

Contents

1. The Foundation of Classical Mechanics	1
1.1 Principia	1
1.2 Prerequisites for Newton	1
1.3 The Masterpiece	5
<i>The Acceleration of Gravity</i>	11
<i>Circular Motion</i>	12
<i>Communication Satellite</i>	13
<i>Horizontal Throw</i>	14
<i>The Gravitational Constant</i>	17
<i>String Force</i>	18
<i>Forces and Tension</i>	19
<i>Dimensional Analysis</i>	20
1.4 Concluding Remarks	21
1.5 Problems	22
2. Newton's Five Laws	27
2.1 Newton's Laws of Motion	27
2.2 Integration of the Equation of Motion	31
<i>Constant Force</i>	31
<i>The Harmonic Oscillator</i>	33
<i>Mass on a Spring in the Gravitational Field of Earth</i>	36
<i>Sphere Falling Through a Liquid</i>	38
<i>Solid Against Solid</i>	40
<i>The Atwood Machine</i>	41
<i>Force in Harmonic Motion</i>	42
<i>Charged Particle in a Uniform Magnetic Field</i>	44
<i>Thomson's Experiment</i>	48
<i>Work and Energy in Linear Motion of a Particle</i>	51
<i>Free Fall Towards the Sun from a Great Distance</i>	53
<i>Momentum Conservation</i>	54
<i>Inelastic Collisions</i>	56
<i>Rocket Propulsion</i>	57
<i>Some Qualitative Remarks on Rocket Propulsion</i>	59
<i>Ball Against a Wall</i>	61
2.3 Problems	62

3. Gravitational and Inertial Mass	73
3.1 Gravitational Mass	73
3.2 Inertial Mass	74
3.3 Proportionality Between Inertial and Gravitational Mass ..	75
3.4 Newton's Experiment	76
<i>The Satellite</i>	78
<i>An Elevator in Free Fall</i>	79
<i>Three Balls</i>	80
3.5 Problem	80
4. The Galilei Transformation	83
4.1 The Galilei Transformation	84
4.2 Galileo Speaks	90
<i>Velocity Transformation</i>	91
4.3 Problems	93
5. The Motion of the Earth	95
5.1 Examples	95
<i>Vectors and the Rotation of a Rigid Body</i>	95
<i>Angular Velocities in the Solar System</i>	97
5.2 Problems	99
6. Motion in Accelerated Reference Frames	101
6.1 Newton's 2nd Law Within Accelerated Reference Frames ..	101
6.2 The Equivalence Principle of Mechanics	108
6.3 The Einstein Box	111
<i>Balloon in Accelerated Frame</i>	114
<i>Mass on an Oscillating Plate</i>	115
<i>Pendulum in an Elevator</i>	115
6.4 The Centrifugal Force	116
<i>Earth's Orbit Around the Sun</i>	117
<i>Grass on a Rotating Disk</i>	117
<i>The Variation of g with Latitude</i>	118
6.5 Tidal Fields	121
<i>The Roche Limit</i>	126
6.6 The Coriolis Force	128
<i>Coriolis Force on a Train</i>	133
<i>Particle on a Frictionless Disc</i>	133
<i>The Vertical Throw</i>	134
6.7 Tidal Forces and Local Inertial Frames	135
<i>Global and Local Inertial Frames</i>	137
6.8 The Foucault Pendulum	137
6.9 Newton's Bucket	142
6.10 Review: Fictitious Forces	145
6.11 Problems	146

7. The Problem of Motion	153
7.1 Kinematic and Dynamic Views of the Problem of Motion ..	153
7.2 Einstein Speaks	155
7.3 Symmetry	157
7.4 The Symmetry (Invariance) of Newton's 2nd Law	157
7.5 Limited Absolute Space	159
7.6 The Asymmetry (Variance) of Newton's 2nd Law	159
7.7 Critique of the Newtonian View	162
7.8 Concluding Remarks	163
8. Energy	167
8.1 Work and Kinetic Energy	167
8.2 Conservative Force Fields	169
8.3 Central Force Fields	170
8.4 Potential Energy and Conservation of Energy	171
8.5 Calculation of Potential Energy	174
<i>Constant Gravitational Field</i>	175
<i>Spring Force</i>	175
<i>Gravity Outside a Homogeneous Sphere</i>	175
8.6 The Gravitational Field Around a Homogeneous Sphere ...	176
8.6.1 The Field Around a Spherical Shell	176
8.6.2 A Solid Sphere	179
8.7 Examples	181
<i>Particle on a Frictionless Curve</i>	181
<i>String Force in the Pendulum</i>	182
<i>The Gravitational Potential Outside the Earth</i>	183
<i>Potential Energy Due to Electric Forces</i>	183
<i>A Tunnel Through the Earth</i>	184
<i>The Asymmetry of Nature</i>	186
8.8 Review: Conservative Forces and Potential Energy	188
8.9 Problems	189
9. The Center-of-Mass Theorem	193
9.1 The Center of Mass	193
9.2 The Center-of-Mass Frame	197
9.3 Examples	199
<i>Two Masses Connected with a Spring</i>	199
<i>Inelastic Collisions</i>	202
<i>The Collision Approximation</i>	204
<i>Freely Falling Spring</i>	207
<i>The Wedge</i>	209
9.4 Review: Center of Mass and Center-of-Mass Theorems ...	212
9.5 Comments on the Conservation Theorems	212
9.6 Problems	213

10. The Angular Momentum Theorem	219
10.1 The Angular Momentum Theorem for a Particle	219
10.2 Conservation of Angular Momentum	221
10.3 Torque and Angular Momentum Around an Axis	223
10.4 The Angular Momentum Theorem for a System of Particles	224
10.5 Center of Gravity	227
10.6 Angular Momentum Around the Center of Mass	228
10.7 Review: Equations of Motion for a System of Particles	230
10.8 Examples of Conservation of Angular Momentum	230
<i>Particle in Circular Motion</i>	230
<i>Rotation of Galaxies, Solar Systems, etc.</i>	231
11. Rotation of a Rigid Body	237
11.1 Equations of Motion	237
11.2 The Rotation Vector	238
11.3 Kinetic Energy of a Rotating Disk	239
11.3.1 The Parallel Axis Theorem	240
11.3.2 The Perpendicular Axis Theorem	242
11.4 Angular Momentum of an Arbitrary Rigid Body in Rotation Around a Fixed Axis	243
11.4.1 The Parallel Axis Theorem in General Form	244
11.5 Calculation of the Moment of Inertia for Simple Bodies	245
11.5.1 Homogenous Thin Rod	245
11.5.2 Circular Disk	246
11.5.3 Thin Spherical Shell	247
11.5.4 Homogenous (Solid) Sphere, Mass M and Radius R	248
11.5.5 Rectangular Plate	249
11.6 Equation of Motion for a Rigid Body Rotating Around a Fixed Axis	250
11.6.1 Conservation of Angular Momentum	253
11.7 Work and Power in the Rotation of a Rigid Body Around a Fixed Axis	254
11.7.1 Torsion Pendulum	255
11.8 The Angular Momentum Theorem Referred to Various Points	256
11.9 Examples	258
<i>Rotating Cylinder</i>	258
<i>Falling Cylinder</i>	260
<i>The Atwood Machine</i>	262
<i>The Physical Pendulum</i>	263
<i>The Rod</i>	264
11.10 Review: Linear Motion and Rotation About a Fixed Axis	266
11.11 Problems	267

12. The Laws of Motion	279
12.1 Review: Classical Mechanics	279
12.2 Remarks on the Three Conservation Theorems	280
12.3 Examples	280
<i>Conservation of Angular Momentum</i>	280
<i>Rotating Rod</i>	284
<i>Man on Disk</i>	286
<i>The Sprinkler</i>	287
<i>Rolling</i>	289
<i>Yo-Yo on the Floor</i>	295
<i>Rolling Over an Edge</i>	297
<i>Determinism and Predictability</i>	299
12.4 Problems	300
13. The General Motion of a Rigid Body	313
13.1 Inertia in Rotational Motion	313
<i>The Dumbbell</i>	314
<i>Flywheel on an Axis</i>	316
<i>Precession of a Gyroscope</i>	318
13.2 The Inertia Tensor	321
<i>The Dumbbell Revisited</i>	324
13.3 Euler's Equations	326
13.3.1 Derivation of Euler's Equations	328
13.4 Kinetic Energy	330
13.5 Determination of the Principal Coordinate System	331
<i>Rotating Dumbbell</i>	333
<i>Flywheel</i>	334
<i>The Gyroscope</i>	335
<i>Gyroscope Supported at the Center of Mass</i>	340
<i>The Earth as a Gyroscope</i>	341
13.6 Problems	342
14. The Motion of the Planets	345
14.1 Tycho Brahe	345
14.2 Kepler and the Orbit of Mars	346
14.2.1 The Length of a Martian Year	347
14.2.2 The Orbit of the Planet Mars	349
14.2.3 Determination of Absolute Distance in the Solar System	351
14.3 Conic Sections	352
14.4 Newton's Law of Gravity Derived from Kepler's Laws	355
14.5 The Kepler Problem	359
14.5.1 Derivation of Kepler's 3rd Law from Newton's Law of Gravity	364

14.6	The Effective Potential	366
14.7	The Two-Body Problem	367
14.7.1	The Two-Body Problem and Kepler's 3rd Law	370
14.8	Double Stars:	
	The Motion of the Heliocentric Reference Frame	370
14.9	Review: Kepler Motion	372
14.10	Examples	373
	<i>Planetary Orbits and Initial Conditions</i>	373
	<i>Shape and Size of Planetary Orbits</i>	374
	<i>Motion Near the Surface of the Earth</i>	376
	<i>Velocities in an Elliptical Orbit</i>	377
	<i>Hohman Orbit to Mars</i>	378
	<i>The Face of the Moon (Spin-Orbit Locking)</i>	381
14.11	Problems	385
15.	Harmonic Oscillators	389
15.1	Small Oscillations	389
15.2	Energy in Harmonic Oscillators	391
15.3	Free Damped Oscillations	392
15.3.1	Weakly Damped Oscillations	393
15.3.2	Strongly Damped Oscillations	394
15.3.3	Critical Damping	394
15.4	Energy in Free, Weakly Damped Oscillations	395
15.5	Forced Oscillations	396
15.6	The Forced Damped Harmonic Oscillator	398
15.7	Frequency Characteristics	400
15.7.1	$\omega \ll \omega_0$: A Low Driving Frequency	400
15.7.2	$\omega \gg \omega_0$: A High Driving Frequency	400
15.7.3	$\omega \cong \omega_0$: Resonance	401
15.8	Power Absorption	402
15.9	The Q -Value of a Weakly Damped Harmonic Oscillator	403
15.10	The Lorentz Curve	405
15.11	Complex Numbers	406
15.12	Problems	408
16.	Remarks on Nonlinearity and Chaos	411
16.1	Determinism vs Predictability	411
16.2	Linear and Nonlinear Differential Equations	412
	<i>Superposition</i>	413
16.3	Phase Space	414
	<i>The Simple Harmonic Oscillator</i>	415
	<i>Phase Space of the Pendulum</i>	416
	<i>Bifurcation in a Nonlinear Model</i>	421

16.4	A Forced, Damped Nonlinear Oscillator	424
16.5	Liapunov Exponents	427
16.6	Chaos in the Solar System	429
16.7	Problems	431
Appendix. Vectors and Vector Calculus		433
Selected References		439
Answers to Problems		441
Index		449