

Index

- θ -schemes, 151, 172, 228
- nD wave equation, *see* wave equation, nD
- A-stability, 20
- abstract sound synthesis, 1–8
 - difficulties with, 8
 - physical modeling sound synthesis and, 16, 18–19, 45
- accuracy, ix–x
 - finite difference schemes and, 155, 321
 - modal methods and, 155, 321
 - of difference operators, 29–30, 104
 - of numerical boundary conditions, 138, 312
 - of schemes for the 1D wave equation, 131, 136–137
 - of schemes for the SHO, 52–53, 60–61
 - of schemes for Webster's equation, 257–258
 - perceptual effects of, 155
 - spectral methods and, 388
- acoustic tube, 249–250
 - 1D wave equation and, 117, 118
 - admittance of, 262
 - boundary conditions and, 124, 126, 253–254
 - coupling to reed model, 267
 - formants and, 259
 - glottal excitation and, 258–259
 - scattering methods and, 261–263
 - time-varying, 264
 - transmission line analogy and, 258
 - wall vibration and, 259–260
- adaptor, 59
- additive synthesis, 3–4
 - modal synthesis and, 2, 18–19
- Adrien, J.-M., 2
- aliasing, 21
 - grid interpolation and, 104
 - nonlinear systems and, 231
- all-pass interpolation, 5, 102
- AM synthesis, 6
- Ames, W., 383
- amplification factor, 32, 105
- amplification polynomial, 33, 106, 295
- analysis–synthesis methods, 2, 4, 178
- anisotropy
 - numerical, 290, 295, 307, 313
 - of thin plates, 292, 349–352
- ansatz, 32, 96, 105, 290, 294
- arched bars, 211–213
- artificial reverberation
 - computational complexity and, 169, 381
 - digital waveguides and, 13
 - finite difference schemes and, 311
 - plates and, 345
 - psychoacoustic model reduction techniques and, 22
 - room acoustics and, 305
 - springs and, 199
- aspect ratio, 289
- auto-oscillations
 - bow and, 86, 180
 - reed-bore system and, 269
- averaging operators, 27, 99, 100, 302
 - as used in finite difference schemes, 55–56

- bandwidth
 - finite difference schemes for
 - spatially-varying systems and, 207–208, 212
 - schemes in radial coordinates and, 320–321, 353, 354
 - stability conditions and, 134–136, 170, 186, 225
- Bank, B., 239
- bar
 - ideal, *see* ideal bar
 - nonlinear vibration of, 232
 - of variable cross-section, 210–213
 - thick, *see* Timoshenko beam theory
- bassoon, 278
- beating, 185
- Berger's equation, 361–362
- Bernoulli's law, 266
- bi-Laplacian, 289, 293
- biharmonic operator, 289, 293
- bilinear interpolation, 293
- bilinear transformation, 38
- BlockCompiler, 15
- boundary conditions
 - for Webster's equation, 253–254
 - digital waveguides and, 147–148
 - energy analysis and, 97
 - energy-storing, 126, 254, 322
 - for 1D wave equation, 124–126
 - for 2D wave equation, 307–308, 318
 - for helical springs, 201–202
 - for ideal bar, 165–166
 - for Kirchhoff–Carrier equation, 222–223
 - for stiff string, 175
 - for thin plate model, 334–335, 352–353
 - for von Kármán system, 365
 - integration by parts and, 98, 290–291
 - lossy, 125–126
 - modal density and, 167, 381
 - modes and, 128, 166
 - numerical, *see* numerical boundary conditions
 - radiation, *see* radiation boundary condition
 - traveling waves and, 126
- boundary element methods, 390
- bow, 82–84
 - finite width of, 183
 - interaction with mass–spring system, 84–86
 - interaction with plate, 344
 - interaction with string, 180–183
- bow force, 84, 180
- bow velocity, 84, 180
- BRASS, 278
- brass instruments, 11, 82, 252, 258, 278
 - digital waveguides and, 13
- brightness, 184, 342, 374
- Cadoz, C., 2, 9
- Cage, J., 187
- Cartesian coordinates, 288
- Cauchy–Schwartz inequality, 97, 109, 290, 295
- cent, 57, 69
- CFL condition, *see* Courant–Friedrichs–Lewy condition
- Chaigne, A., 2, 17
- Chebyshev norm, 128
- Chebyshev polynomials, 8, 389
- Chowning, J., 2, 6
- circulant delay networks, 14
- clarinet, 252, 269
- collisions, 78–79
 - brightness and, 78, 342
 - hammer–string interaction and, 183
 - mallet–plate interaction and, 342–343
 - reed model and, 266, 269–270
- collocation methods, 20, 389
- commuted synthesis, 13, 18, 346, 349
- compact schemes, 61, 150–152, 314
- computational complexity, 20–22, 379–382
 - acoustic tubes and, 254
 - implicit schemes and, 151, 173
 - modal density and, 130–131, 167, 254, 314, 337, 381–382
 - modal methods and, 321–322
 - numerical stability and, 133–134, 169
 - of scattering methods vs. finite difference schemes, 263, 316, 321
 - schemes for the 1D wave equation and, 145–146
 - schemes for the 2D wave equation and, 314, 321–322
 - schemes for the ideal bar equation and, 169
 - wave speeds and, 236, 252
- conical tubes, 252–253

- coordinate changes, 112–113
 - spatially-varying systems and, 208, 212, 208–213
- CORDIS, 9, 382
- Courant number, 131, 310
- Courant–Friedrichs–Lewy condition, 117, 133, 139
 - as bound on computational complexity, 133–134
 - geometrical interpretation of, 133, 208, 225
- crash, 368, 374–376
- critical band, 22
- cutoff
 - frequency, numerical, *see* numerical cutoff frequency
 - wavenumber, 154
- cylindrical tubes, 129, 252–253

- d’Alembert, 123
- damper
 - connection between bars, 197
 - connection with string, 188–190
- decay time
 - 1D wave equation with loss and, 154
 - SHO with loss and, 65–66
 - stiff membrane and, 341
 - stiff string and, 178
- degeneracy, 309
- degrees of freedom
 - computational complexity and, 130–131, 169–170, 322, 379–382
 - finite difference schemes and, 133, 169–170, 380–381
 - for 1D wave equation, 130–131
 - for 2D wave equation, 309
 - for ideal bar equation, 167
 - for stiff string, 176
 - for thin plate equation, 336
 - memory requirements and, 155
 - modal density and, 130–131, 167, 309, 336, 381
- detuning
 - acoustic tubes and, 258
 - due to stiffness, 176
 - numerical boundary conditions and, 143
 - numerical dispersion and, 142, 257, 321
 - of sets of strings, 186
 - string preparation and, 193
- difference operators
 - accuracy of, 29–30, 104
 - anisotropy of, 295
 - combining of, 29, 100
 - digital filter interpretation of, 35–37
 - energy analysis and, 39–40, 110–111, 296, 301
 - frequency domain analysis and, 31–33, 105–106, 294–295
 - in transformed coordinates, 112
 - matrix forms of, 107–108, 296–299
 - mixed spatial–temporal, 101
 - parameterized, 100, 293
 - spatial
 - in 1D, 100–101
 - in 2D, Cartesian, 291–293
 - in 2D, radial, 299–301
 - in 3D, 324–325
 - stencils of, 100, 292, 299
 - temporal, 27–28, 99–100
 - temporal width of, 28–29
- differential operators
 - frequency domain analysis and, 96, 289–290
 - in 1D, 93–94
 - in 2D, 289–291
 - in transformed coordinates, 112
- digital filters, 35–38
- digital waveguides, 11–13
 - 1D wave equation and, 117, 146–148
 - boundary termination of, 147–148
 - cylindrical and conical tubes and, 252
 - efficiency of, 21, 156, 384–385
 - finite difference schemes and, 19–20, 146, 261
 - in multiple dimensions, *see* waveguide mesh
 - Karplus–Strong algorithm and, 12
 - Kelly–Lochbaum speech synthesis model and, 14, 258
 - multiple channel output and, 144
 - numerical stability and, 157
 - scattering methods and, 261
 - toneholes and, 272
 - transmission lines and, 118
 - traveling wave decompositions and, 123
 - wavetable synthesis and, 6, 18
 - wind instruments and, 265

- direct numerical simulation, 16–18
 - digital waveguide synthesis and, 19–20
 - lumped mass–spring networks and, 19
 - scattering methods and, 20
- Dirichlet condition
 - in 1D, 124
 - in 2D, 297, 308
 - losslessness of, 125, 207, 222
 - modes and, 129, 317
 - numerical, 108, 138, 312, 319
 - wave reflection and, 126
 - Webster’s equation and, 253
- dispersion
 - acoustic tubes and, 251–252, 254
 - helical springs and, 200–201
 - ideal bar and, 164, 165
 - inharmonicities and, 163, 165, 168
 - numerical, *see* numerical dispersion
 - thin plates and, 332
- dispersion relation, 96
 - for 1D wave equation, 122
 - for 2D wave equation, 307
 - for an anisotropic plate equation, 351
 - for helical spring, 200–201
 - for ideal bar, 164
 - for stiff string, 175
 - for thin plates, 332
 - for Webster’s equation, 251
 - numerical, 134–135
- dissipation, *see* loss
- domains
 - in 1D, 93–94, 98
 - in 2D, 288–289, 291, 299
- double reed instruments, 278
- drift, 127
- drums, 310, 318, 342
- Duffing’s equation, 75
- energy analysis, x–xi, 38–42
 - boundary conditions and, 93, 97, 125–126, 137–141, 165–166, 171–172, 202, 222, 226, 253–256, 307–308, 312, 318, 334–335, 338–339, 365
 - modular connections and, 189, 192
 - nonlinear systems and, xi, 38, 73
 - numerical stability conditions and, xi, 38, 39, 42, 54, 77, 83, 86, 93, 139, 171, 198, 207, 209, 212, 226, 231, 238, 256, 311–312, 339
 - of a bar of variable cross-section, 211
 - of a string of variable density, 207
 - and schemes for, 207, 209
 - of bow mechanism, 83
 - and schemes for, 83
 - of collisions, 79
 - of coupled ideal bars, 196–197
 - and schemes for, 198
 - of helical springs, 201–202
 - of nonlinear oscillator, 74–75
 - and schemes for, 77
 - of nonlinear string vibration, 234–236
 - and schemes for, 237–238
 - of plate-string connection, 347–348
 - of prepared strings, 188–189
 - and schemes for, 189, 191–192
 - of the 1D wave equation, 123–126
 - and schemes for, 137–141, 152
 - of the 1D wave equation with loss, 154
 - and schemes for, 155
 - of the 2D wave equation, 307–308, 318
 - and schemes for, 311–312, 319
 - of the bow-mass–spring interaction, 85
 - and schemes for, 86, 181–182
 - of the bow-string interaction, 180–181
 - and schemes for, 181–182
 - of the hammer-string interaction, 184
 - of the ideal bar equation, 165–166
 - and schemes for, 170–172
 - of the Kirchhoff–Carrier equation, 222–223
 - and modal decompositions for, 230
 - and schemes for, 226
 - of the SHO, 48
 - and schemes for, 53–54, 56–57
 - of the SHO with loss, 64
 - and schemes for, 65
 - of the single reed model, 267–268
 - of the stiff string, 175–176
 - of the stiff string with loss, 179
 - of the thin plate equation, 333–335
 - and schemes for, 338–339
 - of the tonehole, 276–277
 - of the von Kármán system, 364–365
 - and schemes for, 370–371
 - of Webster’s equation, 253–254
 - and schemes for, 255–256
 - vs. frequency domain analysis, x–xi
 - wave digital filters and, 59, 60

- energy method, 48, 54
- Erkut, C., 2
- Euler-Bernoulli beam model, *see* ideal bar
- fast Fourier transform, 2
 - modal synthesis and, 153, 156
 - spectral methods and, 389
- FDTD, *see* finite difference time domain method
- feedback delay networks, 14
- FEM, *see* finite element methods
- Fender–Rhodes electric piano, 195
- Fettweis, A., 2, 15, 58
- FFT, *see* fast Fourier transform
- finite difference schemes, x, 16–17
 - bandwidth of, *see* bandwidth
 - boundary conditions for, *see* numerical boundary conditions
 - causality and, 37
 - digital waveguides and, 19, 146–147, 156, 261
 - for a bar of variable cross-section, 211–213
 - for a nonlinear oscillator, 75–78
 - for a reed model, 268–269
 - for a string of variable density, 207–209
 - for an anisotropic plate equation, 351–352
 - for Berger’s equation, 362
 - for collisions, 79
 - for helical springs, 202–204
 - for multiple strings, 186
 - for nonlinear string vibration, 236–241
 - for non-planar string vibration, 243
 - for plate excitation, 341–342
 - for shell system, 373
 - for the 1D wave equation, 131–143, 148–152
 - for the 1D wave equation with loss, 154–155
 - for the 2D wave equation, 310–315, 318–321
 - for the bow mechanism, 83–84
 - for the bow-mass–spring interaction, 85–86
 - for the bow-plate interaction, 344
 - for the bow-string interaction, 181–182
 - for the hammer-mass–spring interaction, 81
 - for the hammer-string interaction, 184–185
 - for the ideal bar equation, 168–174
 - for the Kirchhoff–Carrier equation, 224–229
 - for the plate-string interaction, 348
 - for the SHO, 49–61
 - for the SHO with a source term, 68
 - for the SHO with loss, 64–67
 - for the stiff membrane, 341
 - for the stiff string, 176–177
 - for the thin plate equation, 337–340
 - for the time-varying vocal tract, 264
 - for the von Kármán system, 367–371
 - for toneholes, 277
 - for Webster’s equation, 255–258, 260
- implicit, *see* implicit schemes
- lumped mass–spring networks and, 19, 119, 156, 316, 321, 382–383
- matrix representations of, *see* matrix representations, of finite difference schemes
- multiple channel output and, 144
- numerical dispersion in, *see* numerical dispersion
- parameterized, 56–57, 148–152, 172–174, 176–177, 202, 228–229, 312–314, 320–321, 339–340, 353, 373
- scattering methods and, 146–147, 253, 257, 258, 261, 263, 316
- spatial variation and, 207, 209, 211–213, 255
- stability of, *see* numerical stability
- wave digital filters and, 59, 269
- waveguide mesh and, 321
- finite difference time domain method, 16, 49, 258
- finite element methods, 17–18, 20, 35, 46, 48, 49, 62, 258, 288, 299, 333, 346, 386–388
- finite precision, 54, 137
- finite volume methods, 390
- flexural rigidity, 331
- Florens, J.-L., 9
- flutes, 278
- FM synthesis, 6–7, 45
 - waveshaping and, 8
- FOF, 8
- formants, 254, 259
 - transitions of, 264–265
 - wall vibration and, 260

- Fourier series
 - modal synthesis and, 96, 129, 309
 - representations of nonlinear strings, 229
 - spectral methods and, 388, 389
- Fourier transform
 - discrete spatial, 105
 - spatial, 96
- fractional delay, 5, 145, 263
- frequency domain analysis
 - limitations of, x , 38, 73
 - modal analysis and, 128–129, 166–167, 176, 254, 309, 336
 - of an anisotropic plate equation, 351
 - of difference operators, 31–33, 105–106, 294–295
 - of differential operators, 96–97, 289–290
 - of finite difference schemes, *see* von Neumann analysis
 - of the 1D wave equation, 122
 - of the 1D wave equation with loss, 153–154
 - of the 2D wave equation, 306–307
 - of the ideal bar equation, 164–165
 - of the SHO, 47
 - and schemes for, 51–52, 55–56, 60
 - of the SHO with loss, 63–64
 - and schemes for, 64–67
 - of the stiff string, 175
 - of the stiff string with
 - frequency-dependent loss, 178
 - of the thin plate equation, 332
 - of toneholes, 273–275
 - of Webster's equation, 251–252
 - vs. energy analysis, x –xi, 38
- frequency warping, 9
 - in difference schemes for the SHO, 52, 57
 - in schemes for coupled systems of oscillators, 62
 - wave digital filters and, 59
- frequency-dependent loss
 - in stiff membranes, 341
 - in strings, 177–180, 241
 - mixed spatial–temporal derivatives and, 101
- FTM, *see* functional transformation method
- functional transformation method, 10
 - scattering methods and, 15
- Giordano, N., 17, 351
- glottal excitation, 258–259
- granular synthesis, 8
- grid function, 98, 291, 299
- grid spacing, 98, 291–292, 299
- group velocity, *see* phase and group velocity
- half plane, 289, 291
- Hall, D., 81
- hammer (mallet), 78–80
 - finite difference schemes for, 81
 - interaction with mass–spring system, 80–81
 - interaction with multiple strings, 186–187
 - interaction with plate, 342–343
 - interaction with string, 183–185
- helical spring, 199–206
- Helmholtz motion, 180
- Helmholtz, H., 180
- Hélie, T., 10
- ideal bar
 - boundary conditions and, 165–166
 - connected to another, 194–199
 - dispersion and, 164–165
 - energy analysis and, 165–166
 - equation of motion for, 163–164
 - finite difference schemes and, 168–174
 - longitudinal motion of, 118, 119
 - modes and, 166–167
 - of varying cross-sectional area, 210–213
 - phase and group velocity for, 164–165
- implicit schemes
 - averaging operators and, 27
 - boundary conditions and, 152
 - causality and, 37
 - computational complexity and, 151–152
 - for a nonlinear oscillator, 77
 - for shell vibration, 373
 - for the 1D wave equation, 150–152
 - for the 2D wave equation, 314, 320
 - for the bow mechanism, 84
 - for the ideal bar equation, 172–174
 - for the stiff string, 176–177
 - for the thin plate equation, 339–340, 353
 - for the von Kármán system, 367
 - matrix methods and, 107, 109, 141, 238–239
 - mixed derivatives and, 101

- modularity and, 192
- nonlinear systems and, 226, 240, 367
- reduction of numerical dispersion and, 174, 177, 202, 321, 340, 353
- suppression of numerical oscillations and, 185, 228–229
- uniqueness of solutions to, 77, 84, 182
- vs. explicit, 106, 151–152, 179, 202, 353
- inharmonicity
 - computational complexity and, 21
 - frequency warping and, 57
 - ideal bar and, 165, 168
 - in prepared strings, 190
 - nonlinear string vibration and, 233
 - numerical, 97, 142–143
 - psychoacoustic significance of, 22
 - stiff strings and, 175
- inharmonicity factor, 176
- initial conditions
 - corresponding to strikes and plucks, 120–121
 - digital waveguides and, 123, 147
 - for 1D wave equation, 120–121
 - for 2D wave equation, 306
 - for a nonlinear oscillator, 74
 - for difference schemes, *see* initialization
 - for ideal bar, 164
 - for SHO, 46
 - for stiff string, 175
 - for traveling waves, 123
- initialization
 - digital waveguides and, 147
 - of schemes for the 1D wave equation, 131–132
 - of schemes for the ideal bar equation, 169
 - of schemes for the SHO, 50
- inner product
 - at boundary, 291
 - in 1D, definition of, 97, 109
 - in 2D, definition of, 290, 295, 300
 - vector form of, 98
- instantaneous frequency, 4, 7
- integration by parts, 98, 290
 - in transformed coordinates, 113
- interpolation
 - accuracy of, 104
 - all-pass, 5, 102
 - bilinear, 293
 - digital waveguides and, 21
 - excitation and, 181, 185, 342
 - in 1D, 101–102
 - in 2D, 293–294
 - Karplus–Strong algorithm and, 12
 - modular connections and, 189
 - output and, 143, 345
 - perceptual aspects of, 182
 - schemes for nonlinear string vibration and, 240–241
 - vocal tract configurations and, 265
 - wavetable synthesis and, 5
- iterative methods
 - determination of modal frequencies and, 167
 - implicit schemes and, 109
 - lumped mass–spring networks and, 62
 - Newton–Raphson, 90–91
- K variables, 15, 265
- Karjalainen, M., 2
- Karplus, K., 2, 12
- Karplus–Strong algorithm, 12, 16
- Kelly, J., 2, 9, 258
- Kelly–Lochbaum speech synthesis model, 14, 261–263
 - finite difference schemes and, 257, 263
 - scattering methods and, 15, 258
 - transmission line analogy and, 250
- kettledrum, 323, 325
- Kirchhoff plate vibration model, *see* thin plate, Kirchhoff model of
- Kirchhoff–Carrier equation, 221–222
 - boundary conditions and, 222
 - energy analysis and, 222–223
 - loss and, 223
 - modal analysis of, 229–231
 - pitch glides and, 223–224
 - schemes for, 224–229
 - tension modulation and, 221
- Lagrange interpolation, 5, 102
- Laplace transform, 31–32, 96
 - frequency domain ansatz and, 32, 96
- Laplacian, 289
 - five-point approximations to, 293
 - matrix forms of, 297–299
 - in radial coordinates and approximations to, 300–301
 - integration by parts and, 290, 291

- Laplacian (*continued*)
 nine-point approximations to, 293
 summation by parts and, 296, 301
- lattice–Boltzmann method, 390
- LC circuit, 46
 wave digital filters and, 58, 59
- Leslie speaker, 199
- linear and shift-invariant systems, 94–95, 206
 anisotropy and, 349
 frequency domain analysis and, 33, 95
 modal analysis and, 167
 musical systems and, 379–380
 phase and group velocities and, 97
- linear and time-invariant systems, 94–95
 computational complexity and, 20–22
 frequency domain analysis and, 38, 95
 matrix method and, 140
 modal synthesis and, 19, 157, 384
 musical systems and, 38
- linear systems, 94
- Lochbaum, C., 2, 9, 258
- loss
 1D wave equation with, 153–155
 acoustic tubes and, 259–260
 boundary conditions and, *see* boundary conditions, lossy
 computational complexity and, 379
 damper and, 190
 decay time and, 65–66, 154, 178
 frequency-dependent, *see* frequency-dependent loss
 in nonlinear string models, 223, 242
 nonlinear oscillators and, 82
 phase and group velocity and, 97
 pitch glides and, 223, 362
 plate models and, 341
 reed models and, 267
 SHO with, 63–64
 stability conditions and, 64, 155
 stiff string and, 177–180
 toneholes and, 273, 274
- LSI, *see* linear and shift-invariant systems
- LTI, *see* linear and time-invariant systems
- Luciani, A., 9
- lumped mass–spring networks, 9–10, 382–383
 1D wave equation and, 118–119
 2D wave equation and, 316
 coupled SHOs and, 61–62
 difficulties with, 382–383
 direct numerical simulation and, 19
 finite difference schemes and, 119, 321, 382–383
 glottis modeling and, 258
 SHO and, 46
 wave digital filters and, 58
- Lyapunov stability, 42
- mallet, *see* hammer (mallet)
- marimba, 210
- masking, 22
- mass-spring networks, *see* lumped mass-spring networks
- Mathews, M., 2, 6, 258
- matrix method, 140
- matrix representations
 of difference operators, 107–109, 296–299
 of finite difference schemes, 141–142, 151, 172, 177, 180, 227, 238–239, 314
 of interpolation operators, 104
- membrane
 2D wave equation and, 305
 boundary conditions and, 308
 drum modeling and, 310, 311
 finite difference schemes and, 17
 lumped mass–spring networks and, 9, 316
 modal synthesis and, 10, 317
 stiff, 341
 vs. plate, 331, 337
 waveguide mesh and, 14
- memory requirements
 for general simulations of LTI systems, 21, 380
 modal synthesis and, 11, 22, 62, 156, 321–322, 381, 384
 of difference schemes vs. scattering structures, 316
 sampling synthesis and, 23
 schemes for the 1D wave equation and, 133, 146, 155–156
 schemes for the 2D wave equation and, 321–322
 schemes for the ideal bar equation and, 170
 schemes for the SHO and, 55
 schemes for Webster’s equation and, 263
 simulation of nonlinear systems and, 22

- sparse matrices and, 108
 - time domain methods and, 22
- Mindlin–Reissner thick plate theory, 332, 333
- modal density
 - 1D wave equation and, 130–131
 - 2D wave equation and, 309–310
 - boundary conditions and, 156, 381
 - computational complexity and, 310, 337
 - degeneracy and, 381
 - general LTI systems and, 381
 - ideal bar and, 167–168
 - problem geometry and, 381
 - thin plate equation and, 336–337
 - Webster’s equation and, 254
- modal synthesis, 10–11, 383–384
 - 1D wave equation and, 152–153
 - 2D wave equation and, 317–318
 - accuracy and, 321, 384
 - additive synthesis and, 2, 18–19
 - analysis–synthesis methods and, 178
 - loss and, 178
 - memory requirements and, 11, 22, 62, 131, 156, 167, 321–322, 384
 - multiple channel output and, 144
 - nonlinear string vibration and, 229–231, 242
 - numerical stability and, 157
 - output and, 157
 - range of applicability of, 17, 19, 384
 - spatial variation and, 207
 - spectral methods and, 18, 20, 389
 - stability and, 157
- Modalys/MOSAIC, 10, 317
- modes
 - acoustic tubes and, 254
 - finite difference schemes and, 142, 257–258, 313
 - for 1D wave equation, 128–129
 - for 2D wave equation, 309–310
 - for general LTI systems, 381–382
 - for ideal bar, 166–167
 - for stiff string, 176
 - for thin plate equation, 336
 - of coupled systems, 349
- modified equation methods, 61, 137
- modular connections, 187
 - among distributed objects, 194–199
 - energy analysis and, 189, 196, 198
 - modal synthesis and, 384
 - numerical stability and, 190–192
 - rigid, 196
 - scattering methods and, 192
- modular synthesis, 15, 187
 - CORDIS and, 9
 - finite difference schemes and, 20
 - scattering methods and, 269
 - wave digital filters and, 60
- moment of inertia, 164, 210
- Moog synthesizer, 83
- multiphonics, 271, 277
- Neumann condition
 - in 1D, 124
 - in 2D, 308
 - losslessness of, 125, 207, 222
 - modes and, 129, 317
 - numerical, 108, 138–139, 298, 312, 319
 - Webster’s equation and, 253
- non-dimensionalization, 94
 - 1D domains and, 120
 - 2D domains and, 305
 - of dependent variables, 222, 251, 267
- nonlinear bar vibration, 222
- nonlinear string vibration, *see* string, nonlinear vibration of
- nonlinear systems, 94
 - computational complexity and, 22, 381–382
 - energy analysis and, 25, 38
 - finite difference schemes and, 17
 - frequency domain analysis and, 5, 38, 95
- nonlinearity, 221, 223, 361
 - bow and, 82–83
 - center-limited, 81–82
 - cubic, 75
 - in plates, 361
 - in reed, 86–87, 266
 - in strings, 221
 - one-sided, 78
 - perceptual effects of, 76, 78
 - power law, 78
- norm
 - in 1D, definition of, 97, 109
 - in 2D, definition of, 290, 295
- numerical boundary conditions
 - accuracy and, 138
 - choice of inner product and, 109, 111, 138, 171, 312
 - detuning of modes and, 143, 174
 - for plate-string connection, 348

- numerical boundary conditions (*continued*)
 - for schemes for the 1D wave equation, 137–139
 - for schemes for the 2D wave equation, 312, 319
 - for schemes for the ideal bar equation, 171–172
 - for schemes for the thin plate equation, 338–339, 353–354
 - for schemes for the von Kármán system, 371
 - for schemes for Webster's equation, 255–256
- instability and, 125, 140–141
- matrix representations of difference operators and, 107–108, 297–299
- stencil width and, 28, 150
- summation by parts and, 110, 296
- virtual grid points and, 107–109
- numerical cutoff frequency, 57, 170, 236, 239, 240
- numerical dispersion
 - anisotropic, 313
 - computational complexity and, 156, 172–174
 - frequency warping and, 52, 57
 - implicit schemes and, 152, 172, 174, 340
 - in schemes for helical springs, 203–204
 - in schemes for nonlinear strings, 225, 236, 240
 - in schemes for the 1D wave equation, 134–135
 - in schemes for the 2D wave equation, 313, 321
 - in schemes for the ideal bar, 170
 - in schemes for Webster's equation, 257–258
 - inharmonicities and, 142, 155
 - modal methods and, 318
 - of schemes in radial coordinates, 320, 354
 - perceptual significance of, 93, 142–143, 257, 318, 388
 - phase and group velocities and, 106
 - spatially-varying systems and, 208, 257–258
 - stability conditions and, 136, 170, 229
 - vs. physical dispersion, 134
- numerical instability
 - in schemes for the 1D wave equation, 133
 - in schemes for the Kirchhoff–Carrier equation, 225
 - in schemes for the SHO, 50–51
 - in schemes for the von Kármán system, 369
 - modular connections and, 190–192
 - nonlinear systems and, 77, 225, 369
 - numerical boundary conditions and, 125, 140–141
 - time-varying systems and, 262, 271
- numerical oscillations
 - hammer-string interaction and, 185
 - nonlinear systems and, 227–229
 - suppression of, 185, 228–229
- numerical phase and group velocity, 38, 106
 - for schemes for the 1D wave equation, 134–135, 150
 - for schemes for the 2D wave equation, 313
 - for schemes for the ideal bar, 170
 - for schemes for the stiff string, 177
 - for schemes for the thin plate equation, 339
- numerical stability
 - bandwidth and, 134–136, 170
 - collisions and, 79
 - computational complexity and, 21, 133–134, 169, 321, 382
 - digital waveguides and, 148, 157
 - energy analysis and, 38, 93
 - frequency domain analysis and, 31, 38, 140
 - implicit schemes and, 152
 - modal synthesis and, 157
 - modular connections and, 189, 192
 - of schemes for a bar of varying cross-section, 212
 - of schemes for a cubic nonlinear oscillator, 77
 - of schemes for a nonlinear oscillator, 75
 - of schemes for a string of varying density, 207, 209
 - of schemes for anisotropic plate vibration, 352
 - of schemes for coupled oscillators, 62
 - of schemes for nonlinear string vibration, 238

- of schemes for helical spring vibration, 202–203
 - of schemes for plate-string connections, 348
 - of schemes for shell vibration, 374
 - of schemes for the 1D wave equation, 132–133, 139, 149–151, 157
 - of schemes for the 1D wave equation with loss, 155
 - of schemes for the 2D wave equation, 311–314, 319
 - of schemes for the bow mechanism, 83–84
 - of schemes for the bow-mass-spring system, 86
 - of schemes for the bow-string interaction, 181–182
 - of schemes for the ideal bar equation, 169, 171, 173
 - of schemes for the Kirchhoff-Carrier equation, 226, 231
 - of schemes for the SHO, 51–54, 56
 - of schemes for the SHO with loss, 64, 65
 - of schemes for the stiff string, 176–177
 - of schemes for the thin plate equation, 338–340, 354
 - of schemes for the time-varying vocal tract, 264
 - of schemes for the von Kármán system, 370–371
 - of schemes for toneholes, 277
 - of schemes for Webster's equation, 256
 - polynomial root conditions and, 33–35, 106, 295
 - quadratic forms and, 39
 - sampling theory and, 52, 133
 - spatially-varying systems and, 163, 206
 - wave digital filters and, 60
 - waveguide meshes and, 316
- oboe, 278
- operation count
- bounds on, 20
 - dependence on sample rate, 21
 - in schemes for general LTI systems, 380
 - in schemes for the 1D wave equation, 156
 - in schemes for the 2D wave equation, 322
 - in schemes for the SHO, 55
- orthotropic plate vibration, 351
- oscillator
- additive synthesis and, 3
 - nonlinear, 74–75
 - nonlinear lossy, 82–83
 - simple harmonic, *see* simple harmonic oscillator
 - single reed model and, 265
- output, 157
- digital waveguides and, 13
 - from moving locations, 101, 144
 - from schemes for multiple strings, 187
 - from schemes for the 1D wave equation, 143–145
 - from schemes for the 2D wave equation, 310–311
 - interpolation and, 101, 143, 310–311
 - modal synthesis and, 10
 - multiple channel, 11, 144–145
 - plate reverberation and, 345
 - time domain methods and, 11
- parameter reduction, 120
- Parseval's relation, 230
- partial conservation, 79
- partial differential equation
- 1D wave equation, 118, 120
 - with loss, 153
 - 2D wave equation, 305
 - Berger's equation, 362
 - classification of, 94–95
 - coordinate changes and, 112
 - for anisotropic plate vibration, 351
 - for bar of variable cross-section, 210
 - for ideal bar, 163, 164
 - for nonlinear bar, 232
 - for stiff string, 175
 - with frequency-dependent loss, 177
 - for string of variable density, 206
 - for thin plate vibration, 331
 - for time-varying acoustic tube, 264
 - Kirchhoff-Carrier equation, 221
 - non-planar form of, 243
 - with loss, 223
 - musical instrument models and, 8, 379–380
 - system for coupled ideal bars, 195
 - system for helical spring vibration, 200
 - system for nonlinear shell system, 372

- partial differential equation (*continued*)
 - system for planar string vibration
 - general form of, 232
 - series-approximated form of, 236
 - von Kármán system, 363
 - Webster's equation, 250
- PDE, *see* partial differential equation
- phantom partials, 76, 221, 232–234, 242, 346
- phase and group velocity, 97
 - for 1D wave equation, 122
 - for 2D wave equation, 307
 - for ideal bar equation, 164
 - for stiff string, 175
 - for thin plates, 332
 - numerical, 106
 - Webster's equation and, 251
- phase plane analysis, 42
- phase vocoder, 4
- physical modeling sound synthesis, 8–18
 - abstract synthesis and, 1, 18–19
 - audio signal processing and, 26–27
 - modularity and, 15
 - motivations for, 22
 - subtractive synthesis and, 5
- piano
 - bridge and, 234, 346
 - commuted synthesis and, 349
 - frequency-dependent loss in, 178
 - modal synthesis and, 242
 - multiple strings in, 81, 185, 186
 - phantom partials and, 221, 234
 - preparation of, 187
 - sampling synthesis and, 6, 23
 - soundboard and, 346
 - stiff string modeling and, 174
 - two-stage decay in, 187
- pitch
 - arched bars and, 211
 - boundary conditions and, 129
 - delay lines and, 12
 - for vibrating bars, 167–168
 - numerical dispersion and, 143
- pitch flattening, 86
- pitch glides, 76
 - digital waveguides and, 13, 224
 - in bars, 232
 - in plates, 361, 362, 368
 - in strings, 221, 223–224
- plate, *see* thin plate
- plate reverberation, 169, 199, 341, 345–346
- plucks, 121
- Poisson's ratio, 331
- polynomials in z , 33–35
- port resistance, 59
- Portnoff, M., 17, 258
- positive realness, 254
- power law nonlinearity, 78
 - hammer (mallet) and, 78, 183, 342
 - mouthpiece flow and, 266
 - rattle and, 81
 - reed beating and, 266
- precomputation, 156, 322, 346, 384
- prepared piano, 187
- quadratic forms, 41–42
- quarter plane, 289, 291
- Rabenstein, R., 2, 10
- radial coordinates, 288
- radiation boundary condition
 - 1D wave equation and, 126
 - formant bandwidth and, 259
 - numerical, 140–141
 - Webster's equation and, 253–254
- raised cosine distribution
 - in 1D, 121
 - in 2D, 306
- Raman, C., 180
- rattle, 81
 - connection with string, 192–193
- reed beating, 87, 269–270
- rigid body motion, 129, 336, 345
- ring modulation, 6
- Risset, J.-C., 2, 3
- Rocchesso, D., 10
- room acoustics, 143, 305, 310, 322, 379, 381
 - boundary conditions and, 308
 - waveguide mesh and, 14
- Ruiz, P., 2, 9, 17, 178
- Rule of Thumb #1, 136
- Rule of Thumb #2, 174
- Rule of Thumb #3, 192
- Rule of Thumb #4, 229
- Rule of Thumb #5, 354
- Runge–Kutta methods, 35, 49, 61
- sample rate, *see* sampling frequency
- sampling frequency, 26
- sampling synthesis, 6
 - memory requirements and, 23

- sampling theorem, 26
 - computational complexity and, 380–381
- saxophone, 252, 271
- scanned synthesis, 144, 327
- scattering junction, 12, 262, 315
- scattering methods, 15, 47, 58, 59
 - acoustic tubes and, 261–264
 - digital waveguides as, 157
 - finite difference schemes and, 146, 253, 258, 263, 316
 - in 2D, 315
 - modular connections and, 192
 - time-varying systems and, 262
 - transmission lines and, 258
- scheme, *see* finite difference schemes
- self-sustained oscillation, *see* auto-oscillations
- shape matrix, 156
- SHO, *see* simple harmonic oscillator
- shock waves, 278
- short-time Fourier transformation, 4
- simple harmonic oscillator
 - coupled systems and, 49
 - definition of, 46
 - energy analysis of, 48
 - first-order system and, 48–49
 - frequency domain analysis of, 47
 - schemes for, 49–61
 - wave digital filters and, 58–60
 - with a source term, 67–68
 - with loss, 63–67
- single reed, 86–87, 265–268
- sitar, 193
- Smith III, J. O., 2, 3, 11, 147, 265, 315
- soundboard, 346, 351
- source-filter models, 5
 - subtractive synthesis and, 3
 - vocal synthesis and, 259
- sources, 67–68
- spatial variation
 - acoustic tubes and, 251
 - bars and, 210–213
 - coordinate changes and, 112
 - dispersion and, 251
 - strings and, 206–209
- spectral methods, 18, 20, 231, 388–390
 - modal synthesis and, 20, 389
- spectral modeling synthesis, 4
- speech synthesis, 258
 - finite difference methods and, 17
 - Kelly–Lochbaum model, 261–264
- spreading operators, 103, 294
 - excitation and, 181, 185, 342
 - gain of, 112
 - modular connections and, 189, 198, 348
- spring, 46, 118, 316
 - connection between bars, 197
 - connection with string, 188–190
 - helical, *see* helical spring
 - stiffening, 75
- squeaks, 271–272
- stability, *see* numerical stability
- state space, 142
 - representations of finite difference schemes, *see* matrix representations, of finite difference schemes
 - sound synthesis, 18
 - stability conditions and, 140
- stencil
 - of 1D difference operators, 99
 - of 1D schemes, 106
 - of 2D difference operators, 292–293, 299
 - of 2D schemes, 313
 - wide, 149, 150, 155, 299
 - width, 28
- stick-slip interaction, 86
- stiff systems, 236
- strikes, 121
- string
 - 1D wave equation and, 118
 - boundary conditions and, 124
 - bow interaction and, 180–183
 - connection with thin plate, 346–349
 - coupled transverse-longitudinal motion in, 232
 - digital waveguide modeling and, 13
 - finite difference schemes for, 17
 - frequency-dependent loss and, 177–178
 - hammer interaction with, 183–185
 - Karplus–Strong algorithm and, 12
 - longitudinal vibration of, 232, 346
 - lumped mass–spring model of, 10
 - modal synthesis and, 10
 - multiple, 185–187
 - non-planar vibration of, 242–244
 - nonlinear vibration of, 221
 - preparation and, 81, 187–193
 - spatial variation in, 206–209

- string (*continued*)
 stiffness and, 174–175, 241–242
 strikes and plucks and, 120
 sympathetic vibration of, 349
- Strong, A., 2, 12
- Sturm–Liouville problem, 10
- subharmonic generation, 361, 366
- subtractive synthesis, 4–5, 45
- summation by parts, 110–111, 296, 301
 in transformed coordinates, 113
- symbol, 96
- sympathetic vibration, 349
- symplectic methods, 42, 54, 75
- TAO synth, 316
- telegrapher's equations, 250
- tension modulation, 13, 22, 221, 242
 plate vibration and, 361
- thin plate
 anisotropic, 349–352
 boundary conditions and, 333–335
 bow interaction and, 344
 connection with string, 346–349
 energy analysis and, 333–335
 excitation and, 341–342
 Kirchhoff model of, 331–332
 loss in, 341
 mallet interaction and, 342–343
 modal analysis and, 336
 nonlinear vibration of, *see* Berger's
 equation, von Kármán system
 reverberation and, 345–346
 schemes for, 337–340
 vs. thick, 332, 333
- Thomas algorithm, 109, 151
- time series, 26–27
 identities for, 31, 40
- time step, 26
- Timoshenko beam theory, 97, 164, 213,
 333
- Timoshenko, S., 165
- TLM, *see* transmission line matrix method
- Toeplitz matrices, 108
- torsional wave motion, 183
- transmission line
 1D wave equation and, 118
 acoustic tubes and, 258
 Webster's equation and, 250
- transmission line matrix method,
 15, 315, 316
- trapezoid rule, 37–38
 wave digital filters and, 58
- Trautmann, L., 2, 10
- traveling wave decomposition, 123
 acoustic tubes and, 261
 digital waveguides and, 12, 123,
 146–147
 dispersion relation for 1D wave equation
 and, 122
 reflection at boundary and, 126
- triangle inequality, 97, 109, 290, 295
- tube, *see* acoustic tube
- tuning fork, 195
- two-stage decay, 187
- van Duyne, S., 315
- vibrato, 259
- virtual analog, 199
- virtual grid points, 108, 172
- vocal synthesis, 258
 digital waveguide models and, 13
 finite difference methods and,
 17, 258
 granular methods and, 8
 source-filter models and, 5
 waveguide mesh and, 14
- vocal tract
 2D models of, 13–14, 305
 acoustic tube modeling and, 258
 formants and, 259
 time variation and, 264
- Volterra series, 10, 73, 229
- von Kármán system, 363–371
- von Neumann analysis, 35, 38, 47
 of schemes for the 1D wave equation,
 132–133, 149–151
 with loss, 154–155
 of schemes for the 2D wave equation,
 311
 of schemes for the ideal bar, 169
 of schemes for the thin plate, 338
- VOSIM, 8
- vowels, 259
- wave digital filters, 38, 47, 58, 118
 computability and, 269
 digital waveguides and, 11
 finite difference schemes and, 20,
 59–60, 269
 hybrid methods and, 15

- SHO and, 58–60
 speech synthesis and, 14
 toneholes and, 13, 14, 272
- wave equation
- 1D
 - boundary conditions for, 124–126
 - definition of, 118
 - digital waveguides and, 11, 12, 146–148
 - dispersion relation for, 122
 - energy analysis and, 123–126
 - finite difference schemes for, 131–143, 148–152
 - initial conditions for, 120–121
 - loss and, 153–155
 - lumped mass–spring networks and, 118–119
 - modes and, 128–129
 - phase and group velocity for, 122
 - traveling wave solutions and, 123
 - Webster's equation and, 252
 - 2D
 - boundary conditions for, 307–308, 318
 - definition of, 305
 - dispersion relation for, 307
 - energy analysis and, 307–308
 - finite difference schemes for, 310–315
 - initial conditions for, 306
 - lumped mass–spring networks and, 316
 - modes and, 309–310
 - phase and group velocity for, 307
 - waveguide mesh and, 315–316
 - 3D
 - definition of, 323
 - finite difference schemes for, 311, 324–325
 - modes and, 310, 323
- wave speed, 118, 120, 305
- acoustic tubes and, 250, 251
 - amplitude-dependent, 225
 - computational complexity and, 236
 - numerical dispersion and, 258
 - spatially varying systems and, 207, 208
- wave variables
- acoustic tube modeling and, 262
 - digital waveguides and, 12, 146
 - power-normalized, 59
 - scattering methods and, 15
 - wave digital filters and, 58
 - waveguide mesh and, 315
- waveguide, *see* digital waveguides
- waveguide mesh, 14, 315–316
- computational complexity and, 21, 321
 - finite difference schemes and, 19, 310, 316
 - vocal tract modeling and, 258
- wavenumber, 96, 105
- in 2D, 290
- waveshaping, 8
- wavetable synthesis, 5–6, 45
- digital waveguides and, 12, 16, 18
 - Karplus–Strong algorithm and, 12, 16
- Webster's equation, 250
- boundary conditions and, 253–254
 - dispersion and, 251–252
 - energy analysis and, 253–254
 - finite difference schemes for, 255–258
 - modes and, 254
 - phase and group velocity and, 251
 - time-varying form of, 264
- whirling, 221, 243
- woodwind instruments, 11, 82, 258, 265
- digital waveguides and, 13
- Young's modulus, 118, 164, 222
- z transform, 32, 105