 188
 - orthonormal polynomials 149
 - Perron's theorems 180f.
 - Pincherle's theorem 181
 - polynomial interpolation 109, 189
 - primitive polynomials modulo 2 297f.
 - random number generator 276
 - rational function interpolation 111f.
 - sequence of trig functions 178f.
 - sine function 178, 506
 - spherical harmonics 253
 - stability of 30f., 179ff., 182f., 231, 239, 253
 - trig functions 579
 - weight of Gaussian quadrature 150f.
- Recursion, in multigrid method 874
- Recursive Monte Carlo integration 316ff.
- Recursive stratified sampling 323ff.
- Red-black *see* Odd-even ordering
- Reduction of variance in Monte Carlo integration 308, 316ff.
- References (explanation) 4
- References (general bibliography) 926ff.
- Reflection formula for gamma function 213
- register storage class 25
- Regula falsi (false position) 354ff.
- Regularity condition 784
- Regularization
 - compared with optimal filtering 810
 - constrained linear inversion method 808ff.
 - of inverse problems 805ff.
 - linear 808ff.
 - nonlinear 822f.
 - objective criterion 811
 - Phillips-Twomey method 808ff.
 - Tikhonov-Miller 808ff.
 - trade-off curve 808
 - two-dimensional 812
 - zeroth order 805ff.
 - see also* Inverse problems
- Regularizing operator 807
- Rejection method for random number generator 290ff.
- Relaxation method
 - for algebraically difficult sets 772
 - automated allocation of mesh points 783f., 786
 - computation of spheroidal harmonics 772ff.
 - for differential equations 754f., 762ff.
 - elliptic partial differential equations 832f., 863ff.
 - example 772ff.
 - Gauss-Seidel method 864, 873ff., 884
 - internal boundary conditions 784ff.
 - internal singular points 784ff.

- Jacobi's method 864f., 873
 successive over-relaxation (SOR) 866ff., 871, 875
see also Multigrid method
- Remes algorithms
 exchange algorithm 560
 for minimax rational function 205
- Residual 57, 62, 85
 in multigrid method 872
- Resolution function, in Backus-Gilbert method 816
- Response function 538
- Restriction operator 873
- Reward, \$1000 offered 281
- Richardson's deferred approach to the limit 140, 143, 188, 708, 724ff., 733f., 796, 878
see also Bulirsch-Stoer method
- Richtmyer artificial viscosity 846
- Ridders' method, for numerical derivatives 188
- Ridders' method, root finding 348, 356, 358
- Riemann shock problem 846
- Right eigenvalues and eigenvectors 458
- Rise/fall time 554f.
- Robust estimation 659, 699ff., 705
 Andrew's sine 702
 average deviation 611
 double exponential errors 701
 Kalman filtering 705
 Lorentzian errors 701f.
 mean absolute deviation 611
 nonparametric correlation 639ff.
 Tukey's biweight 702
 use of a priori covariances 705
see also Statistical tests
- Romberg integration 130, 140f., 143, 188, 723, 797
- Root finding 149f., 347ff.
 advanced implementations of Newton's rule 393
 Bairstow's method 371, 377
 bisection 350, 353, 359ff., 366, 397, 476, 703
 bracketing of roots 348, 350ff., 360, 369, 371, 376
 Brent's method 348, 356, 666
 Broyden's method 380, 389ff., 393
 compared with multidimensional minimization 382
 complex analytic functions 371
 in complex plane 210
 convergence criteria 353, 381
 deflation of polynomials 369ff., 377
 without derivatives 361
 double root 348
 eigenvalue methods 375
 false position 354ff.
 Jenkins-Traub method 376
 Laguerre's method 348, 371ff.
 Lehmer-Schur algorithm 376
 Maehly's procedure 370, 378
 matrix method 375
 Muller's method 371, 379
 multiple roots 348
- Newton's rule 149f., 185, 348, 362ff., 369, 371, 377, 379ff., 383f., 476, 749, 757f., 762, 796, 882, 884, 919, 921
 pathological cases 350f., 362ff., 369, 380
 polynomials 348, 369ff., 456
 in relaxation method 762
 Ridders' method 348, 356, 358
 root-polishing 365, 370f., 376ff., 378
 safe Newton's rule 366
 secant method 354ff., 365, 371, 406
 in shooting method 754, 757f.
 singular Jacobian in Newton's rule 393
 stopping criterion for polynomials 373
 use of minimum finding 348
 using derivatives 362ff.
 zero suppression 379
see also Roots
- Root polishing 365, 370, 376ff.
- Roots
 Chebyshev polynomials 190
 cubic equations 184f.
 multiple 348, 371ff.
 nonlinear equations 347ff.
 polynomials 348, 369ff., 456
 quadratic equations 183f.
 reflection in unit circle 567
 square, multiple precision 921
see also Root finding
- Rosenbrock method 737ff.
 compared with semi-implicit extrapolation 747
 stepsize control 738
- Roundoff error 29, 889f.
 bracketing a minimum 406
 conjugate gradient method 833
 eigensystems 465, 474, 476, 478, 483, 485, 489
 extended trapezoidal rule 138
 general linear least squares 674, 677
 graceful 891
 hardware aspects 890
 Householder reduction 472
 IEEE standard 891
 interpolation 107
 least squares fitting 664, 674
 Levenberg-Marquardt method 685
 linear algebraic equations 32f., 36, 38, 55, 64, 91
 linear predictive coding (LPC) 571
 magnification of 29, 55
 maximum entropy method (MEM) 574
 measuring 890
 multidimensional minimization 426, 430
 multiple roots 369f.
 numerical derivatives 186
 recurrence relations 179
 reduction to Hessenberg form 485
 series 170f.
 straight line fitting 664
 variance 613
- Row degeneracy 32
- Row-indexed sparse storage 78f.
 transpose 80f.
- Row operations on matrix 37, 40
- Row totals 630

- RSS algorithm 323ff.
RST properties (reflexive, symmetric, transitive) 345
Runge-Kutta method 708f., 710ff., 738, 747
 Cash-Karp parameters 716f.
 embedded 715f., 738
 high-order 711
 quality control 728
 stepsize control 714ff.
Run-length encoding 909
Rybicki, G.B. 91f., 120, 151, 259, 528, 581, 606
- S**ampling
 importance 316f.
 Latin square or hypercube 315
 recursive stratified 323ff.
 stratified 317f.
 uneven or irregular 576, 654
Sampling theorem 501, 550
 for numerical approximation 606ff.
Sande-Tukey FFT algorithm 509
Savitzky-Golay filters
 for data smoothing 650ff.
 for numerical derivatives 189, 651
Scallop loss 554
Schrage's algorithm 278
Schrödinger equation 851ff.
Schultz's method for matrix inverse 57, 606
SDLC checksum 898
Searching
 with correlated values 117f.
 an ordered table 117f.
 selection 341ff.
Secant method 348, 354ff., 365, 371, 406
 Broyden's method 389ff.
 multidimensional (Broyden's) 380, 389ff.
Second Euler-Maclaurin summation formula 142
Second order differential equations 732f.
Seed of random number generator 275
Selection 329, 341ff.
 find m largest elements 344
 heap algorithm 344
 for median 703
 operation count 341f.
 by partition-exchange 341
 without rearrangement 342
 timings 344
 use to find median 614f.
Semi-implicit Euler method 737, 743
Semi-implicit extrapolation method 737, 743
 compared with Rosenbrock method 747
 stepsize control 744
Semi-implicit midpoint rule 743
Semi-invariants of a distribution 614
Sentinel, in Quicksort 333, 341
Separable kernel 794
Separation of variables 252
Serial data port 899
Series 165ff.
 accelerating convergence of 166ff.
 alternating 166f.
 asymptotic 167
 Bessel function K_ν 247
 Bessel function Y_ν 242
 Bessel functions 166, 230
 cosine integral 257
 divergent 167
 economization 198ff., 201
 Euler's transformation 166ff.
 exponential integral 222, 224
 Fresnel integral 255
 hypergeometric 208, 271
 incomplete beta function 227
 incomplete gamma function 217
 Laurent 573
 relation to continued fractions 169f.
 roundoff error in 170f.
 sine and cosine integrals 257
 sine function 166
 Taylor 362, 414, 708, 715, 763, 767
 transformation of 166ff.
 van Wijngaarden's algorithm 167
Shaft encoder 894f.
Shakespeare 8
Shampine's Rosenbrock parameters 738
Shell algorithm (Shell's sort) 330ff.
Sherman-Morrison formula 73ff., 90, 389
Shifting of eigenvalues 456, 477f., 486f.
Shock wave 840, 846
Shooting method
 computation of spheroidal harmonics 781
 for differential equations 754, 757ff., 779f., 781
 for difficult cases 760
 example 779f., 781
 interior fitting point 760
Shuffling to improve random number generator 280f.
Sidelobe fall-off 554
Sidelobe level 554
Signal, bandwidth limited 501
Significance (numerical) 28
Significance (statistical) 615f.
 one- vs. two-sided 638
 peak in Lomb periodogram 577
 of 2-d K-S test 646f.
 two-tailed 619
Similarity transform 459ff., 463, 483, 485, 488
Simplex
 defined 408f.
 method in linear programming 396, 408f., 430, 433ff., 439ff.
 method of Nelder and Mead 396, 408ff., 451f., 702f.
 use in simulated annealing 451f.
Simpson's rule 130ff., 134, 139, 143, 590, 791f., 796, 797
Simpson's three-eighths rule 132, 797, 799
Simulated annealing *see* Annealing, method of simulated
Simulation *see* Monte Carlo
Sine function
 evaluated from $\tan(\theta/2)$ 179
 recurrence 178
 series 166
Sine integral 255, 257ff.
 continued fraction 257

- series 257
- see also* Cosine integral
- Sine transform *see* Fast Fourier transform (FFT); Fourier transform
- Singleton's algorithm for FFT 532
- Singular value decomposition (SVD) 33, 34f., 59ff.
 - approximation of matrices 66f.
 - backsubstitution 64
 - and bases for nullspace and range 61
 - confidence levels from 698
 - covariance matrix 698
 - fewer equations than unknowns 65
 - for inverse problems 806
 - and least squares 62, 65f., 205, 674, 676ff.
 - in minimization 416
 - more equations than unknowns 65f.
 - and rational Chebyshev approximation 205
 - of square matrix 61ff.
 - use for ill-conditioned matrices 63f., 66, 456
 - use for orthonormal basis 66, 100
- Singularities
 - of hypergeometric function 209, 271
 - in integral equations 797ff.
 - in integral equations, worked example 801
 - in integrands 141ff., 797f.
 - removal in numerical integration 144ff., 797f.
- Singularity, subtraction of the 798
- SIPSOL 833
- Skewness of distribution 612, 614
- Smoothing, importance in multigrid method 874
- Smoothing of data 120, 650ff.
 - in integral equations 790
- sn function 269
- Snyder, N.L. xii
- Sobol's quasi-random sequence 311
- Sonata 8
- Sonnet 8
- Sorting 329ff.
 - bubble sort cautioned against 330
 - compared to selection 341
 - covariance matrix 675, 687
 - eigenvectors 468f.
 - Heapsort 329, 336f., 344
 - index table 329, 338
 - operation count 329ff.
 - Quicksort 329, 332ff., 338, 341
 - rank table 329, 340f.
 - ranking 338
 - Shell's method 330ff.
 - straight insertion 330f., 468
- SPARC or SPARCstation xvii, 3
- Sparse linear equations 33, 71ff., 739
 - band diagonal 51ff.
 - biconjugate gradient method 84f., 606
 - indexed storage 78f.
 - in inverse problems 813
 - minimum residual method 85
 - named patterns 71, 831
 - partial differential equations 831ff.
 - relaxation method for boundary value problems 762
 - row-indexed storage 78f.
 - wavelet transform 591, 606
 - see also* Matrix
- Spearman rank-order coefficient 640f., 699f.
- Special functions *see* Function
- Spectral analysis *see* Fourier transform; Periodogram
- Spectral density 548
 - and data windowing 553ff.
 - figures of merit for data windows 554f.
 - normalization conventions 550
 - one-sided PSD 498
 - periodogram 550ff., 574
 - power spectral density (PSD) 498f.
 - power spectral density per unit time 499
 - power spectrum estimation by FFT 549ff.
 - power spectrum estimation by MEM 572ff.
 - two-sided PSD 499
 - variance reduction in spectral estimation 552
- Spectral lines, how to smooth 650
- Spectral methods for partial differential equations 833f.
- Spectral radius 865ff., 871
- Spectral test for random number generator 284
- Spectrum *see* Fourier transform
- Spherical Bessel functions 240
 - routine for 251
- Spherical harmonics 252f.
 - orthogonality 252
 - routine for 254
 - stable recurrence for 253
 - table of 253
 - see also* Associated Legendre polynomials
- Spheroidal harmonics 772ff., 779f., 781
 - boundary conditions 774
 - normalization 774
 - routine for 777ff., 780f., 781f.
- Spline 106
 - cubic 113ff.
 - gives tridiagonal system 115
 - natural 115
 - operation count 115
 - two-dimensional (bicubic) 127f.
- Spread matrix 817
- Spread spectrum 300
- Square root, complex 177f.
- Square root, multiple precision 921
- Square window 553
- Squaring, macro in C 27
- Stability 30f.
 - of Clenshaw's recurrence 182f.
 - Courant condition 838, 841ff., 845, 855
 - diffusion equation 849
 - of Gauss-Jordan elimination 36, 38
 - of implicit differencing 735f., 849
 - mesh-drift in PDEs 843f.
 - nonlinear 840, 846
 - partial differential equations 829, 836f.
 - of polynomial deflation 370
 - in quadrature solution of Volterra equation 796

- of recurrence relations 179ff., 182f., 231, 239, 253
- and stiff differential equations 735f.
- von Neumann analysis for PDEs 836f., 839, 842, 849
- see also* Accuracy
- Stabilized Kolmogorov-Smirnov test 626f.
- Stabilizing functional 807
- Staggered leapfrog method 842f.
- Standard deviation
 - of a distribution 611
 - of Fisher's z 637
 - of linear correlation coefficient 636
 - of sum squared difference of ranks 641
- Standard (probable) errors 616, 662, 667, 673, 677, 689
- Statement labels 8
- Statistical error 659
- Statistical tests 609ff.
 - Anderson-Darling 626f.
 - average deviation 611
 - bootstrap method 691f.
 - chi-square 620f., 630ff.
 - contingency coefficient C 631
 - contingency tables 628ff., 644
 - correlation 609f.
 - Cramer's V 631
 - difference of distributions 620ff.
 - difference of means 615ff.
 - difference of variances 617, 619
 - entropy measures of association 632ff.
 - F-test 617, 619
 - Fisher's z -transformation 637f.
 - general paradigm 609
 - Kendall's τ 640, 642ff.
 - Kolmogorov-Smirnov 620, 623ff., 645ff., 699
 - Kuiper's statistic 627
 - kurtosis 612, 614
 - L-estimates 699
 - linear correlation coefficient 636ff.
 - M-estimates 699ff.
 - mean 609ff., 614, 615ff.
 - measures of association 610, 628ff.
 - measures of central tendency 610ff.
 - median 611, 699
 - mode 611
 - moments 610ff., 614
 - nonparametric correlation 639ff.
 - Pearson's r 636ff.
 - for periodic signal 577f.
 - phi statistic 631
 - R-estimates 699f.
 - rank correlation 639ff.
 - robust 611, 640, 699ff.
 - semi-invariants 614
 - for shift vs. for spread 626f.
 - significance 615f.
 - significance, one- vs. two-sided 619, 638
 - skewness 612, 614
 - Spearman rank-order coefficient 640f., 699f.
 - standard deviation 611
 - strength vs. significance 615, 628
 - Student's t 616, 637
 - Student's t , for correlation 637
 - Student's t , paired samples 618
 - Student's t , Spearman rank-order coefficient 640
 - Student's t , unequal variances 617
 - sum squared difference of ranks 640f.
 - Tukey's trimean 699
 - two-dimensional 645ff.
 - variance 609ff., 613, 618
 - Wilcoxon 699
 - see also* Error; Robust estimation
- `--STDC--` macro 17, 930
- Steak, without sizzle 818
- Steed's method
 - Bessel functions 240ff., 246
 - continued fractions 170f.
- Steepest descent method 421
 - in inverse problems 813
- Step
 - doubling 136, 715
 - tripling 143
- Stieltjes, procedure of 157
- Stiff equations 709, 734ff.
 - Kaps-Rentrop method 737
 - methods compared 747
 - predictor-corrector method 737
 - r.h.s. independent of x 736
 - Rosenbrock method 737ff.
 - scaling of variables 737
 - semi-implicit extrapolation method 737
 - semi-implicit midpoint rule 743
- Stiff functions 106, 406
- Stirling's approximation 213, 821
- Stoermer's rule 732f.
- Stopping criterion, in multigrid method 884
- Stopping criterion, in polynomial root finding 373
- Storage
 - band diagonal matrix 52
 - scheme for matrix in C 20f., 33f., 940f.
 - sparse matrices 78f.
- Straight injection 876
- Straight insertion 330f., 468
- Straight line fitting 661ff., 673f.
 - errors in both coordinates 666ff.
 - robust estimation 703
- Strassen's fast matrix algorithms 102ff.
- Stratified sampling, Monte Carlo 317f., 323
- Strongly implicit procedure (SIPSOL) 833
- Structured programming 5ff.
- Student's probability distribution 226, 228
- Student's t -test
 - for correlation 637
 - for difference of ranks 641
 - for difference of means 616
 - for difference of means (paired samples) 618
 - for difference of means (unequal variances) 617
 - Spearman rank-order coefficient 640
- Sturmian sequence 475f.
- `submatrix()` utility 945
- Submatrix
 - caution on freeing 23
 - of existing matrix 22, 945

- Sub-random sequences *see* Quasi-random sequence
- Subtraction, multiple precision 916
- Subtractive method for random number generator 282
- Successive over-relaxation (SOR) 866ff., 871
 bad in multigrid method 875
 Chebyshev acceleration 868f.
 choice of overrelaxation parameter 866f.
- Sum squared difference of ranks 640
- Sums *see* Series
- Sun xvii, 894
 SPARCstation xvii, 3
- Supernova 1987A 645
- SVD *see* Singular value decomposition (SVD)
- switch structure 14
- Symbol, of operator 875f.
- Synthetic division 91, 174, 369, 377
- Systematic errors 659
- T**ableau (interpolation) 109, 189
- Tangent function, continued fraction 169
- Taylor series 186, 362, 414, 708, 715, 750, 763, 767
- Test programs 3
- \TeX xiii
- Thermodynamics, analogy for simulated annealing 444f.
- Threshold multiply of sparse matrices 81ff.
- Tides 568
- Tikhonov-Miller regularization 808ff.
- Time domain 496
- Time splitting 856f., 870
- Toeplitz matrix 90, 92ff., 201
 LU decomposition 94
 new, fast algorithms 95f.
 nonsymmetric 93ff.
- Tongue twisters 341
- Torus 305ff., 313ff.
- Trade-off curve 804, 818
- Trademarks xvii
- Transformation
 Gauss 262
 Landen 262
 method for random number generator 287ff.
- Transforms, number theoretic 509f.
- Transport error 840
- Transpose of sparse matrix 80f.
- Trapezoidal rule 131, 133, 136ff., 140, 586, 590, 791f., 795
- Traveling salesman problem 445ff.
- Tridiagonal matrix 50f., 66, 156, 460f., 494
 in alternating-direction implicit method (ADI) 870f.
 from cubic spline 115
 cyclic 74f.
 in cyclic reduction 862
 eigenvalues 475ff.
 with fringes 831
 from operator splitting 870f.
 reduction of symmetric matrix to 469ff., 476
see also Matrix
- Trigonometric
 functions, linear sequences 178f.
 functions, recurrence relation 178, 579
 functions, $\tan(\theta/2)$ as minimal 179
 interpolation 105
 solution of cubic equation 184f.
- Truncation error 30, 406, 715, 889f.
 in multigrid method 883
 in numerical derivatives 186
- Tukey's biweight 702
- Tukey's trimean 699
- Turbo Pascal (Borland) 7
- Twin errors 902
- Two-dimensional *see* Multidimensional
- Two-dimensional K-S test 645ff.
- Two-pass algorithm for variance 613
- Two-point boundary value problems 708, 753ff.
 automated allocation of mesh points 783f., 786
 boundary conditions 753ff., 757, 760, 779f.
 difficult cases 760
 eigenvalue problem for differential equations 756, 772ff., 779, 781
 free boundary problem 756, 785
 grid (mesh) points 754f., 762, 783f., 786
 internal boundary conditions 784ff.
 internal singular points 784ff.
 linear requires no iteration 759
 multiple shooting 762
 problems reducible to standard form 756
 regularity condition 784
 relaxation method 754f., 762ff.
 relaxation method, example of 772ff.
 shooting to a fitting point 760ff.
 shooting method 754, 757ff., 779f., 781
 shooting method, example of 779f., 781
 singular endpoints 760, 773, 780
see also Elliptic partial differential equations
- Two-sided exponential error distribution 701
- Two-sided power spectral density 499
- Two-step Lax-Wendroff method 844ff.
- U**LTRIX xvii, 3
- Uncertainty coefficient 634
- Uncertainty principle 607
- Underflow, in IEEE arithmetic 891
- Underrelaxation 866
- Uniform deviates *see* Random deviates, uniform
- Unit-offset array 18, 940f.
- Unitary (function) 852f.
- Unitary (matrix) *see* Matrix
- UNIX xii, xvii, 3, 16, 285, 303, 894
- Upper Hessenberg matrix *see* Hessenberg matrix
- Upwind differencing 841f., 846
- U.S. Postal Service barcode 902
- Utility functions
 complex.c 23f., 948ff.
 nrutil.c 2, 19, 21f., 940, 942ff.

- V**-cycle 874
 Validation of Numerical Recipes procedures 2f.
 Valley, long or narrow 410, 413, 416
 Van Cittert's method 813
 Van Wijngaarden-Dekker-Brent method *see* Brent's method
 Vandermonde matrix 90ff., 120
 Variable length code 903
 Variable metric method 397, 425ff.
 compared to conjugate gradient method 425f.
 Variable step-size integration 129, 141, 709, 713, 725ff., 733f., 738, 744, 749f.
 Variance(s)
 of distribution 609ff., 614, 617, 619
 pooled 616
 reduction of (in Monte Carlo) 308, 316ff.
 statistical differences between two 615
 two-pass algorithm for computing 613
 see also Covariance
 Variational methods, partial differential equations 833
 VAX xvii, 285, 303
 Vector *see* Array
 Vectors, representation in C 18
 vector() utility 943
 VEGAS algorithm for Monte Carlo 319ff.
 Verhoeff's algorithm for checksums 902
 Viète's formulas for cubic roots 184f.
 Virus, computer 897
 Viscosity
 artificial 840, 846
 numerical 839, 840, 846
 VMS xvii
 void (parameter type list) 17
 Volterra equations 789f.
 adaptive stepsize control 797
 analogy with ODEs 794f.
 block-by-block method 797
 first kind 790, 795
 nonlinear 790, 796
 second kind 790, 794f.
 unstable quadrature 796
 von Neumann-Richtmyer artificial viscosity 846
 von Neumann stability analysis for PDEs 836f., 839, 842, 849
 Vowellish (coding example) 904f., 910
- W**-cycle 874
 Warranty, disclaimer of xvi
 Wave equation 252, 827, 834f.
 Wavelet transform 591ff.
 appearance of wavelets 598f.
 approximation condition of order p 592f.
 coefficient values 594, 596
 contrasted with Fourier transform 591f., 601
 Daubechies wavelet filter coefficients 592ff., 596, 598, 601, 605
 detail information 593
 discrete wavelet transform (DWT) 594f.
 DWT (discrete wavelet transform) 594f.
 eliminating wrap-around 594f.
 fast solution of linear equations 603ff.
 filters 599f.
 and Fourier domain 599f.
 image processing 603
 for integral equations 791
 inverse 594
 Lemarie's wavelet 600
 of linear operator 603ff.
 mother-function coefficient 594
 mother functions 591
 multidimensional 602
 nonsmoothness of wavelets 598f.
 pyramidal algorithm 594
 quadrature mirror filter 592
 smooth information 593
 truncation 601f.
 wavelet filter coefficient 592, 594
 wavelets 591, 598ff.
 Wavelets *see* Wavelet transform
 Weber function 210
 Weighted Kolmogorov-Smirnov test 626f.
 Weighted least-squares fitting *see* Least squares fitting
 Weighting, full vs. half in multigrid 876
 Weights for Gaussian quadrature 147ff., 797
 nonclassical weight function 157ff., 797
 Welch window 554
 while iteration 12
 Wiener filtering 542, 547ff., 565f., 650
 compared to regularization 810
 Wiener-Khinchin theorem 498, 566, 574
 Wilcoxon test 699
 Window function
 Bartlett 554
 flat-topped 555
 Hamming 554
 Hann 554
 Parzen 554
 square 553
 Welch 554
 Winograd Fourier transform algorithms 509
 Woodbury formula 75ff., 90
 Wordlength 28
 Wraparound
 order for storing spectrum 507
 problem in convolution 540
 Wronskian, of Bessel functions 240, 246
- X**.25 protocol 898
 XMODEM checksum 897
 X-ray diffraction pattern, processing of 814
- Y**ale Sparse Matrix Package 72, 78
- Z**-transform 561, 567, 572
 Z-transformation, Fisher's 637f.
 Zealots 823
 Zebra relaxation 875
 Zero contours 379f.
 Zero-offset array 18
 Zeroth-order regularization 805ff.
 Zip code, barcode for 902
 Ziv-Lempel compression 903