

- Preface p. xiii
- Acknowledgments p. xvii
- List of Figures p. xix
- List of Tables p. xxiii
- 1 Introduction p. 1
- 1.1 MEMS and NEMS p. 1
- 1.2 A Capsule History of MEMS and NEMS p. 2
- 1.3 Dimensional Analysis and Scaling p. 4
- 1.4 Chapter Highlights p. 10
- 1.5 Exercises p. 11
- 1.6 Related Reading p. 12
- 1.7 Notes p. 13
- 2 A Refresher on Continuum Mechanics p. 15
- 2.1 Introduction p. 15
- 2.2 The Continuum Hypothesis p. 17
- 2.3 Heat Conduction p. 19
- 2.3.1 Derivation of the Heat Equation p. 19
- 2.3.2 Initial and Boundary Conditions p. 21
- 2.3.3 The Cooling Sphere p. 22
- 2.4 Elasticity p. 23
- 2.4.1 The Navier Equations p. 23
- 2.4.2 Initial and Boundary Conditions p. 26
- 2.4.3 The Vibrating String p. 26
- 2.4.4 The Vibrating Membrane p. 27
- 2.4.5 Beams, Plates, and Energy Minimization p. 28
- 2.4.6 The String Revisited p. 28
- 2.4.7 Elastic Beams p. 32
- 2.4.8 Elastic Plates p. 36
- 2.5 Linear Thermoelasticity p. 37
- 2.5.1 The Equations of Linear Thermoelasticity p. 37
- 2.5.2 Uncoupled Quasistatic Thermoelasticity p. 38
- 2.5.3 Thermal Expansion of a Rod p. 38
- 2.6 Fluid Dynamics p. 40
- 2.6.1 The Navier-Stokes Equations p. 40
- 2.6.2 Incompressible Flow p. 41
- 2.6.3 The Euler Equations p. 42
- 2.6.4 The Stokes Equations p. 42
- 2.6.5 Boundary and Initial Conditions p. 43
- 2.6.6 Poiseuille Flow p. 46
- 2.6.7 Poiseuille Flow with Slip p. 47
- 2.7 Electromagnetism p. 47
- 2.7.1 Units for Electromagnetism p. 48
- 2.7.2 The Maxwell Equations p. 48
- 2.7.3 Electrostatics p. 50
- 2.7.4 Magnetostatics p. 50
- 2.7.5 Boundary Conditions p. 51

- 2.7.6 Integral Formulation p. 51
- 2.8 Numerical Methods for Continuum Mechanics p. 54
- 2.9 Chapter Highlights p. 56
- 2.10 Exercises p. 57
- 2.11 Related Reading p. 62
- 2.12 Notes p. 63
- 3 Small is Different p. 65
- 3.1 The Backyard p. 65
- 3.2 Scaling p. 66
- 3.2.1 Viscosity of Fluids p. 67
- 3.2.2 Heating and Cooling p. 70
- 3.2.3 Rigidity of Structures p. 74
- 3.2.4 Electrostatics p. 75
- 3.2.5 Fluid Interfaces p. 76
- 3.3 Systems p. 78
- 3.3.1 An Electrostatic Actuator p. 79
- 3.3.2 A Similar Magnetostatic Actuator p. 81
- 3.4 Chapter Highlights p. 83
- 3.5 Exercises p. 83
- 3.6 Related Reading p. 87
- 3.7 Notes p. 88
- 4 Thermally Driven Systems p. 91
- 4.1 Introduction p. 91
- 4.2 Thermally Driven Devices p. 92
- 4.2.1 The Thermoelastic V-Beam Actuator p. 92
- 4.2.2 The Thermal Bimorph Actuator p. 93
- 4.2.3 The Thermopneumatic Valve p. 94
- 4.2.4 The Thermal Anemometer p. 95
- 4.2.5 The Metal Oxide Gas Sensor p. 96
- 4.2.6 The Thermal Data Storage Device p. 96
- 4.2.7 The Shape Memory Actuator p. 97
- 4.2.8 The Microscale PCR Chamber p. 98
- 4.3 From PDE to ODE: Lumped Models p. 98
- 4.4 Joule Heating of a Cylinder p. 102
- 4.4.1 The Electromagnetic Problem p. 103
- 4.4.2 The Thermal Problem p. 105
- 4.4.3 Scaling p. 106
- 4.4.4 An Interesting Limit p. 107
- 4.4.5 Spatially Independent Solutions p. 110
- 4.4.6 Stability of Steady States p. 113
- 4.4.7 Iterative Numerical Schemes p. 116
- 4.5 Analysis of Thermal Data Storage p. 121
- 4.6 Chapter Highlights p. 123
- 4.7 Exercises p. 123
- 4.8 Related Reading p. 127
- 4.9 Notes p. 128

- 5 Modeling Elastic Structures p. 131
- 5.1 Introduction p. 131
- 5.2 Examples of Elastic Structures in MEMS/NEMS p. 132
- 5.2.1 Micromirrors p. 133
- 5.2.2 Carbon Nanotube Caps p. 133
- 5.2.3 Pressure Sensors p. 135
- 5.2.4 Resonant Sensors p. 136
- 5.2.5 Micromachined Switches p. 136
- 5.2.6 Micro- and Nanotweezers p. 137
- 5.2.7 The Nanomechanical Resonator p. 137
- 5.3 The Mass on a Spring p. 138
- 5.3.1 Governing Equation and Scaling p. 139
- 5.3.2 Unforced Oscillations p. 140
- 5.3.3 The Phase Plane p. 143
- 5.3.4 Forced Oscillations and Resonance p. 145
- 5.3.5 Nonlinear Springs p. 148
- 5.3.6 Effective Spring Constants p. 149
- 5.4 Membranes p. 151
- 5.4.1 Governing Equation p. 151
- 5.4.2 One-Dimensional Membrane with Uniform Load p. 152
- 5.4.3 One-Dimensional Membrane with Concentrated Load p. 153
- 5.4.4 One-Dimensional Membrane with Arbitrary Load p. 154
- 5.4.5 Free Vibrations of a One-Dimensional Membrane p. 155
- 5.4.6 Forced Vibrations and Resonance p. 159
- 5.5 Beams p. 160
- 5.5.1 Governing Equation p. 160
- 5.5.2 Cantilevered Beam with Uniform Load p. 161
- 5.5.3 Cantilevered Beam with Concentrated Load p. 162
- 5.5.4 Free Vibrations of a Beam p. 163
- 5.6 Plates p. 164
- 5.6.1 Governing Equation p. 164
- 5.6.2 Circular Plate with Uniform Load p. 165
- 5.6.3 Free Vibrations of a Circular Plate p. 166
- 5.7 The Capacitive Pressure Sensor p. 168
- 5.8 Chapter Highlights p. 170
- 5.9 Exercises p. 171
- 5.10 Related Reading p. 175
- 5.11 Notes p. 175
- 6 Modeling Coupled Thermal-Elastic Systems p. 177
- 6.1 Introduction p. 177
- 6.2 Devices and Phenomena in Thermal-Elastic Systems p. 180
- 6.2.1 Thermoelastic Damping and Thermal Stresses p. 180
- 6.2.2 Thermopneumatic Systems p. 181
- 6.2.3 The Thermoelastic Rod Actuator p. 183
- 6.2.4 The Thermoelastic V-Beam Actuator p. 183
- 6.2.5 Thermal Bimorph Actuator p. 184

- 6.2.6 Bimetallic Thermal Actuators p. 184
- 6.2.7 Shape Memory Actuators p. 185
- 6.3 Modeling Thermopneumatic Systems p. 186
- 6.3.1 A Mass-Spring-Piston Model p. 186
- 6.3.2 A Membrane-Based Model p. 192
- 6.3.3 A Plate-Based Model p. 196
- 6.4 The Thermoelastic Rod Revisited p. 197
- 6.5 Modeling Thermoelastic V-Beam Actuators p. 197
- 6.6 Modeling Thermal Bimorph Actuators p. 202
- 6.7 Modeling Bimetallic Thermal Actuators p. 205
- 6.8 Chapter Highlights p. 205
- 6.9 Exercises p. 206
- 6.10 Related Reading p. 210
- 6.11 Notes p. 211
- 7 Modeling Electrostatic-Elastic Systems p. 213
- 7.1 Introduction p. 213
- 7.2 Devices Using Electrostatic Actuation p. 216
- 7.2.1 Grating Light Valve p. 216
- 7.2.2 Micromirrors p. 217
- 7.2.3 Comb Drive p. 218
- 7.2.4 Micropumps p. 219
- 7.2.5 Microswitches p. 220
- 7.2.6 Microvalves p. 220
- 7.2.7 Micro- and Nanotweezers p. 220
- 7.2.8 The Shuffle Motor p. 220
- 7.3 The Mass-Spring Model p. 221
- 7.3.1 Governing Equation p. 222
- 7.3.2 A Time Scale for Systems Dominated by Inertia p. 224
- 7.3.3 A Time Scale for Viscosity-Dominated Systems p. 225
- 7.3.4 Steady-State Solutions p. 225
- 7.3.5 Stability of Steady States p. 229
- 7.3.6 Iterative Numerical Methods p. 230
- 7.4 Modeling General Electrostatic-Elastic Systems p. 235
- 7.4.1 The Electrostatic Problem p. 235
- 7.4.2 The Elastic Problem p. 236
- 7.4.3 Scaling p. 236
- 7.4.4 The Small-Aspect Ratio Limit p. 237
- 7.5 Electrostatic-Elastic Systems--Membrane Theory p. 238
- 7.5.1 General Results p. 239
- 7.5.2 One-Dimensional Membranes p. 243
- 7.5.3 Circular Membranes p. 247
- 7.6 Electrostatic-Elastic Systems--Beam and Plate Theory p. 251
- 7.6.1 Beams p. 252
- 7.6.2 Circular Plates p. 252
- 7.7 Analysis of Capacitive Control Schemes p. 253
- 7.7.1 The Basic Circuit p. 253

- 7.7.2 A Mass-Spring Model p. 254
- 7.7.3 Control of a General Structure p. 256
- 7.8 Chapter Highlights p. 260
- 7.9 Exercises p. 261
- 7.10 Related Reading p. 263
- 7.11 Notes p. 264
- 8 Modeling Magnetically Actuated Systems p. 267
- 8.1 Introduction p. 267
- 8.2 Magnetically Driven Devices p. 268
- 8.2.1 Micropumps p. 269
- 8.2.2 Plastic Deformation Magnetic Assembly p. 269
- 8.2.3 Magnetic Levitation p. 270
- 8.2.4 Temperature-Controlled Magnetic Actuators p. 272
- 8.2.5 Magnetostrictive Actuators p. 272
- 8.3 Mass-Spring Models p. 273
- 8.3.1 Two Parallel Wires p. 273
- 8.3.2 A Parallel Plate Model p. 275
- 8.3.3 A Coil-Activated Model p. 276
- 8.4 A Simple Membrane Micropump Model p. 278
- 8.5 A Small-Aspect Ratio Model p. 281
- 8.5.1 Formulation of the Model p. 281
- 8.5.2 A Numerical Interlude p. 285
- 8.5.3 Solutions p. 288
- 8.5.4 How Close Did We Get? p. 288
- 8.6 Chapter Highlights p. 292
- 8.7 Exercises p. 293
- 8.8 Notes p. 295
- 9 Microfluidics p. 297
- 9.1 Introduction p. 297
- 9.2 Microfluidic Devices p. 298
- 9.2.1 The Thermopneumatic "Fluistor" Valve p. 298
- 9.2.2 The Ink Jet Printer Head p. 298
- 9.2.3 Membrane Pumps p. 299
- 9.2.4 The MAP Sensor p. 299
- 9.2.5 Electrokinetic Flow p. 300
- 9.2.6 Nanolithography p. 301
- 9.2.7 Nano-Jets p. 303
- 9.3 More Fluidic Scaling p. 303
- 9.3.1 Liquids and Gases p. 303
- 9.3.2 The Boundary Layer p. 304
- 9.3.3 Flow Rates and Pressure p. 305
- 9.3.4 Entrance Length p. 306
- 9.3.5 Mixing p. 307
- 9.4 Modeling Squeeze Film Damping p. 307
- 9.4.1 Lubrication Theory p. 308
- 9.4.2 The Model p. 308

- 9.4.3 Scaling p. 309
- 9.4.4 A Linear Theory p. 310
- 9.5 Chapter Highlights p. 312
- 9.6 Exercises p. 313
- 9.7 Notes p. 314
- 10 Beyond Continuum Theory p. 315
- 10.1 Introduction p. 315
- 10.2 Limits of Continuum Mechanics p. 315
- 10.2.1 The Limit of Newtonian Mechanics p. 316
- 10.2.2 The Limit of Large Numbers p. 317
- 10.3 Devices and Systems Beyond Continuum Theory p. 319
- 10.3.1 Nanostructured Materials p. 320
- 10.3.2 Nanobiological Systems p. 320
- 10.3.3 Nanobots and Other Dream Machines p. 320
- 10.4 Chapter Highlights p. 321
- 10.5 Exercises p. 321
- 10.6 Notes p. 323
- References p. 325
- A Mathematical Results p. 341
- A.1 The Divergence Theorem p. 341
- A.2 Stoke's Theorem p. 341
- A.3 The Laplacian p. 341
- A.4 The Bi-Laplacian p. 342
- A.5 The Mean Value Theorem for Integrals p. 342
- A.6 The Dubois-Reymond Lemma p. 342
- A.7 A Brief Look at Asymptotics, Big O and Little o p. 343
- A.8 Fundamental Lemma of Calculus of Variations p. 345
- A.9 Linear Spaces p. 346
- B Physical Constants p. 351
- Index p. 353