

# CONTENTS

*Preface*      *xiii*

**Chapter 1 INTRODUCTION TO THE MECHANICAL UNIVERSE (Program 1)**      1

- 1.1 The Copernican Revolution      1
- 1.2 Units and Dimensions      5
- 1.3 A Final Word      10

**Chapter 2 THE LAW OF FALLING BODIES (Program 2)**      13

- 2.1 Aristotle's Description of Motion      13
- 2.2 Do Heavy Bodies Fall Faster Than Lighter Ones?      15
- 2.3 Medieval Laws of Falling Bodies      15
- 2.4 "The" Law of Falling Bodies      20
- 2.5 The Average Speed of a Falling Body      25

2.5 Experimental Determination of the Law of Falling Bodies	15
2.6 The Average Velocity of a Falling Body	18
2.7 Instantaneous Velocity: The Derivative	18
2.8 Acceleration	20
2.9 A Final Word	22
Problems	23

**Chapter 3 THE LANGUAGE OF NATURE: DERIVATIVES AND INTEGRALS 27**

3.1 The Development of Differential Calculus	27
3.2 Derivatives and Slopes of Tangent Lines	28
3.3 Leibniz's Notation. Analytic Definition of the Derivative	31
3.4 Rules of Differentiation and Derivatives of Special Functions	32
3.5 Antidifferentiation, the Reverse of Differentiation	38
3.6 Antidifferentiation and Quadrature	39
3.7 The Leibniz Integral Notation	44
3.8 Applications of the Second Fundamental Theorem to Physics	48
3.9 A Final Word	51
Problems	52

**Chapter 4 INERTIA 57**

4.1 If the Earth Moves: Aristotelian Objections	57
4.2 The Earth Moves: Galileo's Law of Inertia	60
4.3 Relative Motion	62
4.4 Projectile Motion: A Consequence of Inertia	63
4.5 Calculating a Particular Trajectory	65
4.6 A Final Word	68
Problems	68

**Chapter 5 VECTORS 75**

5.1 Coordinate Systems	75
5.2 Vectors	77
5.3 Addition and Subtraction of Vectors, and Multiplication by a Scalar	80
5.4 The Scalar Product of Vectors	88
5.5 The Cross Product of Vectors	93
5.6 Derivatives of Vector Functions in a Fixed Coordinate System	96
5.7 Position Vector Expressed in Polar Coordinates	100
5.8 Uniform Circular Motion	101
5.9 A Final Word	105
Problems	106

**Chapter 6 NEWTON'S LAWS AND EQUILIBRIUM 113**

6.1 The End of the Confusion	113
6.2 Newton's Laws of Motion	114

6.3 Units of Mass, Momentum, and Force	117
6.4 Projectile Motion as an Application of Newton's Second Law	119
6.5 Equilibrium: Balance of Forces	120
6.6 Equilibrium: Balance of Torques	125
6.7 A Final Word	134
Problems	134

**Chapter 7 UNIVERSAL GRAVITATION AND CIRCULAR MOTION** 141

7.1 The Genesis of an Idea	141
7.2 The Law of Universal Gravitation	142
7.3 Acceleration of Gravity on the Earth	149
7.4 Why the Moon Doesn't Fall to the Earth	151
7.5 Circular Orbits	154
7.6 Other Examples of Uniform Circular Motion	156
7.7 A Final Word	159
Problems	160

**Chapter 8 FORCES** 163

8.1 The Fundamental Forces: Classification and Unification	163
8.2 The Strength of Gravitational and Electric Forces	165
8.3 Contact Forces	168
8.4 Application of Newton's Laws	172
8.5 Friction	179
8.6 Driving on Curved Roadways	185
8.7 Motion in a Resistive Medium	187
8.8 The Oil-Drop Experiment	192
8.9 A Final Word	196
Problems	197

**Chapter 9 FORCES IN ACCELERATING REFERENCE FRAMES** 203

9.1 Inertial and Noninertial Reference Frames	203
9.2 Galilean Relativity	204
9.3 Inertial Forces	208
9.4 Inertial Forces in a Linearly Accelerating Frame	208
9.5 Centrifugal Force	210
9.6 Effect of the Earth's Rotation on $g$	211
9.7 Centrifuges	213
9.8 A Final Word	215
Problems	216

**Chapter 10 ENERGY: CONSERVATION AND CONVERSION** 219

10.1 Toward an Idea of Energy	219
10.2 Work and Potential Energy	221

10.3 Kinetic Energy and the Conservation of Energy	228
10.4 Gravitational Potential Energy	236
10.5 Potential Energy and Stability	240
10.6 Heat and Energy	246
10.7 Mechanical Advantage and Efficiency of Machines	250
10.8 Power	252
10.9 A Final Word	253
Problems	254

**Chapter 11 THE CONSERVATION OF MOMENTUM** 263

11.1 The Universe as a Machine	263
11.2 Newton's Laws in Retrospect	265
11.3 The Center of Mass	266
11.4 The Law of Conservation of Momentum	269
11.5 Rocket Propulsion	273
11.6 Energy and Momentum Conservation in Collisions	275
11.7 Center-of-Mass Coordinates	282
11.8 Impulse: Collision Forces and Times	286
11.9 A Final Word	288
Problems	289

**Chapter 12 OSCILLATORY MOTION** 295

12.1 Finding a Clock That Wouldn't Get Seasick	295
12.2 Simple Harmonic Motion	297
12.3 The General Solution of the Differential Equation of Simple Harmonic Motion	301
12.4 Examples of Simple Harmonic Oscillators	303
12.5 Energy Conservation and Simple Harmonic Motion	306
12.6 The Simple Pendulum	309
12.7 Gaining Insight Through Approximations	312
12.8 Damped Oscillations	313
12.9 Forced Oscillations	316
12.10 Describing Resonance	317
12.11 Damped Forced Oscillations	321
12.12 Swinging and Singing Wires in the Wind	326
12.13 A Final Word	327
Problems	330

**Chapter 13 ANGULAR MOMENTUM** 335

13.1 Rotary Motion	335
13.2 Torque and Angular Momentum	336
13.3 Angular Momentum Conservation	338
13.4 Force and Torque	342

13.5 Kepler's Law of Equal Areas	344
13.6 Vortices and Firestorms	348
13.7 Conservation of Angular Momentum and Energy	350
13.8 A Final Word	355
Problems	356

**Chapter 14 ROTATIONAL DYNAMICS FOR RIGID BODIES** 363

14.1 Rotation of a Rigid Body About a Fixed Axis	363
14.2 Center of Mass of a Continuous Mass Distribution	364
14.3 Moment of Inertia	371
14.4 Calculation of Moments of Inertia	374
14.5 The Parallel-Axis Theorem	378
14.6 Energy and Work in Rigid-Body Rotation	381
14.7 Analogies Between Rotational and Translational Motion	383
14.8 The Physical Pendulum	384
14.9 The Torsion Pendulum	387
14.10 Combined Translations and Rotations	388
14.11 Kinematics of the Rolling Wheel	393
14.12 Rolling Down an Inclined Plane	394
14.13 Coriolis Forces	396
14.14 A Final Word	401
Problems	401

**Chapter 15 GYROSCOPES** 413

15.1 An Ancient Question	413
15.2 The Gyroscope	415
15.3 Angular Velocity of Precession	422
15.4 The Earth as a Gyroscope	425
15.5 A Final Word	426
Problems	427

**Chapter 16 KEPLER'S LAWS AND THE CONIC SECTIONS** 431

16.1 The Quest for Precision	431
16.2 Kepler's Laws	433
16.3 Conic Sections	437
16.4 The Ellipse	439
16.5 The Conics and Eccentricity	439
16.6 Properties of the Ellipse	442
16.7 Cartesian Equations for Conic Sections	446
16.8 A Final Word	448
Problems	448

**Chapter 17 SOLVING THE KEPLER PROBLEM 451**

17.1	Setting the Stage	451
17.2	Polar Coordinates and the Unit Vectors $\hat{r}$ and $\hat{\theta}$	452
17.3	Solution of the Kepler Problem	457
17.4	Celestial Omens: Comets	459
17.5	Energy and Eccentricity	460
17.6	Orbits and Eccentricity	461
17.7	Kepler's Third Law	463
17.8	Planetary Motion and Effective Potential	464
17.9	Applications of Orbital Dynamics	466
17.10	Calculating the Orbit From Initial Conditions	469
17.11	A Final Word	472
	Problems	473

**Chapter 18 NAVIGATING IN SPACE 477**

18.1	Freeways in the Sky	477
18.2	Navigating in Space	478
18.3	Transfer Orbits	480
18.4	Gravity Assist	485
18.5	A Final Word	487
	Problems	489

**Chapter 19 TEMPERATURE AND THE GAS LAWS 491**

19.1	Temperature and Pressure	491
19.2	The Gas Laws of Boyle, Charles, and Gay-Lussac	497
19.3	The Ideal-Gas Law	499
19.4	Temperature and Energy	500
19.5	A Final Word	501
	Problems	503

**Chapter 20 THE ENGINE OF NATURE 505**

20.1	The Age of Steam	505
20.2	Work and the Pressure-Volume Diagram	507
20.3	The First Law of Thermodynamics	512
20.4	Adiabatic and Isothermal Processes	515
20.5	The Second Law of Thermodynamics	519
20.6	The Carnot Engine	521
20.7	A Final Word	525
	Problems	526

<b>Chapter 21 ENTROPY</b>	<b>531</b>
21.1 Toward an Understanding of Entropy	531
21.2 Engines and Entropy	534
21.3 Entropy and the Second Law of Thermodynamics	539
21.4 An Implication of the Entropy Principle	541
21.5 A Final Word	544
Problems	544
<b>Chapter 22 THE QUEST FOR LOW TEMPERATURE</b>	<b>547</b>
22.1 Cooling Off	547
22.2 The States of Matter	548
22.3 Behavior of Water	551
22.4 Liquefaction of Gases	553
22.5 The Joule–Thomson Effect	557
22.6 A Final Word	559
Problems	560
<b>Appendix A THE INTERNATIONAL SYSTEM OF UNITS</b>	<b>563</b>
<b>Appendix B CONVERSION FACTORS</b>	<b>565</b>
<b>Appendix C FORMULAS FROM ALGEBRA, GEOMETRY, AND TRIGONOMETRY</b>	<b>569</b>
<b>Appendix D ASTRONOMICAL DATA</b>	<b>571</b>
<b>Appendix E PHYSICAL CONSTANTS</b>	<b>573</b>
<b>SELECTED BIBLIOGRAPHY</b>	<b>575</b>
<i>Index</i>	579