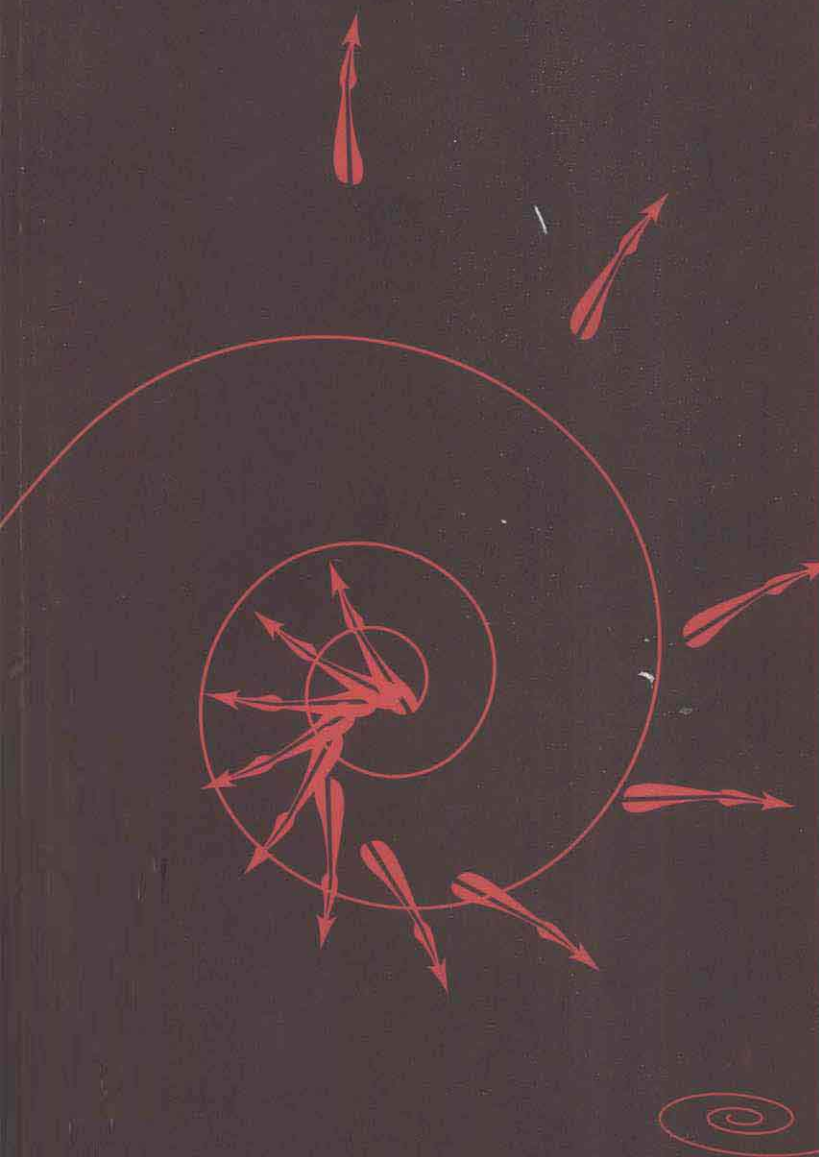


# Physics 2000

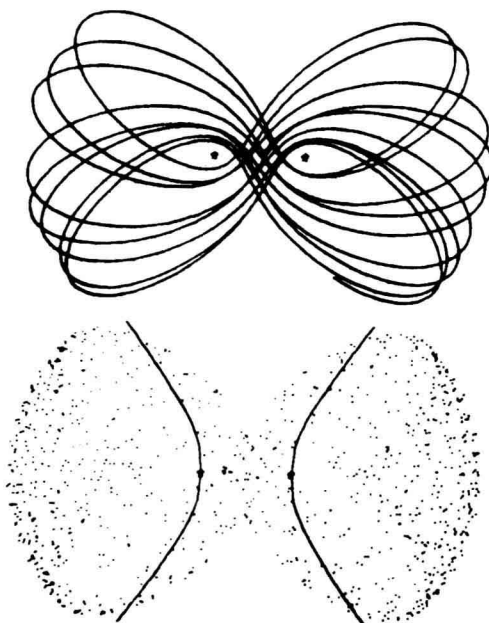
**E. R. Huggins**  
Dartmouth College

## **Part I** Mechanics, Waves & Particles



[physics2000.com](http://physics2000.com)

# ***Physics2000***



Student project by Bob Piela  
explaining the hydrogen  
molecule ion.

by E. R. Huggins  
Department of Physics  
Dartmouth College  
Hanover, New Hampshire

ISBN 0-9707836-0-4 (*Physics 2000* 2–PART SET + CD)  
ISBN 0-9707836-1-2 (*Physics 2000* PART 1 + CD)  
ISBN 0-9707836-2-0 (*Physics 2000* PART 2 + CD)  
ISBN 0-9707836-3-9 (*Physics 2000* CD)  
ISBN 0-9707836-4-7 (*Calculus 2000* + CD)  
ISBN 0-9707836-5-5 (*Physics 2000* Solutions)  
ISBN 0-9707836-6-3 (*Physics 2000* 2–PART SET + *Calculus 2000* + CD)

Copyright © 1999 **Moose Mountain Digital Press**  
Etna, New Hampshire 03750  
All rights reserved

## ABOUT THE *PHYSICS2000* CD

The *Physics2000* CD contains the complete color version of the *Physics2000* text in Acrobat™ form along with a supplementary chapter covering all the calculus needed for the text. Included on the CD is the 36 minute motion picture *Time Dilation - An Experiment With Mu-Mesons*, and short movie segments of various physics demonstrations. Also a short cookbook on several basic dishes of Caribbean cooking.

The CD is available, for \$10 postpaid, at the web site [www.physics2000.com](http://www.physics2000.com)

The black and white printed copy of the text, with the calculus chapter, is also available at the web site at a cost of \$25. That includes the CD and shipping within the United States.

## Use of the Text Material

Because we are trying to change the way physics is taught, Chapter 1 on special relativity, although copyrighted, may be used freely (except for the copyrighted photograph of Andromeda and frame of the muon film). All chapters may be printed and distributed to a class on a non profit basis.

## ABOUT THE AUTHOR

E. R. Huggins has taught physics at Dartmouth College since 1961. He was an undergraduate at MIT and got his Ph.D. at Caltech. His Ph.D. thesis under Richard Feynman was on aspects of the quantum theory of gravity and the non uniqueness of energy momentum tensors. Since then most of his research has been on superfluid dynamics and the development of new teaching tools like the student-built electron gun and MacScope™. He wrote the non calculus introductory physics text *Physics I* in 1968 and the computer based text *Graphical Mechanics* in 1973. The *Physics2000* text, which summarizes over thirty years of experimenting with ways to teach physics, was written and class tested over the period from 1990 to 1998. All the work of producing the text was done by the author, and his wife, Anne Huggins. The text layout and design was by the author's daughter Cleo Huggins who designed eWorld™ for Apple Computer and the Sonata™ music font for Adobe Systems.

The author's eMail address is

[lish.huggins@dartmouth.edu](mailto:lish.huggins@dartmouth.edu)

The author welcomes any comments.

## Preface

### ABOUT THE COURSE

Physics2000 is a calculus based, college level introductory physics course that is designed to include twentieth century physics throughout. This is made possible by introducing Einstein's special theory of relativity in the first chapter. This way, students start off with a modern picture of how space and time behave, and are prepared to approach topics such as mass and energy from a modern point of view.

The course, which was developed during 30 plus years working with premedical students at Dartmouth College, makes very gentle assumptions about the student's mathematical background. All the calculus needed for studying Physics2000 is contained in a supplementary chapter which is the first chapter of a *Physics Based Calculus* text. We can cover all the necessary calculus in one reasonable length chapter because the concepts are introduced in the physics text and the calculus chapter only needs to handle the formalism. (The remaining chapters of the calculus text introduce the mathematical tools and concepts used in advanced introductory courses for physics and engineering majors. These chapters will be available at [www.physics2000.com](http://www.physics2000.com) in late 2000.)

In the physics text, the concepts of velocity and acceleration are introduced through the use of strobe photographs in Chapter 3. How these definitions can be used to predict motion is discussed in Chapter 4 on calculus and Chapter 5 on the use of the computer.

Students themselves have made major contributions to the organization and content of the text. Student's enthusiasm for the use of Fourier analysis to study musical instruments led to the development of the MacScope™ program. The program makes it easy to use Fourier analysis to study such topics as the normal modes of a coupled aircart system and how the energy-

time form of the uncertainty principle arises from the particle-wave nature of matter.

Most students experience difficulty when they first encounter abstract concepts like vector fields and Gauss' law. To provide a familiar model for a vector field, we begin the section on electricity and magnetism with a chapter on fluid dynamics. It is easy to visualize the velocity field of a fluid, and Gauss' law is simply the statement that the fluid is incompressible. We then show that the electric field has mathematical properties similar to those of the velocity field.

The format of the standard calculus based introductory physics text is to put a chapter on special relativity following Maxwell's equations, and then put modern physics after that, usually in an extended edition. This format suggests that the mathematics required to understand special relativity may be even more difficult than the integral-differential equations encountered in Maxwell's theory. Such fears are enhanced by the strangeness of the concepts in special relativity, and are driven home by the fact that relativity appears at the end of the course where there is no time to comprehend it. This format is a disaster.

Special relativity does involve strange ideas, but the mathematics required is only the Pythagorean theorem. By placing relativity at the beginning of the course you let the students know that the mathematics is not difficult, and that there will be plenty of time to become familiar with the strange ideas. By the time students have gone through Maxwell's equations in *Physics2000*, they are thoroughly familiar with special relativity, and are well prepared to study the particle-wave nature of matter and the foundations of quantum mechanics. This material is not in an extended edition because there is time to cover it in a comfortably paced course.

# Table of Contents

## PART 1

### INTRODUCTION—AN OVERVIEW OF PHYSICS

|                                      |        |
|--------------------------------------|--------|
| Space And Time .....                 | int-2  |
| The Expanding Universe .....         | int-3  |
| Structure of Matter .....            | int-5  |
| Atoms .....                          | int-5  |
| Light .....                          | int-7  |
| Photons .....                        | int-8  |
| The Bohr Model .....                 | int-8  |
| Particle-Wave Nature of Matter ..... | int-10 |
| Conservation of Energy .....         | int-11 |
| Anti-Matter .....                    | int-12 |
| Particle Nature of Forces .....      | int-13 |
| Renormalization .....                | int-14 |
| Gravity .....                        | int-15 |
| A Summary .....                      | int-16 |
| The Nucleus .....                    | int-17 |
| Stellar Evolution .....              | int-19 |
| The Weak Interaction .....           | int-20 |
| Leptons .....                        | int-21 |
| Nuclear Structure .....              | int-22 |
| A Confusing Picture .....            | int-22 |
| Quarks .....                         | int-24 |
| The Electroweak Theory .....         | int-26 |
| The Early Universe .....             | int-27 |
| The Thermal Photons .....            | int-29 |

### CHAPTER 1 PRINCIPLE OF RELATIVITY 1-1

|  |      |
|--|------|
| The Principle of Relativity .....              | 1-2  |
| A Thought Experiment .....                     | 1-3  |
| Statement of the Principle of Relativity ..... | 1-4  |
| Basic Law of Physics .....                     | 1-4  |
| Wave Motion .....                              | 1-6  |
| Measurement of the Speed of Waves .....        | 1-7  |
| Michaelson-Morley Experiment .....             | 1-11 |
| Einstein's Principle of Relativity .....       | 1-12 |
| The Special Theory of Relativity .....         | 1-13 |
| Moving Clocks .....                            | 1-13 |
| Other Clocks .....                             | 1-18 |
| Real Clocks .....                              | 1-20 |
| Time Dilation .....                            | 1-22 |
| Space Travel .....                             | 1-22 |
| The Lorentz Contraction .....                  | 1-24 |
| Relativistic Calculations .....                | 1-28 |
| Approximation Formulas .....                   | 1-30 |
| A Consistent Theory .....                      | 1-32 |
| Lack of Simultaneity .....                     | 1-32 |
| Causality .....                                | 1-36 |
| Appendix A .....                               | 1-39 |
| Class Handout .....                            | 1-39 |

### CHAPTER 2 VECTORS

|   |      |
|---|------|
| Vectors .....                                 | 2-2  |
| Displacement Vectors .....                    | 2-2  |
| Arithmetic of Vectors .....                   | 2-3  |
| Rules for Number Arithmetic .....             | 2-4  |
| Rules for Vector Arithmetic .....             | 2-4  |
| Multiplication of a Vector by a Number .....  | 2-5  |
| Magnitude of a Vector .....                   | 2-6  |
| Vector Equations .....                        | 2-6  |
| Graphical Work .....                          | 2-6  |
| Components .....                              | 2-8  |
| Vector Equations in Component Form .....      | 2-10 |
| Vector Multiplication .....                   | 2-11 |
| The Scalar or Dot Product .....               | 2-12 |
| Interpretation of the Dot Product .....       | 2-14 |
| Vector Cross Product .....                    | 2-15 |
| Magnitude of the Cross Product .....          | 2-17 |
| Component Formula for the Cross Product ..... | 2-17 |
| Right Handed Coordinate System .....          | 2-18 |

### CHAPTER 3 DESCRIPTION OF MOTION

|   |      |
|---|------|
| Displacement Vectors .....                              | 3-5  |
| A Coordinate System .....                               | 3-7  |
| Manipulation of Vectors .....                           | 3-8  |
| Measuring the Length of a Vector .....                  | 3-9  |
| Coordinate System and Coordinate Vectors .....          | 3-11 |
| Analysis of Strobe Photographs .....                    | 3-11 |
| Velocity .....  | 3-11 |
| Acceleration .....                                      | 3-13 |
| Determining Acceleration                                |      |
| from a Strobe Photograph .....                          | 3-15 |
| The Acceleration Vector .....                           | 3-15 |
| Projectile Motion .....                                 | 3-16 |
| Uniform Circular Motion .....                           | 3-17 |
| Magnitude of the Acceleration for Circular Motion ..... | 3-18 |
| An Intuitive Discussion of Acceleration .....           | 3-20 |
| Acceleration Due to Gravity .....                       | 3-21 |
| Projectile Motion with Air Resistance .....             | 3-22 |
| Instantaneous Velocity .....                            | 3-24 |
| Instantaneous Velocity from a Strobe Photograph .....   | 3-26 |

**CHAPTER 4 CALCULUS IN PHYSICS**

|   |      |
|---|------|
| Limiting Process .....  | 4-1  |
| The Uncertainty Principle .....                                 | 4-1  |
| Calculus Definition of Velocity .....                           | 4-3  |
| Acceleration .....  | 4-5  |
| Components .....  | 4-6  |
| Distance, Velocity and<br>Acceleration versus Time Graphs ..... | 4-7  |
| The Constant Acceleration Formulas .....                        | 4-9  |
| Three Dimensions .....  | 4-11 |
| Projectile Motion with Air Resistance .....                     | 4-12 |
| Differential Equations .....                                    | 4-14 |
| Solving the Differential Equation .....                         | 4-14 |
| Solving Projectile Motion Problems .....                        | 4-16 |
| Checking Units .....  | 4-19 |

**CHAPTER 5 COMPUTER PREDICTION OF MOTION**

|  |      |
|--|------|
| Step-By-Step Calculations .....                | 5-1  |
| Computer Calculations .....                    | 5-2  |
| Calculating and Plotting a Circle .....        | 5-2  |
| Program for Calculation .....                  | 5-4  |
| The DO LOOP .....                              | 5-4  |
| The LET Statement .....                        | 5-5  |
| Variable Names .....                           | 5-6  |
| Multiplication .....                           | 5-6  |
| Plotting a Point .....                         | 5-6  |
| Comment Lines .....                            | 5-7  |
| Plotting Window .....                          | 5-7  |
| Practice .....                                 | 5-8  |
| Selected Printing (MOD Command) .....          | 5-10 |
| Prediction of Motion .....                     | 5-12 |
| Time Step and Initial Conditions .....         | 5-14 |
| An English Program for Projectile Motion ..... | 5-16 |
| A BASIC Program for Projectile Motion .....    | 5-18 |
| Projectile Motion with Air Resistance .....    | 5-22 |
| Air Resistance Program .....                   | 5-24 |

**CHAPTER 6 MASS**

|                                       |      |
|---------------------------------------|------|
| Definition of Mass .....              | 6-2  |
| Recoil Experiments .....              | 6-2  |
| Properties of Mass .....              | 6-3  |
| Standard Mass .....                   | 6-3  |
| Addition of Mass .....                | 6-4  |
| A Simpler Way to Measure Mass .....   | 6-4  |
| Inertial and Gravitational Mass ..... | 6-5  |
| Mass of a Moving Object .....         | 6-5  |
| Relativistic Mass .....               | 6-6  |
| Beta ( $\beta$ ) Decay .....          | 6-6  |
| Electron Mass in $\beta$ Decay .....  | 6-7  |
| Plutonium 246 .....                   | 6-8  |
| Protactinium 236 .....                | 6-9  |
| The Einstein Mass Formula .....       | 6-10 |
| Nature's Speed Limit .....            | 6-11 |
| Zero Rest Mass Particles .....        | 6-11 |
| Neutrinos .....                       | 6-13 |
| Solar Neutrinos .....                 | 6-13 |
| Neutrino Astronomy .....              | 6-14 |

**CHAPTER 7 CONSERVATION OF LINEAR & ANGULAR MOMENTUM**

|   |      |
|---|------|
| Conservation of Linear Momentum .....               | 7-2  |
| Collision Experiments .....                         | 7-4  |
| Subatomic Collisions .....                          | 7-7  |
| Example 1 Rifle and Bullet .....                    | 7-7  |
| Example 2 .....                                     | 7-8  |
| Conservation of Angular Momentum .....              | 7-9  |
| A More General Definition of Angular Momentum ..... | 7-12 |
| Angular Momentum as a Vector .....                  | 7-14 |
| Formation of Planets .....                          | 7-17 |

**CHAPTER 8 NEWTONIAN MECHANICS**

|   |      |
|---|------|
| Force .....                                   | 8-2  |
| The Role of Mass .....                        | 8-3  |
| Newton's Second Law .....                     | 8-4  |
| Newton's Law of Gravity .....                 | 8-5  |
| Big Objects .....                             | 8-5  |
| Galileo's Observation .....                   | 8-6  |
| The Cavendish Experiment .....                | 8-7  |
| "Weighing" the Earth .....                    | 8-8  |
| Inertial and Gravitational Mass .....         | 8-8  |
| Satellite Motion .....                        | 8-8  |
| Other Satellites .....                        | 8-10 |
| Weight .....                                  | 8-11 |
| Earth Tides .....                             | 8-12 |
| Planetary Units .....                         | 8-14 |
| Table 1 Planetary Units .....                 | 8-14 |
| Computer Prediction of Satellite Orbits ..... | 8-16 |
| New Calculational Loop .....                  | 8-17 |
| Unit Vectors .....                            | 8-18 |
| Calculational Loop for Satellite Motion ..... | 8-19 |
| Summary .....                                 | 8-20 |
| Working Orbit Program .....                   | 8-20 |
| Projectile Motion Program .....               | 8-21 |
| Orbit-1 Program .....                         | 8-21 |
| Satellite Motion Laboratory .....             | 8-23 |
| Kepler's Laws .....                           | 8-24 |
| Kepler's First Law .....                      | 8-26 |
| Kepler's Second Law .....                     | 8-27 |
| Kepler's Third Law .....                      | 8-28 |
| Modified Gravity and General Relativity ..... | 8-29 |
| Conservation of Angular Momentum .....        | 8-32 |
| Conservation of Energy .....                  | 8-35 |

## CHAPTER 9 APPLICATIONS OF NEWTON'S SECOND LAW

|  |      |
|--|------|
| Addition of Forces .....                           | 9-2  |
| Spring Forces .....                                | 9-3  |
| The Spring Pendulum .....                          | 9-4  |
| Computer Analysis of the Ball Spring Pendulum .... | 9-8  |
| The Inclined Plane .....                           | 9-10 |
| Friction .....                                     | 9-12 |
| Inclined Plane with Friction .....                 | 9-12 |
| Coefficient of Friction .....                      | 9-13 |
| String Forces .....                                | 9-15 |
| The Atwood's Machine .....                         | 9-16 |
| The Conical Pendulum .....                         | 9-18 |
| Appendix The ball spring Program .....             | 9-20 |

## CHAPTER 10 ENERGY

|   |       |
|---|-------|
| Conservation of Energy .....                          | 10-2  |
| Mass Energy .....                                     | 10-3  |
| Ergs and Joules .....                                 | 10-4  |
| Kinetic Energy .....                                  | 10-5  |
| Example 1 .....                                       | 10-5  |
| Slowly Moving Particles .....                         | 10-6  |
| Gravitational Potential Energy .....                  | 10-8  |
| Example 2 .....                                       | 10-10 |
| Example 3 .....                                       | 10-11 |
| Work .....  | 10-12 |
| The Dot Product .....                                 | 10-13 |
| Work and Potential Energy .....                       | 10-14 |
| Non-Constant Forces .....                             | 10-14 |
| Potential Energy Stored in a Spring .....             | 10-16 |
| Work Energy Theorem .....                             | 10-18 |
| Several Forces .....                                  | 10-19 |
| Conservation of Energy .....                          | 10-20 |
| Conservative and Non-Conservative Forces .....        | 10-21 |
| Gravitational Potential Energy on a Large Scale ..... | 10-22 |
| Zero of Potential Energy .....                        | 10-22 |
| Gravitational Potential Energy in a Room .....        | 10-25 |
| Satellite Motion and Total Energy .....               | 10-26 |
| Example 4 Escape Velocity .....                       | 10-28 |
| Black Holes .....                                     | 10-29 |
| A Practical System of Units .....                     | 10-31 |

## CHAPTER 11 SYSTEMS OF PARTICLES

|  |       |
|--|-------|
| Center of Mass .....                               | 11-2  |
| Center of Mass Formula .....                       | 11-3  |
| Dynamics of the Center of Mass .....               | 11-4  |
| Newton's Third Law .....                           | 11-6  |
| Conservation of Linear Momentum .....              | 11-7  |
| Momentum Version of Newton's Second Law .....      | 11-8  |
| Collisions .....                                   | 11-9  |
| Impulse .....                                      | 11-9  |
| Calibration of the Force Detector .....            | 11-10 |
| The Impulse Measurement .....                      | 11-11 |
| Change in Momentum .....                           | 11-12 |
| Momentum Conservation during Collisions .....      | 11-13 |
| Collisions and Energy Loss .....                   | 11-14 |
| Collisions that Conserve Momentum and Energy ..... | 11-16 |
| Elastic Collisions .....                           | 11-17 |
| Discovery of the Atomic Nucleus .....              | 11-19 |
| Neutrinos .....                                    | 11-20 |
| Neutrino Astronomy .....                           | 11-21 |

## CHAPTER 12 ROTATIONAL MOTION

|   |       |
|---|-------|
| Radian Measure .....  | 12-2  |
| Angular Velocity .....  | 12-2  |
| Angular Acceleration .....  | 12-3  |
| Angular Analogy .....   | 12-3  |
| Tangential Distance, Velocity and Acceleration ...                | 12-4  |
| Radial Acceleration .....   | 12-5  |
| Bicycle Wheel .....   | 12-5  |
| Angular Momentum .....  | 12-6  |
| Angular Momentum of a Bicycle Wheel .....                         | 12-6  |
| Angular Velocity as a Vector .....                                | 12-7  |
| Angular Momentum as a Vector .....                                | 12-7  |
| Angular Mass or Moment of Inertia .....                           | 12-7  |
| Calculating Moments of Inertia .....                              | 12-8  |
| Vector Cross Product .....  | 12-9  |
| Right Hand Rule for Cross Products .....                          | 12-10 |
| Cross Product Definition of Angular Momentum .....                | 12-11 |
| The $\vec{r} \times \vec{p}$ Definition of Angular Momentum ..... | 12-12 |
| Angular Analogy to Newton's Second Law .....                      | 12-14 |
| About Torque .....  | 12-15 |
| Conservation of Angular Momentum .....                            | 12-16 |
| Gyroscopes .....  | 12-18 |
| Start-up .....  | 12-18 |
| Precession .....  | 12-19 |
| Rotational Kinetic Energy .....                                   | 12-22 |
| Combined Translation and Rotation .....                           | 12-24 |
| Example—Objects Rolling .....                                     | 12-25 |
| Down an Inclined Plane .....                                      | 12-25 |
| Proof of the Kinetic Energy Theorem .....                         | 12-26 |



## CHAPTER 13 EQUILIBRIUM

|  |       |
|--|-------|
| Equations for equilibrium .....                        | 13-2  |
| Example 1 Balancing Weights .....                      | 13-2  |
| Gravitational Force acting at the Center of Mass ..... | 13-4  |
| Technique of Solving Equilibrium Problems .....        | 13-5  |
| Example 3 Wheel and Curb .....                         | 13-5  |
| Example 4 Rod in a Frictionless Bowl .....             | 13-7  |
| Example 5 A Bridge Problem .....                       | 13-9  |
| Lifting Weights and Muscle Injuries .....              | 13-11 |

## CHAPTER 14 OSCILLATIONS AND RESONANCE

|   |       |
|---|-------|
| Oscillatory Motion .....  | 14-2  |
| The Sine Wave .....   | 14-3  |
| Phase of an Oscillation .....   | 14-6  |
| Mass on a Spring; Analytic Solution .....   | 14-7  |
| Conservation of Energy .....  | 14-11 |
| The Harmonic Oscillator .....   | 14-12 |
| The Torsion Pendulum .....  | 14-12 |
| The Simple Pendulum .....   | 14-15 |
| Small Oscillations .....  | 14-16 |
| Simple and Conical Pendulums .....  | 14-17 |
| Non Linear Restoring Forces .....   | 14-19 |
| Molecular Forces .....  | 14-20 |
| Damped Harmonic Motion .....  | 14-21 |
| Critical Damping .....  | 14-23 |
| Resonance .....   | 14-24 |
| Resonance Phenomena .....   | 14-26 |
| Transients .....  | 14-27 |
| Appendix 14-1 Solution of the Differential Equation<br>for Forced Harmonic Motion ..... | 14-28 |
| Appendix 14-2 Computer analysis<br>of oscillatory motion .....                          | 14-30 |
| English Program .....   | 14-31 |
| The BASIC Program .....   | 14-32 |
| Damped Harmonic Motion .....  | 14-34 |

## CHAPTER 15 ONE DIMENSIONAL WAVE MOTION 15-1

|   |       |
|---|-------|
| Wave Pulses .....                       | 15-3  |
| Speed of a Wave Pulse .....             | 15-4  |
| Dimensional Analysis .....              | 15-6  |
| Speed of Sound Waves .....              | 15-8  |
| Linear and nonlinear Wave Motion .....  | 15-10 |
| The Principle of Superposition .....    | 15-11 |
| Sinusoidal Waves .....                  | 15-12 |
| Wavelength, Period, and Frequency ..... | 15-13 |
| Angular Frequency $\omega$ .....        | 15-14 |
| Spacial Frequency $k$ .....             | 15-14 |
| Traveling Wave Formula .....            | 15-16 |
| Phase and Amplitude .....               | 15-17 |
| Standing Waves .....                    | 15-18 |
| Waves on a Guitar String .....          | 15-20 |
| Frequency of Guitar String Waves .....  | 15-21 |
| Sound Produced by a Guitar String ..... | 15-22 |

## CHAPTER 16 FOURIER ANALYSIS, NORMAL MODES AND SOUND

|   |       |
|---|-------|
| Harmonic Series .....                         | 16-3  |
| Normal Modes of Oscillation .....             | 16-4  |
| Fourier Analysis .....                        | 16-6  |
| Analysis of a Sine Wave .....                 | 16-7  |
| Analysis of a Square Wave .....               | 16-9  |
| Repeated Wave Forms .....                     | 16-11 |
| Analysis of the Coupled Air Cart System ..... | 16-12 |
| The Human Ear .....                           | 16-15 |
| Stringed Instruments .....                    | 16-18 |
| Wind Instruments .....                        | 16-20 |
| Percussion Instruments .....                  | 16-22 |
| Sound Intensity .....                         | 16-24 |
| Bells and Decibels .....                      | 16-24 |
| Sound Meters .....                            | 16-26 |
| Speaker Curves .....                          | 16-27 |
| Appendix A Fourier Analysis Lecture .....     | 16-28 |
| Square Wave .....                             | 16-28 |
| Calculating Fourier Coefficients .....        | 16-28 |
| Amplitude and Phase .....                     | 16-31 |
| Amplitude and Intensity .....                 | 16-33 |
| Appendix B Inside the Cochlea .....           | 16-34 |

## CHAPTER 17 ATOMS, MOLECULES AND ATOMIC PROCESSES

|  |       |
|--|-------|
| Molecules .....  | 17-2  |
| Atomic Processes .....                                   | 17-4  |
| Thermal Motion .....                                     | 17-6  |
| Thermal Equilibrium .....                                | 17-8  |
| Temperature .....  | 17-9  |
| Absolute Zero .....                                      | 17-9  |
| Temperature Scales .....                                 | 17-10 |
| Molecular Forces .....                                   | 17-12 |
| Evaporation .....  | 17-14 |
| Pressure .....   | 17-16 |
| Stellar Evolution .....                                  | 17-17 |
| The Ideal Gas Law .....                                  | 17-18 |
| Ideal Gas Thermometer .....                              | 17-20 |
| The Mercury Barometer<br>and Pressure Measurements ..... | 17-22 |
| Avogadro's Law .....                                     | 17-24 |
| Heat Capacity .....                                      | 17-26 |
| Specific Heat .....                                      | 17-26 |
| Molar Heat Capacity .....                                | 17-26 |
| Molar Specific Heat of Helium Gas .....                  | 17-27 |
| Other Gases .....  | 17-27 |
| Equipartition of Energy .....                            | 17-28 |
| Real Molecules .....                                     | 17-30 |
| Failure of Classical Physics .....                       | 17-31 |
| Freezing Out of Degrees of Freedom .....                 | 17-32 |
| Thermal Expansion .....                                  | 17-33 |
| Osmotic Pressure .....                                   | 17-34 |
| Elasticity of Rubber .....                               | 17-35 |
| A Model of Rubber .....                                  | 17-36 |

**CHAPTER 18 ENTROPY**

|  |       |
|--|-------|
| Introduction .....                           | 18-2  |
| Work Done by an Expanding Gas .....          | 18-5  |
| Specific Heats $c_v$ and $c_p$ .....         | 18-6  |
| Isothermal Expansion and PV Diagrams .....   | 18-8  |
| Isothermal Compression .....                 | 18-9  |
| Isothermal Expansion of an Ideal Gas .....   | 18-9  |
| Adiabatic Expansion .....                    | 18-9  |
| The Carnot Cycle .....                       | 18-11 |
| Thermal Efficiency of the Carnot Cycle ..... | 18-12 |
| Reversible Engines .....                     | 18-13 |
| Energy Flow Diagrams .....                   | 18-15 |
| Maximally Efficient Engines .....            | 18-15 |
| Reversibility .....                          | 18-17 |
| Applications of the Second Law .....         | 18-17 |
| Electric Cars .....                          | 18-19 |
| The Heat Pump .....                          | 18-19 |
| The Internal Combustion Engine .....         | 18-21 |
| Entropy .....                                | 18-22 |
| The Direction of Time .....                  | 18-25 |
| Appendix: Calculation of the Efficiency      |       |
| of a Carnot Cycle .....                      | 18-26 |
| Isothermal Expansion .....                   | 18-26 |
| Adiabatic Expansion .....                    | 18-26 |
| The Carnot Cycle .....                       | 18-28 |

**CHAPTER 19 THE ELECTRIC INTERACTION**

|  |       |
|--|-------|
| The Four Basic Interactions .....                  | 19-1  |
| Atomic Structure .....                             | 19-3  |
| Isotopes .....                                     | 19-6  |
| The Electric Force Law .....                       | 19-7  |
| Strength of the Electric Interaction .....         | 19-8  |
| Electric Charge .....                              | 19-8  |
| Positive and Negative Charge .....                 | 19-10 |
| Addition of Charge .....                           | 19-10 |
| Conservation of Charge .....                       | 19-13 |
| Stability of Matter .....                          | 19-14 |
| Quantization of Electric Charge .....              | 19-14 |
| Molecular Forces .....                             | 19-15 |
| Hydrogen Molecule .....                            | 19-16 |
| Molecular Forces—A More Quantitative Look .....    | 19-18 |
| The Bonding Region .....                           | 19-19 |
| Electron Binding Energy .....                      | 19-20 |
| Electron Volt as a Unit of Energy .....            | 19-21 |
| Electron Energy in the Hydrogen Molecule Ion ..... | 19-21 |

**CHAPTER 20 NUCLEAR MATTER**

|   |       |
|---|-------|
| Nuclear Force .....                     | 20-2  |
| Range of the Nuclear Force .....        | 20-3  |
| Nuclear Fission .....                   | 20-3  |
| Neutrons and the Weak Interaction ..... | 20-6  |
| Nuclear Structure .....                 | 20-7  |
| $\alpha$ (Alpha) Particles .....        | 20-8  |
| Nuclear Binding Energies .....          | 20-9  |
| Nuclear Fusion .....                    | 20-12 |
| Stellar Evolution .....                 | 20-13 |
| Neutron Stars .....                     | 20-17 |
| Neutron Stars                           |       |
| and Black Holes .....                   | 20-18 |

## PART 2

### CHAPTER 23 FLUID DYNAMICS

|   |       |
|---|-------|
| The Current State of Fluid Dynamics .....   | 23-1  |
| The Velocity Field .....                    | 23-2  |
| The Vector Field .....                      | 23-3  |
| Streamlines .....                           | 23-4  |
| Continuity Equation .....                   | 23-5  |
| Velocity Field of a Point Source .....      | 23-6  |
| Velocity Field of a Line Source .....       | 23-7  |
| Flux .....                                  | 23-8  |
| Bernoulli's Equation .....                  | 23-9  |
| Applications of Bernoulli's Equation .....  | 23-12 |
| Hydrostatics .....                          | 23-12 |
| Leaky Tank .....                            | 23-12 |
| Airplane Wing .....                         | 23-13 |
| Sailboats .....                             | 23-14 |
| The Venturi Meter .....                     | 23-15 |
| The Aspirator .....                         | 23-16 |
| Care in Applying Bernoulli's Equation ..... | 23-16 |
| Hydrodynamic Voltage .....                  | 23-17 |
| Town Water Supply .....                     | 23-18 |
| Viscous Effects .....                       | 23-19 |
| Vortices .....                              | 23-20 |
| Quantized Vortices in Superfluids .....     | 23-22 |

### CHAPTER 24 COULOMB'S LAW AND GAUSS' LAW

|   |       |
|---|-------|
| Coulomb's Law .....                           | 24-1  |
| CGS Units .....                               | 24-2  |
| MKS Units .....                               | 24-2  |
| Checking Units in MKS Calculations .....      | 24-3  |
| Summary .....                                 | 24-3  |
| Example 1 Two Charges .....                   | 24-3  |
| Example 2 Hydrogen Atom .....                 | 24-4  |
| Force Produced by a Line Charge .....         | 24-6  |
| Short Rod .....                               | 24-9  |
| The Electric Field .....                      | 24-10 |
| Unit Test Charge .....                        | 24-11 |
| Electric Field lines .....                    | 24-12 |
| Mapping the Electric Field .....              | 24-12 |
| Field Lines .....                             | 24-13 |
| Continuity Equation for Electric Fields ..... | 24-14 |
| Flux .....                                    | 24-15 |
| Negative Charge .....                         | 24-16 |
| Flux Tubes .....                              | 24-17 |
| Conserved Field Lines .....                   | 24-17 |
| A Mapping Convention .....                    | 24-17 |
| Summary .....                                 | 24-18 |
| A Computer Plot .....                         | 24-19 |

|   |       |
|---|-------|
| Gauss' Law .....                              | 24-20 |
| Electric Field of a Line Charge .....         | 24-21 |
| Flux Calculations .....                       | 24-22 |
| Area as a Vector .....                        | 24-22 |
| Gauss' Law for the Gravitational Field .....  | 24-23 |
| Gravitational Field of a Point Mass .....     | 24-23 |
| Gravitational Field of a Spherical Mass ..... | 24-24 |
| Gravitational Field Inside the Earth .....    | 24-24 |
| Solving Gauss' Law Problems .....             | 24-26 |
| Problem Solving .....                         | 24-29 |

### CHAPTER 25 FIELD PLOTS AND ELECTRIC POTENTIAL

|  |       |
|--|-------|
| The Contour Map .....                        | 25-1  |
| Equipotential Lines .....                    | 25-3  |
| Negative and Positive Potential Energy ..... | 25-4  |
| Electric Potential of a Point Charge .....   | 25-5  |
| Conservative Forces .....                    | 25-5  |
| Electric Voltage .....                       | 25-6  |
| A Field Plot Model .....                     | 25-10 |
| Computer Plots .....                         | 25-12 |

### CHAPTER 26 ELECTRIC FIELDS AND CONDUCTORS

|   |       |
|---|-------|
| Electric Field                                |       |
| Inside a Conductor .....                      | 26-1  |
| Surface Charges .....                         | 26-2  |
| Surface Charge Density .....                  | 26-3  |
| Example: Field in a Hollow Metal Sphere ..... | 26-4  |
| Van de Graaff generator .....                 | 26-6  |
| Electric Discharge .....                      | 26-7  |
| Grounding .....                               | 26-8  |
| The Electron Gun .....                        | 26-8  |
| The Filament .....                            | 26-9  |
| Accelerating Field .....                      | 26-10 |
| A Field Plot .....                            | 26-10 |
| Equipotential Plot .....                      | 26-11 |
| Electron Volt                                 |       |
| as a Unit of Energy .....                     | 26-12 |
| Example .....                                 | 26-13 |
| About Computer Plots .....                    | 26-13 |
| The Parallel Plate Capacitor .....            | 26-14 |
| Deflection Plates .....                       | 26-16 |

**CHAPTER 27 BASIC ELECTRIC CIRCUITS**

|   |        |
|---|--------|
| Electric Current .....                              | 27- 2  |
| Positive and Negative Currents .....                | 27- 3  |
| A Convention .....                                  | 27- 5  |
| Current and Voltage .....                           | 27- 6  |
| Resistors .....                                     | 27- 6  |
| A Simple Circuit .....                              | 27- 8  |
| The Short Circuit .....                             | 27- 9  |
| Power .....   | 27- 9  |
| Kirchoff's Law .....                                | 27- 10 |
| Application of Kirchoff's Law .....                 | 27- 11 |
| Series Resistors .....                              | 27- 11 |
| Parallel Resistors .....                            | 27- 12 |
| Capacitance and Capacitors .....                    | 27- 14 |
| Hydrodynamic Analogy .....                          | 27- 14 |
| Cylindrical Tank as a Constant Voltage Source ..... | 27- 15 |
| Electrical Capacitance .....                        | 27- 16 |
| Energy Storage in Capacitors .....                  | 27- 18 |
| Energy Density in an Electric Field .....           | 27- 19 |
| Capacitors as Circuit Elements .....                | 27- 20 |
| The RC Circuit .....                                | 27- 22 |
| Exponential Decay .....                             | 27- 23 |
| The Time Constant RC .....                          | 27- 24 |
| Half-Lives .....                                    | 27- 25 |
| Initial Slope .....                                 | 27- 25 |
| The Exponential Rise .....                          | 27- 26 |
| The Neon Bulb Oscillator .....                      | 27- 28 |
| The Neon Bulb .....                                 | 27- 28 |
| The Neon Oscillator Circuit .....                   | 27- 29 |
| Period of Oscillation .....                         | 27- 30 |
| Experimental Setup .....                            | 27- 31 |

**CHAPTER 28 MAGNETISM**

|  |        |
|--|--------|
| Two Garden Peas .....                  | 28- 2  |
| A Thought Experiment .....             | 28- 4  |
| Charge Density on the Two Rods .....   | 28- 6  |
| A Proposed Experiment .....            | 28- 7  |
| Origin of Magnetic Forces .....        | 28- 8  |
| Magnetic Forces .....                  | 28- 10 |
| Magnetic Force Law .....               | 28- 10 |
| The Magnetic Field $B$ .....           | 28- 10 |
| Direction of the Magnetic Field .....  | 28- 11 |
| The Right Hand Rule for Currents ..... | 28- 13 |
| Parallel Currents Attract .....        | 28- 14 |
| The Magnetic Force Law .....           | 28- 14 |
| Lorentz Force Law .....                | 28- 15 |
| Dimensions of the                      |        |
| Magnetic Field, Tesla and Gauss .....  | 28- 16 |
| Uniform Magnetic Fields .....          | 28- 16 |
| Helmholtz Coils .....                  | 28- 18 |

|  |        |
|--|--------|
| Motion of Charged Particles in Magnetic Fields ..... | 28- 19 |
| Motion in a Uniform Magnetic Field .....             | 28- 20 |
| Particle Accelerators .....                          | 28- 22 |
| Relativistic Energy and Momenta .....                | 28- 24 |
| Bubble Chambers .....                                | 28- 26 |
| The Mass Spectrometer .....                          | 28- 28 |
| Magnetic Focusing .....                              | 28- 29 |
| Space Physics .....                                  | 28- 31 |
| The Magnetic Bottle .....                            | 28- 31 |
| Van Allen Radiation Belts .....                      | 28- 32 |

**CHAPTER 29 AMPERE'S LAW**

|  |       |
|--|-------|
| The Surface Integral .....                 | 29-2  |
| Gauss' Law .....                           | 29-3  |
| The Line Integral .....                    | 29-5  |
| Ampere's Law .....                         | 29-7  |
| Several Wires .....                        | 29-10 |
| Field of a Straight Wire .....             | 29-11 |
| Field of a Solenoid .....                  | 29-14 |
| Right Hand Rule for Solenoids .....        | 29-14 |
| Evaluation of the Line Integral .....      | 29-15 |
| Calculation of $i_{\text{enclosed}}$ ..... | 29-15 |
| Using Ampere's law .....                   | 29-15 |
| One More Right Hand Rule .....             | 29-16 |
| The Toroid .....                           | 29-17 |

**CHAPTER 30 FARADAY'S LAW**

|  |       |
|--|-------|
| Electric Field   |       |
| of Static Charges .....                                | 30-2  |
| A Magnetic Force Experiment .....                      | 30-3  |
| Air Cart Speed Detector .....                          | 30-5  |
| A Relativity Experiment .....                          | 30-9  |
| Faraday's Law .....                                    | 30-11 |
| Magnetic Flux .....                                    | 30-11 |
| One Form of Faraday's Law .....                        | 30-12 |
| A Circular Electric Field .....                        | 30-13 |
| Line Integral of $\vec{E}$ around a Closed Path .....  | 30-14 |
| Using Faraday's Law .....                              | 30-15 |
| Electric Field of an Electromagnet .....               | 30-15 |
| Right Hand Rule for Faraday's Law .....                | 30-15 |
| Electric Field of Static Charges .....                 | 30-16 |
| The Betatron .....                                     | 30-16 |
| Two Kinds of Fields .....                              | 30-18 |
| Note on our $\oint \vec{E} \cdot d\vec{l}$ meter ..... | 30-20 |
| Applications of Faraday's Law .....                    | 30-21 |
| The AC Voltage Generator .....                         | 30-21 |
| Gaussmeter .....                                       | 30-23 |
| A Field Mapping Experiment .....                       | 30-24 |

## CHAPTER 31 INDUCTION AND MAGNETIC MOMENT

|  |       |
|--|-------|
| The Inductor .....                                 | 31-2  |
| Direction of the Electric Field .....              | 31-3  |
| Induced Voltage .....                              | 31-4  |
| Inductance .....                                   | 31-5  |
| Inductor as a Circuit Element .....                | 31-7  |
| The LR Circuit .....                               | 31-8  |
| The LC Circuit .....                               | 31-10 |
| Intuitive Picture of the LC Oscillation .....      | 31-12 |
| The LC Circuit Experiment .....                    | 31-13 |
| Measuring the Speed of Light .....                 | 31-15 |
| Magnetic Moment .....                              | 31-18 |
| Magnetic Force on a Current .....                  | 31-18 |
| Torque on a Current Loop .....                     | 31-20 |
| Magnetic Moment .....                              | 31-21 |
| Magnetic Energy .....                              | 31-22 |
| Summary of Magnetic Moment Equations .....         | 31-24 |
| Charge $q$ in a Circular Orbit .....               | 31-24 |
| Iron Magnets .....                                 | 31-26 |
| The Electromagnet .....                            | 31-28 |
| The Iron Core Inductor .....                       | 31-29 |
| Superconducting Magnets .....                      | 31-30 |
| Appendix The LC circuit and Fourier Analysis ..... | 31-31 |

## CHAPTER 32 MAXWELL'S EQUATIONS

|   |        |
|---|--------|
| Gauss' Law for Magnetic Fields .....                          | 32- 2  |
| Maxwell's Correction to Ampere's Law .....                    | 32- 4  |
| Example: Magnetic Field<br>between the Capacitor Plates ..... | 32- 6  |
| Maxwell's Equations .....                                     | 32- 8  |
| Symmetry of Maxwell's Equations .....                         | 32- 9  |
| Maxwell's Equations in Empty Space .....                      | 32- 10 |
| A Radiated Electromagnetic Pulse .....                        | 32- 10 |
| A Thought Experiment .....                                    | 32- 11 |
| Speed of an Electromagnetic Pulse .....                       | 32- 14 |
| Electromagnetic Waves .....                                   | 32- 18 |
| Electromagnetic Spectrum .....                                | 32- 20 |
| Components of the Electromagnetic Spectrum .....              | 32- 20 |
| Blackbody Radiation .....                                     | 32- 22 |
| UV, X Rays, and Gamma Rays .....                              | 32- 22 |
| Polarization .....  | 32- 23 |
| Polarizers .....  | 32- 24 |
| Magnetic Field Detector .....                                 | 32- 26 |
| Radiated Electric Fields .....                                | 32- 28 |
| Field of a Point Charge .....                                 | 32- 30 |

## CHAPTER 33 LIGHT WAVES

|   |       |
|---|-------|
| Superposition of Circular Wave Patterns .....     | 33-2  |
| Huygens Principle .....                           | 33-4  |
| Two Slit Interference Pattern .....               | 33-6  |
| The First Maxima .....                            | 33-8  |
| Two Slit Pattern for Light .....                  | 33-10 |
| The Diffraction Grating .....                     | 33-12 |
| More About Diffraction Gratings .....             | 33-14 |
| The Visible Spectrum .....                        | 33-15 |
| Atomic Spectra .....                              | 33-16 |
| The Hydrogen Spectrum .....                       | 33-17 |
| The Experiment on Hydrogen Spectra .....          | 33-18 |
| The Balmer Series .....                           | 33-19 |
| .....   | 33-19 |
| The Doppler Effect .....                          | 33-20 |
| Stationary Source and Moving Observer .....       | 33-21 |
| Doppler Effect for Light .....                    | 33-22 |
| Doppler Effect in Astronomy .....                 | 33-23 |
| The Red Shift and the<br>Expanding Universe ..... | 33-24 |
| A Closer Look at Interference Patterns .....      | 33-26 |
| Analysis of the Single Slit Pattern .....         | 33-27 |
| Recording Diffraction Grating Patterns .....      | 33-28 |

## CHAPTER 34 PHOTONS

|   |       |
|---|-------|
| Blackbody Radiation .....                         | 34-2  |
| Planck Blackbody Radiation Law .....              | 34-4  |
| The Photoelectric Effect .....                    | 34-5  |
| Planck's Constant $h$ .....                       | 34-8  |
| Photon Energies .....                             | 34-9  |
| Particles and Waves .....                         | 34-11 |
| Photon Mass .....                                 | 34-12 |
| Photon Momentum .....                             | 34-13 |
| Antimatter .....                                  | 34-16 |
| Interaction of Photons and Gravity .....          | 34-18 |
| Evolution of the Universe .....                   | 34-21 |
| Red Shift and the Expansion of the Universe ..... | 34-21 |
| Another View of Blackbody Radiation .....         | 34-22 |
| Models of the universe .....                      | 34-23 |
| Powering the Sun .....                            | 34-23 |
| Abundance of the Elements .....                   | 34-24 |
| The Steady State Model of the Universe .....      | 34-25 |
| The Big Bang Model .....                          | 34-26 |
| The Helium Abundance .....                        | 34-26 |
| Cosmic Radiation .....                            | 34-27 |
| The Three Degree Radiation .....                  | 34-27 |
| Thermal Equilibrium of the Universe .....         | 34-28 |
| The Early Universe .....                          | 34-29 |
| The Early Universe .....                          | 34-29 |
| Excess of Matter over Antimatter .....            | 34-29 |
| Decoupling (700,000 years) .....                  | 34-31 |
| Guidebooks .....                                  | 34-32 |

**CHAPTER 35 BOHR THEORY OF HYDROGEN**

|  |       |
|--|-------|
| The Classical Hydrogen Atom .....        | 35-2  |
| Energy Levels .....                      | 35-4  |
| The Bohr Model .....                     | 35-7  |
| Angular Momentum in the Bohr Model ..... | 35-8  |
| De Broglie's Hypothesis .....            | 35-10 |

**CHAPTER 36 SCATTERING OF WAVES**

|  |       |
|--|-------|
| Scattering of a Wave by a Small Object ..... | 36-2  |
| Reflection of Light .....                    | 36-3  |
| X Ray Diffraction .....                      | 36-4  |
| Diffraction by Thin Crystals .....           | 36-6  |
| The Electron Diffraction Experiment .....    | 36-8  |
| The Graphite Crystal .....                   | 36-8  |
| The Electron Diffraction Tube .....          | 36-9  |
| Electron Wavelength .....                    | 36-9  |
| The Diffraction Pattern .....                | 36-10 |
| Analysis of the Diffraction Pattern .....    | 36-11 |
| Other Sets of Lines .....                    | 36-12 |
| Student Projects .....                       | 36-13 |
| Student project by Gwendylin Chen .....      | 36-14 |

**CHAPTER 37 LASERS, A MODEL ATOM AND ZERO POINT ENERGY**

|                                      |      |
|--------------------------------------|------|
| The Laser and                        |      |
| Standing Light Waves .....           | 37-2 |
| Photon Standing Waves .....          | 37-3 |
| Photon Energy Levels .....           | 37-4 |
| A Model Atom .....                   | 37-4 |
| Zero Point Energy .....              | 37-7 |
| Definition of Temperature .....      | 37-8 |
| Two dimensional standing waves ..... | 37-8 |

**CHAPTER 38 ATOMS**

|   |       |
|---|-------|
| Solutions of Schrödinger's                      |       |
| Equation for Hydrogen .....                     | 38-2  |
| The $\ell = 0$ Patterns .....                   | 38-4  |
| The $\ell \neq 0$ Patterns .....                | 38-5  |
| Intensity at the Origin .....                   | 38-5  |
| Quantized Projections of Angular Momentum ..... | 38-5  |
| The Angular Momentum Quantum Number .....       | 38-7  |
| Other notation .....                            | 38-7  |
| An Expanded Energy Level Diagram .....          | 38-8  |
| Multi Electron Atoms .....                      | 38-9  |
| Pauli Exclusion Principle .....                 | 38-9  |
| Electron Spin .....                             | 38-9  |
| The Periodic Table .....                        | 38-10 |
| Electron Screening .....                        | 38-10 |
| Effective Nuclear Charge .....                  | 38-12 |
| Lithium .....                                   | 38-12 |
| Beryllium .....                                 | 38-13 |
| Boron .....                                     | 38-13 |
| Up to Neon .....                                | 38-13 |
| Sodium to Argon .....                           | 38-13 |
| Potassium to Krypton .....                      | 38-14 |
| Summary .....                                   | 38-14 |
| Ionic Bonding .....                             | 38-15 |

**CHAPTER 39 SPIN**

|   |       |
|---|-------|
| The Concept of Spin .....                                 | 39-3  |
| Interaction of the Magnetic Field with Spin .....         | 39-4  |
| Magnetic Moments and the Bohr Magneton .....              | 39-4  |
| Insert 2 here .....                                       | 39-5  |
| Electron Spin Resonance Experiment .....                  | 39-5  |
| Nuclear Magnetic Moments .....                            | 39-6  |
| Sign Conventions .....                                    | 39-6  |
| Classical Picture of Magnetic Resonance .....             | 39-8  |
| Electron Spin Resonance Experiment .....                  | 39-9  |
| Appendix Classical Picture of Magnetic Interactions ..... | 39-14 |

**CHAPTER 40 QUANTUM MECHANICS**

|   |       |
|---|-------|
| Two Slit Experiment .....                               | 40-2  |
| The Two Slit Experiment from a                          |       |
| Particle Point of View .....                            | 40-3  |
| Two Slit Experiment—One Particle at a Time .....        | 40-3  |
| Born's Interpretation                                   |       |
| of the Particle Wave .....                              | 40-6  |
| Photon Waves .....                                      | 40-6  |
| Reflection and Fluorescence .....                       | 40-8  |
| A Closer Look at the Two Slit Experiment .....          | 40-9  |
| The Uncertainty Principle .....                         | 40-14 |
| Position-Momentum Form                                  |       |
| of the Uncertainty Principle .....                      | 40-15 |
| Single Slit Experiment .....                            | 40-16 |
| Time-Energy Form of the Uncertainty Principle .....     | 40-19 |
| Probability Interpretation .....                        | 40-22 |
| Measuring Short Times .....                             | 40-22 |
| Short Lived Elementary Particles .....                  | 40-23 |
| The Uncertainty Principle and Energy Conservation ..... | 40-24 |
| Quantum Fluctuations and Empty Space .....              | 40-25 |
| Appendix how a pulse is formed from sine waves .....    | 40-27 |

## CHAPTER ON GEOMETRICAL OPTICS

|  |           |
|--|-----------|
| Reflection from Curved Surfaces .....            | Optics-3  |
| The Parabolic Reflection .....                   | Optics-4  |
| Mirror Images .....                              | Optics-6  |
| The Corner Reflector .....                       | Optics-7  |
| Motion of Light through a Medium .....           | Optics-8  |
| Index of Refraction .....                        | Optics-9  |
| Cerenkov Radiation .....                         | Optics-10 |
| Snell's Law .....                                | Optics-11 |
| Derivation of Snell's Law .....                  | Optics-12 |
| Internal Reflection .....                        | Optics-13 |
| Fiber Optics .....                               | Optics-14 |
| Medical Imaging .....                            | Optics-15 |
| Prisms .....                                     | Optics-15 |
| Rainbows .....                                   | Optics-16 |
| The Green Flash .....                            | Optics-17 |
| Halos and Sun Dogs .....                         | Optics-18 |
| Lenses .....                                     | Optics-18 |
| Spherical Lens Surface .....                     | Optics-19 |
| Focal Length of a Spherical Surface .....        | Optics-20 |
| Aberrations .....                                | Optics-21 |
| Thin Lenses .....                                | Optics-23 |
| The Lens Equation .....                          | Optics-24 |
| Negative Image Distance .....                    | Optics-26 |
| Negative Focal Length and Diverging Lenses ..... | Optics-26 |
| Negative Object Distance .....                   | Optics-27 |
| Multiple Lens Systems .....                      | Optics-28 |
| Two Lenses Together .....                        | Optics-29 |
| Magnification .....                              | Optics-30 |
| The Human Eye .....                              | Optics-31 |
| Nearsightedness and Farsightedness .....         | Optics-32 |
| The Camera .....                                 | Optics-33 |
| Depth of Field .....                             | Optics-34 |
| Eye Glasses and a Home Lab Experiment .....      | Optics-36 |
| The Eyepiece .....                               | Optics-37 |
| The Magnifier .....                              | Optics-38 |
| Angular Magnification .....                      | Optics-39 |
| Telescopes .....                                 | Optics-40 |
| Reflecting telescopes .....                      | Optics-42 |
| Large Reflecting Telescopes .....                | Optics-43 |
| Hubble Space Telescope .....                     | Optics-44 |
| World's Largest Optical Telescope .....          | Optics-45 |
| Infrared Telescopes .....                        | Optics-46 |
| Radio Telescopes .....                           | Optics-48 |
| The Very Long Baseline Array (VLBA) .....        | Optics-49 |
| Microscopes .....                                | Optics-50 |
| Scanning Tunneling Microscope .....              | Optics-51 |

## Calculus 1 INTRODUCTION TO CALCULUS

|   |          |
|---|----------|
| Limiting Process .....                                      | Cal 1-3  |
| The Uncertainty Principle .....                             | Cal 1-3  |
| Calculus Definition of Velocity .....                       | Cal 1-5  |
| Acceleration .....  | Cal 1-7  |
| Components .....  | Cal 1-7  |
| Integration .....   | Cal 1-8  |
| Prediction of Motion .....                                  | Cal 1-9  |
| Calculating Integrals .....                                 | Cal 1-11 |
| The Process of Integrating .....                            | Cal 1-13 |
| Indefinite Integrals .....                                  | Cal 1-14 |
| Integration Formulas .....                                  | Cal 1-14 |
| New Functions .....   | Cal 1-15 |
| New Functions .....   | Cal 1-15 |
| Logarithms .....  | Cal 1-15 |
| The Exponential Function .....                              | Cal 1-16 |
| Exponents to the Base 10 .....                              | Cal 1-16 |
| The Exponential Function $y^x$ .....                        | Cal 1-16 |
| Euler's Number $e = 2.7183$ .....                           | Cal 1-17 |
| Differentiation and Integration .....                       | Cal 1-18 |
| A Fast Way to go Back and Forth .....                       | Cal 1-20 |
| Constant Acceleration Formulas .....                        | Cal 1-20 |
| Constant Acceleration Formulas<br>in Three Dimensions ..... | Cal 1-22 |
| More on Differentiation .....                               | Cal 1-23 |
| Series Expansions .....                                     | Cal 1-23 |
| Derivative of the Function $x^n$ .....                      | Cal 1-24 |
| The Chain Rule .....  | Cal 1-25 |
| Remembering The Chain Rule .....                            | Cal 1-25 |
| Partial Proof of the Chain Rule (optional) .....            | Cal 1-26 |
| Integration Formulas .....                                  | Cal 1-27 |
| Derivative of the Exponential Function .....                | Cal 1-28 |
| Integral of the Exponential Function .....                  | Cal 1-29 |
| Derivative as the Slope of a Curve .....                    | Cal 1-30 |
| Negative Slope .....  | Cal 1-31 |
| The Exponential Decay .....                                 | Cal 1-32 |
| Muon Lifetime .....   | Cal 1-32 |
| Half Life .....   | Cal 1-33 |
| Measuring the Time Constant from a Graph .....              | Cal 1-34 |
| The Sine and Cosine Functions .....                         | Cal 1-35 |
| Radian Measure .....  | Cal 1-35 |
| The Sine Function .....                                     | Cal 1-36 |
| Amplitude of a Sine Wave .....                              | Cal 1-37 |
| Derivative of the Sine Function .....                       | Cal 1-38 |

# Introduction

## An Overview of Physics

*With a brass tube and a few pieces of glass, you can construct either a microscope or a telescope. The difference is essentially where you place the lenses. With the microscope, you look down into the world of the small, with the telescope out into the world of the large.*

*In the twentieth century, physicists and astronomers have constructed ever larger machines to study matter on even smaller or even larger scales of distance. For the physicists, the new microscopes are the particle accelerators that provide views well inside atomic nuclei. For the astronomers, the machines are radio and optical telescopes whose large size allows them to record the faintest signals from space. Particularly effective is the Hubble telescope that sits above the obscuring curtain of the earth's atmosphere.*

*The new machines do not provide a direct image like the ones you see through brass microscopes or telescopes. Instead a good analogy is to the Magnetic Resonance Imaging (MRI) machines that first collect a huge amount of data, and then through the use of a computer program construct the amazing images showing cross sections through the human body. The telescopes and particle accelerators collect the vast amounts of data. Then through the use of the theories of quantum mechanics and relativity, the data is put together to construct meaningful images.*

*Some of the images have been surprising. One of the greatest surprises is the increasingly clear image of the universe starting out about fourteen billion years ago*

*as an incredibly small, incredibly hot speck that has expanded to the universe we see today. By looking farther and farther out, astronomers have been looking farther and farther back in time, closer to that hot, dense beginning. Physicists, by looking at matter on a smaller and smaller scale with the even more powerful accelerators, have been studying matter that is even hotter and more dense. By the end of the twentieth century, physicists and astronomers have discovered that they are looking at the same image.*

*It is likely that telescopes will end up being the most powerful microscopes. There is a limit, both financial and physical, to how big and powerful an accelerator we can build. Because of this limit, we can use accelerators to study matter only up to a certain temperature and density. To study matter that is still hotter and more dense, which is the same as looking at still smaller scales of distance, the only "machine" we have available is the universe itself. We have found that the behavior of matter under the extreme conditions of the very early universe have left an imprint that we can study today with telescopes.*

*In the rest of this introduction we will show you some of the pictures that have resulted from looking at matter with the new machines. In the text itself we will begin to learn how these pictures were constructed.*



## SPACE AND TIME

The images of nature we see are images in both space and time, for we have learned from the work of Einstein that the two cannot be separated. They are connected by the speed of light, a quantity we designate by the letter  $c$ , which has the value of a billion (1,000,000,000) feet (30 cm) in a second. Einstein's remarkable discovery in 1905 was that the speed of light is an absolute speed limit. Nothing in the current universe can travel faster than the speed  $c$ .

Because the speed of light provides us with an absolute standard that can be measured accurately, we use the value of  $c$  to relate the definitions of time and distance. The meter is defined as the distance light travels in an interval of  $1/299,792,458$  of a second. The length of a second itself is provided by an atomic standard. It is the time interval occupied by 9,192,631,770 vibrations of a particular wavelength of light radiated by a cesium atom.

Using the speed of light for conversion, clocks often make good meter sticks, especially for measuring astronomical distances. It takes light 1.27 seconds to travel from the earth to the moon. We can thus say that the moon is 1.27 **light seconds** away. This is simpler than saying that the moon is 1,250,000,000 feet or 382,000 kilometers away. Light takes 8 minutes to reach us from the sun, thus the earth's orbit about the sun has a radius of 8 **light minutes**. Radio signals, which also travel at the speed of light, took 2 1/2 hours to reach the earth when Voyager II passed the planet Uranus (temporarily the most distant planet). Thus Uranus is 2 1/2 light hours away and our solar system

has a diameter of 5 light hours (not including the cloud of comets that lie out beyond the planets.)

The closest star, Proxima Centauri, is 4.2 **light years** away. Light from this star, which started out when you entered college as a freshman, will arrive at the earth shortly after you graduate (assuming all goes well). Stars in our local area are typically 2 to 4 light years apart, except for the so called **binary stars** which are pairs of stars orbiting each other at distances as small as light days or light hours.

On a still larger scale, we find that stars form island structures called **galaxies**. We live in a fairly typical galaxy called the Milky Way. It is a flat disk of stars with a slight bulge at the center much like the Sombrero Galaxy seen edge on in Figure (1) and the neighboring spiral galaxy Andromeda seen in Figure (2). Our Milky Way is a spiral galaxy much like Andromeda, with the sun located about 2/3 of the way out in one of the spiral arms. If you look at the sky on a dark clear night you can see the band of stars that cross the sky called the Milky Way. Looking at these stars you are looking sideways through the disk of the Milky Way galaxy.



**Figure 1**  
*The Sombrero galaxy.*



**Figure 2**  
*The Andromeda galaxy.*