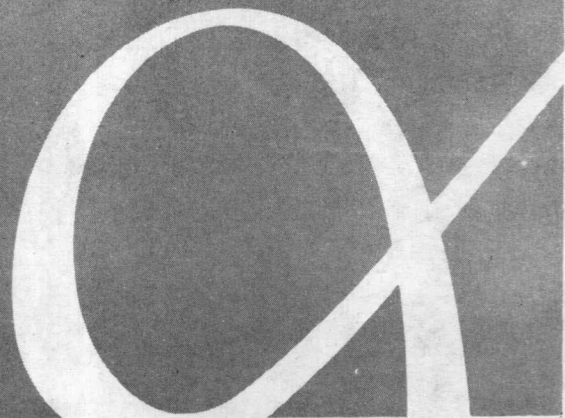


UNIVERSITY PHYSICS

EXPERIMENT AND THEORY

George D. Freier



UNIVERSITY PHYSICS

EXPERIMENT AND THEORY

George D. Freier

UNIVERSITY OF MINNESOTA

HING COMPANY

of must not be used or reproduced in any
transmission without the publisher's approval.
Hing Company, 440 Park Avenue South

000

Copyright © 1965 by MEREDITH PUBLISHING COMPANY

All rights reserved. This book, or parts thereof, must not be used or reproduced in any manner without written permission. For information address the publisher, Appleton-Century-Crofts, Division of Meredith Publishing Company, 440 Park Avenue South, New York, New York 10016

665-2

Library of Congress Card Number: 65-12900

PRINTED IN THE UNITED STATES OF AMERICA

E33130

PREFACE



The study of physics is a process in which we learn to apply logically a sequence of operational definitions. Starting with a few fundamental concepts and using operational definitions, we construct new concepts which help us probe our natural surroundings. When we design and perform experiments we apply the definitions as we make the necessary measurements, and when we solve problems we apply the operational concepts to a set of given numbers or data. Ideally, the student should carry out simple experiments while learning each operational definition. In doing these experiments he will obtain a much better feeling for the physical quantity involved.

Most teachers of general physics feel that simple demonstrations will aid the student in learning how to apply the definitions. Although demonstrations are not designed with entertainment as their sole purpose, they often have this added feature; and they lead to a much better rapport between the teacher and the students in a large class.

This book was written in the hope that it might serve as a collection of simple demonstrations set into a rigorous theoretical development of the subject matter in physics. A teacher using this book will want to do some of the demonstrations for his class, while the student who takes a lecture demonstration course in physics will find that the material presented in this book can serve as a useful record of the experiments that he has seen. The demonstrations presented here are certainly not all-inclusive and they are not always the best that can be done to illustrate a certain point, but in each case it is hoped that they will suggest some experiment that can be adapted to available apparatus. The descriptions of the demonstrations are supplemented by perspective drawings which show only essential parts of the apparatus. Through these drawings the student can have a more complete visualization of the experiment even though it may not always be performed.

Possibly, there is too much material for an ordinary course in physics, but this depends on the student's background. All the fundamentals are included so that the student with no previous training in physics can acquire the necessary background, while the student with good pre-college training can quickly review the fundamentals and be challenged by more complex concepts. In the present structure of courses taken by students, a second course in physics is either of a theoretical nature or of a detailed experimental nature where the student either does no experiments or does highly detailed work on a few special experiments. In either case this book describes many experiments which he is not able to perform himself.

No special effort is made to adapt the principles to engineering disciplines. The units are mostly in terms of the meter, kilogram, and second. Although other units are often defined and used, it will remain for the teacher to develop them. The engineering student himself must learn the facility for handling them. If the operational definitions are properly learned and followed, the problem of units should be trivial. Until the student learns his physics in this way, he is always going to have trouble with units and have to resort to formula plugging.

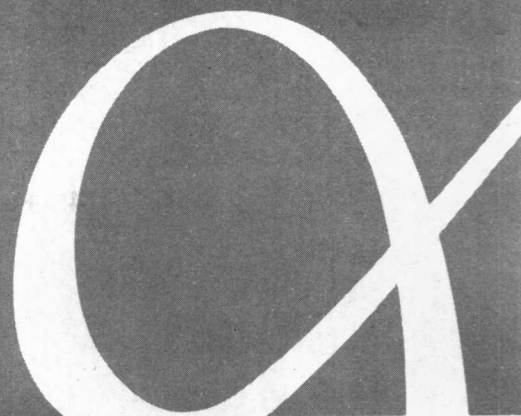
Some modern physics has been included. Special relativity is introduced from an experimental standpoint and is treated as a problem in measurement where the velocity of light is a universal constant for all observers. Relativistic mechanics is introduced as a plausible outcome of an application of the conservation laws. The student can thus become acquainted with relativistic properties of physical quantities and then return to them later for a more rigorous development in a course in theoretical physics. Wherever possible an effort has been made to lead the student to the forefront of physics and point out to him the problems which are currently under investigation.

The material has been kept quite general in order to acquaint students with the broad range of subject matter found in the studies of physics. Often the mechanisms learned in one field of physical investigation suggest useful models for study and analysis in another. In case the student has not yet formulated a definite interest for specialization we hope that this book will challenge him to pursue further any interest that may develop during this course of study.

The author is deeply grateful to the many teachers before him who have taken time and effort to develop the demonstrations presented in this book. The author is particularly grateful to Professor Richard M. Sutton for many helpful suggestions in preparing the manuscript. We hope that the teachers and students who use this text will find ways to improve the experiments and apply them in their own work.

G.D.F.

CONTENTS



Preface

1. Space, Time, and Motion

1.1	Common Senses	1
1.2	Measurements of Space and Displacement	2
1.3	Addition and Subtraction of Displacements	4
1.4	Curves as a Sequence of Infinitesimal Displacements	7
1.5	Time and Motion	7
1.6	Velocity	9
1.7	Analytic Treatment of Velocity	10
1.8	Other Concepts of Motion	13

2. Acceleration

2.1	Definition of Acceleration	18
2.2	Velocity and Displacement in Accelerated Motion	18
2.3	Acceleration Due to Gravity	19
2.4	Independent Motions	20
2.5	Properties of Projectile Motion	22
2.6	Acceleration in Uniform Circular Motion	22
2.7	Inertial Systems—Coriolis Acceleration	23

3. Kinematics of Special Relativity

3.1	Finite Velocities	29
3.2	Use of Signals to Make Measurements	30
3.3	Time Observations by Two Observers	30
3.4	Lorentz Transformation	31

3.5	Lorentz Contraction	33
3.6	Relative Velocities	33
3.7	Relativistic Examples	34
 4. Force		
4.1	Force and Acceleration	36
4.2	Newton's Laws of Motion	36
4.3	Fundamental Concept of Mass	37
4.4	Definition of Force	38
4.5	Weight	39
4.6	Interaction between Bodies	40
4.7	Central Force	42
4.8	Impulse Due to a Force	42
4.9	Conservation of Linear Momentum	44
4.10	Coefficient of Restitution	44
4.11	Rocket Propulsion	46
4.12	Summary	47
 5. Work and Energy		
5.1	Definition of Work	52
5.2	Potential Energy	53
5.3	Kinetic Energy	54
5.4	No Work Done by Central Forces in Circular Motion	54
5.5	Conservation of Energy	55
5.6	Power	56
5.7	Friction	57
5.8	Equilibrium and Stability	58
5.9	Machines	61
 6. Angular Momentum		
6.1	Moment of Momentum	67
6.2	Torque	68
6.3	Conservation of Angular Momentum	68
 7. Equilibrium and Statics		
7.1	First Condition of Equilibrium	72
7.2	Second Condition of Equilibrium	73
7.3	Equilibrium with Frictional Forces	74
7.4	Equilibrium with More than One Body	75

8. Collisions

8.1	Details of a Collision	79
8.2	Changes in Mechanical Energy	80
8.3	Analysis of Collision Problems	81
8.4	An Application in Nuclear Physics	82

9. The Motion of a Particle in an Inverse Square Field of Force

9.1	Kepler's Laws of Planetary Motion	88
9.2	Properties of the Ellipse	89
9.3	Newton's Law of Universal Gravitation	90
9.4	Motion in an Inverse Square Law of Force	92
9.5	Launching Satellites into Prescribed Orbits	94

10. Extended Bodies and the Center of Mass

10.1	External and Internal Forces	98
10.2	Center of Mass	98
10.3	Center of Gravity	100
10.4	Center of Mass Motion during Collisions	101
10.5	Collisions in the Center-of-Mass System of Coordinates	102
10.6	Motion when External Forces are not Applied at Center of Mass	104

11. Rotational Motion of Rigid Bodies

11.1	Degrees of Freedom	108
11.2	Rotational Motion	109
11.3	Relations between Linear and Rotational Equations of Motion	109
11.4	Steiner's Theorem	110
11.5	Demonstrations of $L = I\alpha$	110
11.6	Calculations of Moments of Inertia	111
11.7	Rotational Kinetic Energy for a Definite Axis	112
11.8	Angular Momentum for a Definite Axis	112
11.9	Rotation Combined with Translation	112
11.10	Rotations about Free Axes	114
11.11	Motion when J and ω are not Parallel	115
11.12	Ellipsoids of Inertia	115
11.13	Precession	116
11.14	Precession and Nutation	118
11.15	Stability with Rotation	120

12. Bulk Properties of Matter

12.1	Three States of Matter	126
12.2	Density and Specific Gravity	126
12.3	Stress	127
12.4	Strain	128
12.5	Hooke's Law	128
12.6	Bulk Modulus	129
12.7	Poisson's Ratio	129
12.8	Young's Modulus	129
12.9	Shear Modulus	130
12.10	Viscosity	132

13. Simple Harmonic Motion

13.1	Kinematics of Simple Harmonic Motion	136
13.2	Mass on a Spring	137
13.3	Torsional Oscillations	138
13.4	Energy in Simple Harmonic Motion	139
13.5	Solutions with Complex Numbers	139
13.6	Forced Oscillations	141
13.7	Physical Pendulum	142
13.8	Center of Percussion	144
13.9	Lissajous' Figures	144
13.10	Coupled Oscillations	145

14. Hydrostatics

14.1	Pascal's Principle	151
14.2	Pressure from Body Forces	152
14.3	Buoyancy and Archimedes' Principle	153
14.4	Body Forces in Accelerated Systems	155
14.5	Atmospheric Pressure	156
14.6	Surface Tension	157
14.7	Pressure Changes Due to Surface Tension	159

15. Hydrodynamics

15.1	Fluid Motion	165
15.2	Equation of Continuity	166
15.3	Forces and Acceleration	166
15.4	Equation of Motion	166
15.5	Demonstrations of the Bernoulli Effects	167
15.6	Circulation-Irrotational Flow	168

15.7	Airplane Flight	170
15.8	Propellers	170
15.9	Dimensional Analysis	172

16. Relativistic Mechanics

16.1	Conservation Laws	177
16.2	Relativistic Mass	178
16.3	Energy	179
16.4	Center of Mass	179
16.5	Conversion of Energy to Mass	181

17. Temperature and Properties of Gases

17.1	Definition of Temperature	183
17.2	Effects of Temperature Change	184
17.3	Pressure-Temperature Relations at Constant Volume	184
17.4	Volume-Temperature Relations at Constant Pressure	185
17.5	Boyle's law	185
17.6	Equation of State	186
17.7	Universal Gas Constant	186
17.8	Introduction to Kinetic Theory	188
17.9	Velocity of Molecules	189
17.10	Energy of Molecules	190
17.11	Demonstrations of Kinetic Motions in Gases	190
17.12	Some Consequences of Kinetic Motion	191

18. Further Properties of Gases Derived from Kinetic Theory

18.1	Size of Molecules and Mean Free Path	195
18.2	Molecular Diffusion	195
18.3	Viscosity	196
18.4	Distribution of Velocities	198
18.5	Molecules in Phase Space	199
18.6	Probability of Occupying Volume Elements in Phase Space	199
18.7	Maxwell-Boltzmann Distribution	201
18.8	Examples of Boltzmann Distributions	202

19. Heat as a Form of Energy

19.1	Definition of Calorie and Specific Heat	205
19.2	Caloric Theory and Energy	206

19.3	Mechanical Equivalent of Heat	206
19.4	First Law of Thermodynamics	207
19.5	Specific Heats of Gases	208
19.6	Internal Energy of a Gas	210
19.7	Thermodynamic Changes	211
19.8	Example	212
19.9	Adiabatic Changes	213
19.10	Carnot Cycle and Thermal Efficiency	214
19.11	Second Law of Thermodynamics	215
 20. Change of State		
20.1	Macroscopic and Microscopic Properties	220
20.2	Pressure Due to Vapor when in Equilibrium with a Liquid	221
20.3	Physical Significance of Modified Gas Equation	223
20.4	The Critical Point	224
20.5	Energy to Change the State	225
20.6	Solid Phase	227
20.7	Meteorology	229
20.8	Stability of the Atmosphere	230
 21. Further Thermodynamic Concepts		
21.1	Enthalpy	234
21.2	Free Energy	235
21.3	Dynamics of Gas Flow	236
21.4	Reversible and Irreversible Processes	238
21.5	Entropy and Probability	239
 22. Heat Transfer		
22.1	Convection	240
22.2	Conduction	242
22.3	Propagation of Heat Waves	244
22.4	Radiation	247
22.5	Thermodynamics of Radiation	249
 23. Electrostatic Charging		
23.1	Charge Associated with Matter	251
23.2	Electrostatic Force between Point Charges	252

23.3	Units of Charge	252
23.4	Forces	253
23.5	The Electric Field	253
23.6	Flux of Line of Force	255
23.7	Electric Displacement	255
23.8	Gauss' Law	255
23.9	Fields in a Conductor Are Zero	256
23.10	Experiments with Induction	256
23.11	Surface Distributions of Charge	259
23.12	Volume Distribution of Charge	260

24. Potentials

24.1	Work Done while Moving Charges	262
24.2	Potential and Potential Difference	262
24.3	Relation between Electric Field and Electrostatic Potential	263
24.4	Dipole Fields	264
24.5	Equipotential Surfaces and their Relation to the Electric Field	265
24.6	Surface Charges on Conductors	266
24.7	Field between Parallel Plates	266
24.8	Capacitance of Other Simple Systems	267
24.9	Energy Associated with Stored Charge	268
24.10	Measuring Voltage with a Balance	269
24.11	Pressure Exerted by Electrostatic Fields	269
24.12	Experiments which Demonstrate Fields and Charges	270
24.13	Charge on the Electron	271
24.14	Energy Given to Charged Particles	271
24.15	One-Dimensional Charge Distributions	272
24.16	Classical Radius of the Electron	272

25. Other Charging Processes

25.1	Chemical Charge Separation	277
25.2	Current and Current Density	279
25.3	Ohm's Law	280
25.4	Electrolysis	281
25.5	Thermodynamics of Cells	282
25.6	Resistance	283
25.7	Time Constant of Materials	283
25.8	Kinetic Theory of Resistance	284
25.9	Conduction in Metals	286

26. Circuit Analysis

26.1	Battery Voltages	289
26.2	Power from Batteries	290
26.3	Series and Parallel Resistance	291
26.4	Kirchhoff's Laws	292
26.5	Cells in Series and Parallel	294
26.6	Charge and Discharge of a Capacitor	294
26.7	Four Terminal Network	295

27. Electric Field and Electric Displacement

27.1	Polarization of a Medium	301
27.2	Significance of D and E	302
27.3	Force on Test Charges	303
27.4	Spherical Dielectric Bodies	304
27.5	Molecular Polarizabilities	306
27.6	Force on Dipoles	307

28. Magnetic Force

28.1	Force between Moving Charges	310
28.2	Units for Magnetic Force	311
28.3	Magnetic Induction	312
28.4	Force in Terms of Magnetic Induction	315
28.5	Magnetic Moment of a Current Loop	316
28.6	Magnetic Fields	316
28.7	Effects of the Medium	318
28.8	Total Flux	319

29. Electromagnetic Induction

29.1	Induced Voltages and Lenz's Law	322
29.2	Magnitude of Induced Voltages	323
29.3	Examples of Induction	325
29.4	Inductance	327
29.5	Magnetic Energy	328
29.6	Motors and Generators	331

30. Magnetic Properties of Materials

30.1	Changes in B and H at Boundaries	335
30.2	Permanent Magnets	336

30.3	Field Due to a Magnetic Dipole	337
30.4	Nonclassical Properties of Fundamental Particles	337
30.5	Detailed Structure in Magnetic Materials	338
30.6	Calculation of Magnetic Flux	339
30.7	Galvanometers	339
30.8	Voltmeters and Ammeters	340
30.9	Galvanometer as a Null Instrument	341
30.10	Curie Temperature	342
30.11	Modern Concepts	342

31. Thermoelectricity

31.1	Thermal Electromotive Force	348
31.2	Thomson Effect	349
31.3	Thermodynamics of Thermocouples	349
31.4	Construction of Thermocouples	351

32. Alternating Current

32.1	Sinusoidal Voltages	353
32.2	AC Through a Resistance	354
32.3	AC Through an Inductance	355
32.4	AC Through a Capacitance	356
32.5	AC Series Circuit	356
32.6	AC Parallel Circuit	358
32.7	Transformers	359
32.8	Spark Coil	360
32.9	AC at High Frequencies	362
32.10	Betatron	364

33. Motions of Charged Particles in Electric and Magnetic Fields

33.1	Trajectories of Particles	367
33.2	Deflection by a Transverse Electric Field	368
33.3	Velocity Selector	368
33.4	Magnetic Focusing	369
33.5	Mass Spectrometer	370
33.6	Deflection of Conduction Currents	371
33.7	Hall Voltage	371
33.8	Motion in Converging Magnetic Fields	371

34. Radiation

34.1	Transmission Line	375
34.2	Coaxial Cable	377
34.3	Radiating Dipole	378
34.4	Radiation from Accelerated Charges	378

35. Wave Motion

35.1	Phase Relations in Wave Motion	381
35.2	Phase Velocity	382
35.3	Wave Equation for a Stretched String	383
35.4	Compressional Waves	385
35.5	Effects of Fixed Supports	386
35.6	Allowed Frequencies	388

36. Sound Waves

36.1	Wave Equation for Acoustical Waves	392
36.2	Properties of Sound Waves	393
36.3	Boundary Conditions	394
36.4	Reflection of Pulses	397
36.5	Role of Waves in Collisions	398

37. Effects of Sound

37.1	Doppler Shift	401
37.2	Beats	402
37.3	Helmholtz Theory of Hearing	404
37.4	Interference of Sound Waves	405
37.5	Huygens' Principle	406
37.6	Group Velocity	406
37.7	Finite Wave Trains	408
37.8	Time Resolution with the Ear	408

38. Water Waves; Acoustics of Rooms

38.1	Surface Waves	411
38.2	Sound Waves in a Room	413

39. Music

39.1	Musical Intervals	417
39.2	Harmony	418

39.3	Triads	419
39.4	Musical Scales	420
39.5	Circle Diagram	423

40. Velocity of Light

40.1	Velocity of Light by Astronomical Methods	425
40.2	Velocity of Light along Terrestrial Paths	426
40.3	Velocity of Light is Independent of Velocity of Source	427
40.4	Light as a Wave through Ether	427
40.5	Evidence for No Ether	428
40.6	Summary	428

41. Light Paths

41.1	Straight Line Propagation of Light	432
41.2	Fermat's Principle	433
41.3	Reflection	433
41.4	Multiple Reflections	436
41.5	Reflection from Conic Surfaces	437
41.6	Spherical Surfaces	439
41.7	Constructions for Finite-Sized Objects	440
41.8	Newtonian Form of Equations	441

42. Light Paths with Changing Velocity

42.1	Law of Refraction	444
42.2	Apparent Depth	445
42.3	Critical Angle	446
42.4	Refraction at a Curved Surface	447
42.5	Newtonian Construction	450
42.6	Thin Lens	451
42.7	Ray Tracing	452
42.8	Application of Fermat's Principle	454

43. Properties of Lenses

43.1	Measurement of Focal Length	459
43.2	The Thick Lens	460
43.3	Stops	463
43.4	Resolution and Depth of Focus	466

44. Light as an Electromagnetic Wave

44.1	Derivation of the Wave Equation	469
44.2	Solution of the Wave Equation	471
44.3	Boundary Conditions	473
44.4	Fresnel Equations	474
44.5	Phase Changes at a Boundary	476

45. Photometry

45.1	Standard Light Sources	479
45.2	Luminous Intensity and Illumination Per Unit Area	479
45.3	Relations between Object and Image Brightness	481
45.4	Behavior of the Eye	483
45.5	Color	484

46. Optical Instruments

46.1	The Eye	487
46.2	Simple Magnifier	487
46.3	Telescopes	488
46.4	Compound Microscope	489
46.5	General Combinations of Lenses	490
46.6	Star Magnitudes	491
46.7	Resolution	492
46.8	Application of Special Relativity	492

47. Interference of Electromagnetic Waves

47.1	Wave Nature of Light	496
47.2	Conditions for a Light Source to be in Phase	497
47.3	Coherent Sources	498
47.4	Purity of Color and Length of Wave Train	499
47.5	Air Wedge and Thin Films	500
47.6	Interferometers	502
47.7	Single Slit Diffraction	503
47.8	Diffraction Grating	505
47.9	Fresnel Zones	507

48. Dispersion

48.1	White Light Composed of Many Colors	512
48.2	Deviation with a Prism	512