

18-3 THERMAL EXPANSION	520
Thermal Expansion	520
18-4 ABSORPTION OF HEAT	522
Temperature and Heat	523
The Absorption of Heat by Solids and Liquids	524
18-5 THE FIRST LAW OF THERMODYNAMICS	528
A Closer Look at Heat and Work	528
The First Law of Thermodynamics	531
Some Special Cases of the First Law of Thermodynamics	532
18-6 HEAT TRANSFER MECHANISMS	534
Heat Transfer Mechanisms	534
REVIEW & SUMMARY	538
QUESTIONS	540
PROBLEMS	541
19 The Kinetic Theory of Gases	549
19-1 AVOGADRO'S NUMBER	549
What Is Physics?	549
Avogadro's Number	550
19-2 IDEAL GASES	550
Ideal Gases	551
19-3 PRESSURE, TEMPERATURE, AND RMS SPEED	554
Pressure, Temperature, and RMS Speed	554
19-4 TRANSLATIONAL KINETIC ENERGY	557
Translational Kinetic Energy	557
19-5 MEAN FREE PATH	558
Mean Free Path	558
19-6 THE DISTRIBUTION OF MOLECULAR SPEEDS	560
The Distribution of Molecular Speeds	561
19-7 THE MOLAR SPECIFIC HEATS OF AN IDEAL GAS	564
The Molar Specific Heats of an Ideal Gas	564
19-8 DEGREES OF FREEDOM AND MOLAR SPECIFIC HEATS	568
Degrees of Freedom and Molar Specific Heats	568
A Hint of Quantum Theory	570
19-9 THE ADIABATIC EXPANSION OF AN IDEAL GAS	571
The Adiabatic Expansion of an Ideal Gas	571
REVIEW & SUMMARY	575
QUESTIONS	576
PROBLEMS	577
20 Entropy and the Second Law of Thermodynamics	583
20-1 ENTROPY	583
What Is Physics?	584
Irreversible Processes and Entropy	584
Change in Entropy	585
The Second Law of Thermodynamics	588
20-2 ENTROPY IN THE REAL WORLD: ENGINES	590
Entropy in the Real World: Engines	590
20-3 REFRIGERATORS AND REAL ENGINES	595
Entropy in the Real World: Refrigerators	596
The Efficiencies of Real Engines	597
20-4 A STATISTICAL VIEW OF ENTROPY	598
A Statistical View of Entropy	598
REVIEW & SUMMARY	602
QUESTIONS	603
PROBLEMS	604
21 Coulomb's Law	609
21-1 COULOMB'S LAW	609
What Is Physics?	610
Electric Charge	610
Conductors and Insulators	612
Coulomb's Law	613
21-2 CHARGE IS QUANTIZED	619
Charge Is Quantized	619
21-3 CHARGE IS CONSERVED	621
Charge Is Conserved	621
REVIEW & SUMMARY	622
QUESTIONS	623
PROBLEMS	624
22 Electric Fields	630
22-1 THE ELECTRIC FIELD	630
What Is Physics?	630
The Electric Field	631
Electric Field Lines	631
22-2 THE ELECTRIC FIELD DUE TO A CHARGED PARTICLE	633
The Electric Field Due to a Point Charge	633
22-3 THE ELECTRIC FIELD DUE TO A DIPOLE	635
The Electric Field Due to an Electric Dipole	636
22-4 THE ELECTRIC FIELD DUE TO A LINE OF CHARGE	638
The Electric Field Due to Line of Charge	638
22-5 THE ELECTRIC FIELD DUE TO A CHARGED DISK	643
The Electric Field Due to a Charged Disk	643
22-6 A POINT CHARGE IN AN ELECTRIC FIELD	645
A Point Charge in an Electric Field	645
22-7 A DIPOLE IN AN ELECTRIC FIELD	647
A Dipole in an Electric Field	648
REVIEW & SUMMARY	650
QUESTIONS	651
PROBLEMS	652

- 23 Gauss' Law 659**
- 23-1 ELECTRIC FLUX 659**
 - What Is Physics 659
 - Electric Flux 660
 - 23-2 GAUSS' LAW 664**
 - Gauss' Law 664
 - Gauss' Law and Coulomb's Law 666
 - 23-3 A CHARGED ISOLATED CONDUCTOR 668**
 - A Charged Isolated Conductor 668
 - 23-4 APPLYING GAUSS' LAW: CYLINDRICAL SYMMETRY 671**
 - Applying Gauss' Law: Cylindrical Symmetry 671
 - 23-5 APPLYING GAUSS' LAW: PLANAR SYMMETRY 673**
 - Applying Gauss' Law: Planar Symmetry 673
 - 23-6 APPLYING GAUSS' LAW: SPHERICAL SYMMETRY 675**
 - Applying Gauss' Law: Spherical Symmetry 675
 - REVIEW & SUMMARY 677 QUESTIONS 677 PROBLEMS 679
- 24 Electric Potential 685**
- 24-1 ELECTRIC POTENTIAL 685**
 - What Is Physics? 685
 - Electric Potential and Electric Potential Energy 686
 - 24-2 EQUIPOTENTIAL SURFACES AND THE ELECTRIC FIELD 690**
 - Equipotential Surfaces 690
 - Calculating the Potential from the Field 691
 - 24-3 POTENTIAL DUE TO A CHARGED PARTICLE 694**
 - Potential Due to a Charged Particle 694
 - Potential Due a Group of Charged Particles 695
 - 24-4 POTENTIAL DUE TO AN ELECTRIC DIPOLE 697**
 - Potential Due to an Electric Dipole 697
 - 24-5 POTENTIAL DUE TO A CONTINUOUS CHARGE DISTRIBUTION 698**
 - Potential Due to a Continuous Charge Distribution 698
 - 24-6 CALCULATING THE FIELD FROM THE POTENTIAL 701**
 - Calculating the Field from the Potential 701
 - 24-7 ELECTRIC POTENTIAL ENERGY OF A SYSTEM OF CHARGED PARTICLES 703**
 - Electric Potential Energy of a System of Charged Particles 703
 - 24-8 POTENTIAL OF A CHARGED ISOLATED CONDUCTOR 706**
 - Potential of Charged Isolated Conductor 706
 - REVIEW & SUMMARY 707 QUESTIONS 708 PROBLEMS 710
- 25 Capacitance 717**
- 25-1 CAPACITANCE 717**
 - What Is Physics? 717
 - Capacitance 717
 - 25-2 CALCULATING THE CAPACITANCE 719**
 - Calculating the Capacitance 720
 - 25-3 CAPACITORS IN PARALLEL AND IN SERIES 723**
 - Capacitors in Parallel and in Series 724
 - 25-4 ENERGY STORED IN AN ELECTRIC FIELD 728**
 - Energy Stored in an Electric Field 728
 - 25-5 CAPACITOR WITH A DIELECTRIC 731**
 - Capacitor with a Dielectric 731
 - Dielectrics: An Atomic View 733
 - 25-6 DIELECTRICS AND GAUSS' LAW 735**
 - Dielectrics and Gauss' Law 735
 - REVIEW & SUMMARY 738 QUESTIONS 738 PROBLEMS 739
- 26 Current and Resistance 745**
- 26-1 ELECTRIC CURRENT 745**
 - What Is Physics? 745
 - Electric Current 746
 - 26-2 CURRENT DENSITY 748**
 - Current Density 749
 - 26-3 RESISTANCE AND RESISTIVITY 752**
 - Resistance and Resistivity 753
 - 26-4 OHM'S LAW 756**
 - Ohm's Law 756
 - A Microscopic View of Ohm's Law 758
 - 26-5 POWER, SEMICONDUCTORS, SUPERCONDUCTORS 760**
 - Power in Electric Circuits 760
 - Semiconductors 762
 - Superconductors 763
 - REVIEW & SUMMARY 763 QUESTIONS 764 PROBLEMS 765
- 27 Circuits 771**
- 27-1 SINGLE-LOOP CIRCUITS 771**
 - What Is Physics? 772
 - "Pumping" Charges 772
 - Work, Energy, and Emf 773
 - Calculating the Current in a Single-Loop Circuit 774
 - Other Single-Loop Circuits 776
 - Potential Difference Between Two Points 777

27-2 MULTILoop CIRCUITS 781

Multiloop Circuits 781

27-3 THE AMMETER AND THE VOLTMETER 788

The Ammeter and the Voltmeter 788

27-4 RC CIRCUITS 788

RC Circuits 789

REVIEW & SUMMARY 793 QUESTIONS 793 PROBLEMS 795

28 Magnetic Fields 803

28-1 MAGNETIC FIELDS AND THE DEFINITION OF \vec{B} 803

What Is Physics? 803

What Produces a Magnetic Field? 804

The Definition of \vec{B} 804

28-2 CROSSED FIELDS: DISCOVERY OF THE ELECTRON 808

Crossed Fields: Discovery of the Electron 809

28-3 CROSSED FIELDS: THE HALL EFFECT 810

Crossed Fields: The Hall Effect 811

28-4 A CIRCULATING CHARGED PARTICLE 814

A Circulating Charged Particle 814

28-5 CYCLOTRONS AND SYNCHROTRONS 817

Cyclotrons and Synchrotrons 818

28-6 MAGNETIC FORCE ON A CURRENT-CARRYING WIRE 820

Magnetic Force on a Current-Carrying Wire 820

28-7 TORQUE ON A CURRENT LOOP 822

Torque on a Current Loop 822

28-8 THE MAGNETIC DIPOLE MOMENT 824

The Magnetic Dipole Moment 825

REVIEW & SUMMARY 827 QUESTIONS 827 PROBLEMS 829

29 Magnetic Fields Due to Currents 836

29-1 MAGNETIC FIELD DUE TO A CURRENT 836

What Is Physics? 836

Calculating the Magnetic Field Due to a Current 837

29-2 FORCE BETWEEN TWO PARALLEL CURRENTS 842

Force Between Two Parallel Currents 842

29-3 AMPERE'S LAW 844

Ampere's Law 844

29-4 SOLENOIDS AND TOROIDS 848

Solenoids and Toroids 848

29-5 A CURRENT-CARRYING COIL AS A MAGNETIC DIPOLE 851

A Current-Carrying Coil as a Magnetic Dipole 851

REVIEW & SUMMARY 854 QUESTIONS 855 PROBLEMS 856

30 Induction and Inductance 864

30-1 FARADAY'S LAW AND LENZ'S LAW 864

What Is Physics 864

Two Experiments 865

Faraday's Law of Induction 865

Lenz's Law 868

30-2 INDUCTION AND ENERGY TRANSFERS 871

Induction and Energy Transfers 871

30-3 INDUCED ELECTRIC FIELDS 874

Induced Electric Fields 875

30-4 INDUCTORS AND INDUCTANCE 879

Inductors and Inductance 879

30-5 SELF-INDUCTION 881

Self-Induction 881

30-6 RL CIRCUITS 882

RL Circuits 883

30-7 ENERGY STORED IN A MAGNETIC FIELD 887

Energy Stored in a Magnetic Field 887

30-8 ENERGY DENSITY OF A MAGNETIC FIELD 889

Energy Density of a Magnetic Field 889

30-9 MUTUAL INDUCTION 890

Mutual Induction 890

REVIEW & SUMMARY 893 QUESTIONS 893 PROBLEMS 895

31 Electromagnetic Oscillations and Alternating Current 903

31-1 LC OSCILLATIONS 903

What Is Physics? 904

LC Oscillations, Qualitatively 904

The Electrical-Mechanical Analogy 906

LC Oscillations, Quantitatively 907

31-2 DAMPED OSCILLATIONS IN AN RLC CIRCUIT 910

Damped Oscillations in an RLC Circuit 911

31-3 FORCED OSCILLATIONS OF THREE SIMPLE CIRCUITS 912

Alternating Current 913

Forced Oscillations 914

Three Simple Circuits 914

31-4 THE SERIES RLC CIRCUIT 921

The Series RLC Circuit 921

31-5 POWER IN ALTERNATING-CURRENT CIRCUITS	927
Power in Alternating-Current Circuits	927
31-6 TRANSFORMERS	930
Transformers	930
REVIEW & SUMMARY	933
QUESTIONS	934
PROBLEMS	935
32 Maxwell's Equations; Magnetism of Matter	941
32-1 GAUSS' LAW FOR MAGNETIC FIELDS	941
What Is Physics?	941
Gauss' Law for Magnetic Fields	942
32-2 INDUCED MAGNETIC FIELDS	943
Induced Magnetic Fields	943
32-3 DISPLACEMENT CURRENT	946
Displacement Current	947
Maxwell's Equations	949
32-4 MAGNETS	950
Magnets	950
32-5 MAGNETISM AND ELECTRONS	952
Magnetism and Electrons	953
Magnetic Materials	956
32-6 DIAMAGNETISM	957
Diamagnetism	957
32-7 PARAMAGNETISM	959
Paramagnetism	959
32-8 FERROMAGNETISM	961
Ferromagnetism	961
REVIEW & SUMMARY	964
QUESTIONS	965
PROBLEMS	967
33 Electromagnetic Waves	972
33-1 ELECTROMAGNETIC WAVES	972
What Is Physics?	972
Maxwell's Rainbow	973
The Traveling Electromagnetic Wave, Qualitatively	974
The Traveling Electromagnetic Wave, Quantitatively	977
33-2 ENERGY TRANSPORT AND THE POYNTING VECTOR	980
Energy Transport and the Poynting Vector	981
33-3 RADIATION PRESSURE	983
Radiation Pressure	983
33-4 POLARIZATION	985
Polarization	985
33-5 REFLECTION AND REFRACTION	990
Reflection and Refraction	991
33-6 TOTAL INTERNAL REFLECTION	996
Total Internal Reflection	996
33-7 POLARIZATION BY REFLECTION	997
Polarization by Reflection	998
REVIEW & SUMMARY	999
QUESTIONS	1000
PROBLEMS	1001
34 Images	1010
34-1 IMAGES AND PLANE MIRRORS	1010
What Is Physics?	1010
Two Types of Image	1010
Plane Mirrors	1012
34-2 SPHERICAL MIRRORS	1014
Spherical Mirrors	1015
Images from Spherical Mirrors	1016
34-3 SPHERICAL REFRACTING SURFACES	1020
Spherical Refracting Surfaces	1020
34-4 THIN LENSES	1023
Thin Lenses	1023
34-5 OPTICAL INSTRUMENTS	1030
Optical Instruments	1030
34-6 THREE PROOFS	1033
REVIEW & SUMMARY	1036
QUESTIONS	1037
PROBLEMS	1038
35 Interference	1047
35-1 LIGHT AS A WAVE	1047
What Is Physics?	1047
Light as a Wave	1048
35-2 YOUNG'S INTERFERENCE EXPERIMENT	1053
Diffraction	1053
Young's Interference Experiment	1054
35-3 INTERFERENCE AND DOUBLE-SLIT INTENSITY	1059
Coherence	1059
Intensity in Double-Slit Interference	1060
35-4 INTERFERENCE FROM THIN FILMS	1063
Interference from Thin Films	1064
35-5 MICHELSON'S INTERFEROMETER	1070
Michelson's Interferometer	1071
REVIEW & SUMMARY	1072
QUESTIONS	1072
PROBLEMS	1074

36 **Diffraction** 1081

36-1 SINGLE-SLIT DIFFRACTION 1081

What Is Physics? 1081

Diffraction and the Wave Theory of Light 1081

Diffraction by a Single Slit: Locating the Minima 1083

36-2 INTENSITY IN SINGLE-SLIT DIFFRACTION 1086

Intensity in Single-Slit Diffraction 1086

Intensity in Single-Slit Diffraction, Quantitatively 1088

36-3 DIFFRACTION BY A CIRCULAR APERTURE 1090

Diffraction by a Circular Aperture 1091

36-4 DIFFRACTION BY A DOUBLE SLIT 1094

Diffraction by a Double Slit 1095

36-5 DIFFRACTION GRATINGS 1098

Diffraction Gratings 1098

36-6 GRATINGS: DISPERSION AND RESOLVING POWER 1101

Gratings: Dispersion and Resolving Power 1101

36-7 X-RAY DIFFRACTION 1104

X-Ray Diffraction 1104

REVIEW & SUMMARY 1107 QUESTIONS 1107 PROBLEMS 1108

37 **Relativity** 1116

37-1 SIMULTANEITY AND TIME DILATION 1116

What Is Physics? 1116

The Postulates 1117

Measuring an Event 1118

The Relativity of Simultaneity 1120

The Relativity of Time 1121

37-2 THE RELATIVITY OF LENGTH 1125

The Relativity of Length 1126

37-3 THE LORENTZ TRANSFORMATION 1129

The Lorentz Transformation 1129

Some Consequences of the Lorentz Equations 1131

37-4 THE RELATIVITY OF VELOCITIES 1133

The Relativity of Velocities 1133

37-5 DOPPLER EFFECT FOR LIGHT 1134

Doppler Effect for Light 1135

37-6 MOMENTUM AND ENERGY 1137

A New Look at Momentum 1138

A New Look at Energy 1138

REVIEW & SUMMARY 1143 QUESTIONS 1144 PROBLEMS 1145

38 **Photons and Matter Waves** 1153

38-1 THE PHOTON, THE QUANTUM OF LIGHT 1153

What Is Physics? 1153

The Photon, the Quantum of Light 1154

38-2 THE PHOTOELECTRIC EFFECT 1155

The Photoelectric Effect 1156

38-3 PHOTONS, MOMENTUM, COMPTON SCATTERING, LIGHT INTERFERENCE 1158

Photons Have Momentum 1159

Light as a Probability Wave 1162

38-4 THE BIRTH OF QUANTUM PHYSICS 1164

The Birth of Quantum Physics 1165

38-5 ELECTRONS AND MATTER WAVES 1166

Electrons and Matter Waves 1167

38-6 SCHRÖDINGER'S EQUATION 1170

Schrödinger's Equation 1170

38-7 HEISENBERG'S UNCERTAINTY PRINCIPLE 1172

Heisenberg's Uncertainty Principle 1173

38-8 REFLECTION FROM A POTENTIAL STEP 1174

Reflection from a Potential Step 1174

38-9 TUNNELING THROUGH A POTENTIAL BARRIER 1176

Tunneling Through a Potential Barrier 1176

REVIEW & SUMMARY 1179 QUESTIONS 1180 PROBLEMS 1181

39 **More About Matter Waves** 1186

39-1 ENERGIES OF A TRAPPED ELECTRON 1186

What Is Physics? 1186

String Waves and Matter Waves 1187

Energies of a Trapped Electron 1187

39-2 WAVE FUNCTIONS OF A TRAPPED ELECTRON 1191

Wave Functions of a Trapped Electron 1192

39-3 AN ELECTRON IN A FINITE WELL 1195

An Electron in a Finite Well 1195

39-4 TWO- AND THREE-DIMENSIONAL ELECTRON TRAPS 1197

More Electron Traps 1197

Two- and Three-Dimensional Electron Traps 1200

39-5 THE HYDROGEN ATOM 1201

The Hydrogen Atom Is an Electron Trap 1202

The Bohr Model of Hydrogen, a Lucky Break 1203

Schrödinger's Equation and the Hydrogen Atom 1205

REVIEW & SUMMARY 1213 QUESTIONS 1213 PROBLEMS 1214

40 All About Atoms	1219			
40-1 PROPERTIES OF ATOMS	1219			
What Is Physics?	1220			
Some Properties of Atoms	1220			
Angular Momentum, Magnetic Dipole Moments	1222			
40-2 THE STERN-GERLACH EXPERIMENT	1226			
The Stern-Gerlach Experiment	1226			
40-3 MAGNETIC RESONANCE	1229			
Magnetic Resonance	1229			
40-4 EXCLUSION PRINCIPLE AND MULTIPLE ELECTRONS IN A TRAP	1230			
The Pauli Exclusion Principle	1230			
Multiple Electrons in Rectangular Traps	1231			
40-5 BUILDING THE PERIODIC TABLE	1234			
Building the Periodic Table	1234			
40-6 X RAYS AND THE ORDERING OF THE ELEMENTS	1236			
X Rays and the Ordering of the Elements	1237			
40-7 LASERS	1240			
Lasers and Laser Light	1241			
How Lasers Work	1242			
REVIEW & SUMMARY	1245	QUESTIONS	1246	PROBLEMS 1247
41 Conduction of Electricity in Solids	1252			
41-1 THE ELECTRICAL PROPERTIES OF METALS	1252			
What Is Physics?	1252			
The Electrical Properties of Solids	1253			
Energy Levels in a Crystalline Solid	1254			
Insulators	1254			
Metals	1255			
41-2 SEMICONDUCTORS AND DOPING	1261			
Semiconductors	1262			
Doped Semiconductors	1263			
41-3 THE p-n JUNCTION AND THE TRANSISTOR	1265			
The p - n Junction	1266			
The Junction Rectifier	1267			
The Light-Emitting Diode (LED)	1268			
The Transistor	1270			
REVIEW & SUMMARY	1271	QUESTIONS	1272	PROBLEMS 1272
42 Nuclear Physics	1276			
42-1 DISCOVERING THE NUCLEUS	1276			
What Is Physics?	1276			
Discovering the Nucleus	1276			
42-2 SOME NUCLEAR PROPERTIES	1279			
Some Nuclear Properties	1280			
42-3 RADIOACTIVE DECAY	1286			
Radioactive Decay	1286			
42-4 ALPHA DECAY	1289			
Alpha Decay	1289			
42-5 BETA DECAY	1292			
Beta Decay	1292			
42-6 RADIOACTIVE DATING	1295			
Radioactive Dating	1295			
42-7 MEASURING RADIATION DOSAGE	1296			
Measuring Radiation Dosage	1296			
42-8 NUCLEAR MODELS	1297			
Nuclear Models	1297			
REVIEW & SUMMARY	1300	QUESTIONS	1301	PROBLEMS 1302
43 Energy from the Nucleus	1309			
43-1 NUCLEAR FISSION	1309			
What Is Physics?	1309			
Nuclear Fission: The Basic Process	1310			
A Model for Nuclear Fission	1312			
43-2 THE NUCLEAR REACTOR	1316			
The Nuclear Reactor	1316			
43-3 A NATURAL NUCLEAR REACTOR	1320			
A Natural Nuclear Reactor	1320			
43-4 THERMONUCLEAR FUSION: THE BASIC PROCESS	1322			
Thermonuclear Fusion: The Basic Process	1322			
43-5 THERMONUCLEAR FUSION IN THE SUN AND OTHER STARS	1324			
Thermonuclear Fusion in the Sun and Other Stars	1324			
43-6 CONTROLLED THERMONUCLEAR FUSION	1326			
Controlled Thermonuclear Fusion	1326			
REVIEW & SUMMARY	1329	QUESTIONS	1329	PROBLEMS 1330
44 Quarks, Leptons, and the Big Bang	1334			
44-1 GENERAL PROPERTIES OF ELEMENTARY PARTICLES	1334			
What Is Physics?	1334			
Particles, Particles, Particles	1335			
An Interlude	1339			
44-2 LEPTONS, HADRONS, AND STRANGENESS	1343			
The Leptons	1343			

The Hadrons 1345
Still Another Conservation Law 1346
The Eightfold Way 1347

44-3 QUARKS AND MESSENGER PARTICLES 1349
The Quark Model 1349
Basic Forces and Messenger Particles 1352

44-4 COSMOLOGY 1355
A Pause for Reflection 1355
The Universe Is Expanding 1356
The Cosmic Background Radiation 1357
Dark Matter 1358
The Big Bang 1358
A Summing Up 1361

REVIEW & SUMMARY 1362 QUESTIONS 1362 PROBLEMS 1363

APPENDICES

A The International System of Units (SI) A-1
B Some Fundamental Constants of Physics A-3
C Some Astronomical Data A-4
D Conversion Factors A-5
E Mathematical Formulas A-9
F Properties of The Elements A-12
G Periodic Table of The Elements A-15

ANSWERS

to Checkpoints and Odd-Numbered Questions and Problems AN-1

INDEX I-1