**MATHEMATICAL FORMULAS\**Quadratic Formula***

***Derivatives and Integrals***

If , then

*x*  *b*  1*b*~~2~~  4*ac*

sin *x dx*  cos *x ddx*sin *x*  cos *x*

2*a ax*2  *bx*  *c*  0

***Binomial Theorem***

(1 *x*)*n*  1 *nx*1! *n*(*n*  1)*x*2

cos *x dx*  sin *x ddx*cos *x*  sin *x*  *ex dx*  *ex ddx ex*  *ex*

2!

... (*x*2 1)

***Products of Vectors***

*b*:

*dx*

2*x*2  *a*2  ln(*x*  2*x*2  *a*2)

Let u be the smaller of the two angles between and .

*a*:

Then

*a*: *b*: *b*: *a*:

*axbx* *ayby* *azbz* *ab* cos u

*x dx*

(*x*2  *a*2)3/2 1

(*x*2  *a*2)1/2

*dx*

*a*:  *b*:  *b*:  *a*:

iˆ

*ax bx*

jˆ

*ay by*

kˆ

*bz* *az*

(*x*2  *a*2)3/2 *x*

*a*2(*x*2  *a*2)1/2

***Cramer’s Rule***

iˆ  *ay by*

*bz*  jˆ *ax*

*az*

*bx*

*bz*  kˆ  *ax*

*az*

*bx*

*ay by*

Two simultaneous equations in unknowns *x* and *y*, *a*1*x*  *b*1*y*  *c*1 and *a*2*x*  *b*2*y*  *c*2,

(*axby*  *bxay*  )kˆ (*aybz*  *by az*)iˆ  (*azbx*  *bzax*)jˆ |*a*:  *b*:| *ab* sin u

***Trigonometric Identities***

have the solutions and

*x*

*c*1 *c*2

*a*1 *a*2

*b*1 *b*2 *b*1

*b*2

*c*1*b*2  *c*2*b*1 *a*1*b*2  *a*2*b*1

sin a sin b 2 sin 12(a b) cos 12(a b)

*y*  ~~.~~  *a*1 *c*1

*c*2

*a*2

cos a cos b 2 cos 12(a b) cos 12(a b)

*a*1

*b*1

*b*2

*a*2

\*See Appendix E for a more complete list.

**SI PREFIXES\***

*a*1*c*2  *a*2*c*1 *a*1*b*2  *a*2*b*1

Factor Prefix Symbol Factor Prefix Symbol

1024 yotta Y 10–1 deci d 1021 zetta Z 10–2 centi c 1018 exa E 10–3 milli m 1015 peta P 10–6 micro m 1012 tera T 10–9 nano n 109 giga G 10–12 pico p 106 mega M 10–15 femto f 103 kilo k 10–18 atto a 102 hecto h 10–21 zepto z 101 deka da 10–24 yocto y

\*In all cases, the first syllable is accented, as in ná-no-mé-ter.

**EXTENDED**

FUNDAMENTALS OF PHYSICS **TENTH EDITION**

*This page intentionally left blank*

**EXTENDED**

Halliday & Resnick

FUNDAMENTALS OF PHYSICS **TENTH EDITION**

**JEARL WALKER**

CLEVELAND STATE UNIVERSITY

EXECUTIVE EDITOR Stuart Johnson

SENIOR PRODUCT DESIGNER Geraldine Osnato

CONTENT EDITOR Alyson Rentrop

ASSOCIATE MARKETING DIRECTOR Christine Kushner

TEXT and COVER DESIGNER Madelyn Lesure

PAGE MAKE-UP Lee Goldstein

PHOTO EDITOR Jennifer Atkins

COPYEDITOR Helen Walden

PROOFREADER Lilian Brady

SENIOR PRODUCTION EDITOR Elizabeth Swain

COVER IMAGE © 2007 CERN

This book was set in 10/12 Times Ten by cMPreparé, CSR Francesca Monaco, and was printed and bound by Quad Graphics.The cover was printed by Quad Graphics.

This book is printed on acid free paper.

Copyright © 2014, 2011, 2008, 2005 John Wiley & Sons, Inc. All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except as permitted under Sections 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc. 222 Rosewood Drive, Danvers, MA 01923, website www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030-5774, (201)748-6011, fax (201)748-6008, or online at http://www.wiley.com/go/permissions.

Evaluation copies are provided to qualified academics and professionals for review purposes only, for use in their courses during the next academic year.These copies are licensed and may not be sold or transferred to a third party. Upon completion of the review period, please return the evalua tion copy to Wiley. Return instructions and a free of charge return shipping label are available at www.wiley.com/go/returnlabel. Outside of the United States, please contact your local representative.

Library of Congress Cataloging-in-Publication Data

Walker, Jearl

Fundamentals of physics / Jearl Walker, David Halliday, Robert Resnick—10th edition. volumes cm

Includes index.

ISBN 978-1-118-23072-5 (Extended edition)

Binder-ready version ISBN 978-1-118-23061-9 (Extended edition)

1. Physics—Textbooks. I. Resnick, Robert. II. Halliday, David. III. Title.

QC21.3.H35 2014

530—dc23

2012035307

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

**BRIEF CONTENTS**

**V O L U M E 1**

**1** Measurement

**2** Motion Along a Straight Line

**3** Vectors

**4** Motion in Two and Three Dimensions

**5** Force and Motion—I

**6** Force and Motion—II

**7** Kinetic Energy and Work

**8** Potential Energy and Conservation of Energy **9** Center of Mass and Linear Momentum **10** Rotation

**11** Rolling, Torque, and Angular Momentum **12** Equilibrium and Elasticity

**13** Gravitation

**14** Fluids

**15** Oscillations

**16** Waves—I

**17** Waves—II

**18** Temperature, Heat, and the First Law of Thermodynamics

**19** The Kinetic Theory of Gases

**20** Entropy and the Second Law of Thermodynamics

**V O L U M E 2**

**21** Coulomb’s Law

**22** Electric Fields

**23** Gauss’ Law

**24** Electric Potential

**25** Capacitance

**26** Current and Resistance

**27** Circuits

**28** Magnetic Fields

**29** Magnetic Fields Due to Currents **30** Induction and Inductance

**31** Electromagnetic Oscillations and Alternating Current

**32** Maxwell’s Equations; Magnetism of Matter **33** Electromagnetic Waves

**34** Images

**35** Interference

**36** Diffraction

**37** Relativity

**38** Photons and Matter Waves

**39** More About Matter Waves

**40** All About Atoms

**41** Conduction of Electricity in Solids **42** Nuclear Physics

**43** Energy from the Nucleus

**44** Quarks, Leptons, and the Big Bang

Appendices / Answers to Checkpoints and Odd-Numbered Questions and Problems / Index

v

**CONTENTS**

**1** Measurement 1

**1-1** MEASURING THINGS, INCLUDING LENGTHS 1

What Is Physics? 1

Measuring Things 1

The International System of Units 2

Changing Units 3

Length 3

Significant Figures and Decimal Places 4

**1-2** TIME 5

Time 5

**1-3** MASS 6

Mass 6

REVIEW & SUMMARY 8 PROBLEMS 8

**2** Motion Along a Straight Line 13

**2-1** POSITION, DISPLACEMENT, AND AVERAGE VELOCITY 13 What Is Physics? 13

Motion 14

Position and Displacement 14

Average Velocity and Average Speed 15

**2-2** INSTANTANEOUS VELOCITY AND SPEED 18

Instantaneous Velocity and Speed 18

**2-3** ACCELERATION 20

Acceleration 20

**2-4** CONSTANT ACCELERATION 23

Constant Acceleration: A Special Case 23

Another Look at Constant Acceleration 26

**2-5** FREE-FALL ACCELERATION 27

Free-Fall Acceleration 27

**2-6** GRAPHICAL INTEGRATION IN MOTION ANALYSIS 29

Graphical Integration in Motion Analysis 29

REVIEW & SUMMARY 30 QUESTIONS 31 PROBLEMS 32

**3** Vectors 40

**3-1** VECTORS AND THEIR COMPONENTS 40

What Is Physics? 40

Vectors and Scalars 40

Adding Vectors Geometrically 41

Components of Vectors 42

**3-2** UNIT VECTORS, ADDING VECTORS BY COMPONENTS 46 Unit Vectors 46

Adding Vectors by Components 46

Vectors and the Laws of Physics 47

**3-3** MULTIPLYING VECTORS 50

Multiplying Vectors 50

REVIEW & SUMMARY 55 QUESTIONS 56 PROBLEMS 57

**4** Motion in Two and Three Dimensions 62

**4-1** POSITION AND DISPLACEMENT 62

What Is Physics? 62

Position and Displacement 63

**4-2** AVERAGE VELOCITY AND INSTANTANEOUS VELOCITY 64 Average Velocity and Instantaneous Velocity 65

**4-3** AVERAGE ACCELERATION AND INSTANTANEOUS ACCELERATION 67 Average Acceleration and Instantaneous Acceleration 68

**4-4** PROJECTILE MOTION 70

Projectile Motion 70

**4-5** UNIFORM CIRCULAR MOTION 76

Uniform Circular Motion 76

**4-6** RELATIVE MOTION IN ONE DIMENSION 78

Relative Motion in One Dimension 78

**4-7** RELATIVE MOTION IN TWO DIMENSIONS 80

Relative Motion in Two Dimensions 80

REVIEW & SUMMARY 81 QUESTIONS 82 PROBLEMS 84

**5** Force and Motion—I 94

**5-1** NEWTON’S FIRST AND SECOND LAWS 94

What Is Physics? 94

Newtonian Mechanics 95

Newton’s First Law 95

Force 96

Mass 97

Newton’s Second Law 98

**5-2** SOME PARTICULAR FORCES 102

Some Particular Forces 102

**5-3** APPLYING NEWTON’S LAWS 106

Newton’s Third Law 106

Applying Newton’s Laws 108

REVIEW & SUMMARY 114 QUESTIONS 114 PROBLEMS 116

vi

**6** Force and Motion—II 124

**6-1** FRICTION 124

What Is Physics? 124

Friction 124

Properties of Friction 127

**6-2** THE DRAG FORCE AND TERMINAL SPEED 130

The Drag Force and Terminal Speed 130

**6-3** UNIFORM CIRCULAR MOTION 133

Uniform Circular Motion 133

REVIEW & SUMMARY 138 QUESTIONS 139 PROBLEMS 140

**7** Kinetic Energy and Work 149

**7-1** KINETIC ENERGY 149

What Is Physics? 149

What Is Energy? 149

Kinetic Energy 150

**7-2** WORK AND KINETIC ENERGY 151

Work 151

Work and Kinetic Energy 152

**7-3** WORK DONE BY THE GRAVITATIONAL FORCE 155 Work Done by the Gravitational Force 156

**7-4** WORK DONE BY A SPRING FORCE 159

Work Done by a Spring Force 159

**7-5** WORK DONE BY A GENERAL VARIABLE FORCE 162 Work Done by a General Variable Force 162

**7-6** POWER 166

Power 166

REVIEW & SUMMARY 168 QUESTIONS 169 PROBLEMS 170

**8** Potential Energy and Conservation of Energy 177 **8-1** POTENTIAL ENERGY 177

What Is Physics? 177

Work and Potential Energy 178

Path Independence of Conservative Forces 179

Determining Potential Energy Values 181

**8-2** CONSERVATION OF MECHANICAL ENERGY 184 Conservation of Mechanical Energy 184

**8-3** READING A POTENTIAL ENERGY CURVE 187

Reading a Potential Energy Curve 187

CONTENTS vii

**8-4** WORK DONE ON A SYSTEM BY AN EXTERNAL FORCE 191 Work Done on a System by an External Force 192

**8-5** CONSERVATION OF ENERGY 195

Conservation of Energy 195

REVIEW & SUMMARY 199 QUESTIONS 200 PROBLEMS 202

**9** Center of Mass and Linear Momentum 214

**9-1** CENTER OF MASS 214

What Is Physics? 214

The Center of Mass 215

**9-2** NEWTON’S SECOND LAW FOR A SYSTEM OF PARTICLES 220 Newton’s Second Law for a System of Particles 220

**9-3** LINEAR MOMENTUM 224

Linear Momentum 224

The Linear Momentum of a System of Particles 225

**9-4** COLLISION AND IMPULSE 226

Collision and Impulse 226

**9-5** CONSERVATION OF LINEAR MOMENTUM 230

Conservation of Linear Momentum 230

**9-6** MOMENTUM AND KINETIC ENERGY IN COLLISIONS 233 Momentum and Kinetic Energy in Collisions 233

Inelastic Collisions in One Dimension 234

**9-7** ELASTIC COLLISIONS IN ONE DIMENSION 237

Elastic Collisions in One Dimension 237

**9-8** COLLISIONS IN TWO DIMENSIONS 240

Collisions in Two Dimensions 240

**9-9** SYSTEMS WITH VARYING MASS: A ROCKET 241

Systems with Varying Mass: A Rocket 241

REVIEW & SUMMARY 243 QUESTIONS 245 PROBLEMS 246

**10** Rotation 257

**10-1** ROTATIONAL VARIABLES 257

What Is Physics? 258

Rotational Variables 259

Are Angular Quantities Vectors? 264

**10-2** ROTATION WITH CONSTANT ANGULAR ACCELERATION 266 Rotation with Constant Angular Acceleration 266

**10-3** RELATING THE LINEAR AND ANGULAR VARIABLES 268 Relating the Linear and Angular Variables 268

viii CONTENTS

**10-4** KINETIC ENERGY OF ROTATION 271

Kinetic Energy of Rotation 271

**10-5** CALCULATING THE ROTATIONAL INERTIA 273

Calculating the Rotational Inertia 273

**10-6** TORQUE 277

Torque 278

**10-7** NEWTON’S SECOND LAW FOR ROTATION 279

Newton’s Second Law for Rotation 279

**10-8** WORK AND ROTATIONAL KINETIC ENERGY 282

Work and Rotational Kinetic Energy 282

REVIEW & SUMMARY 285 QUESTIONS 286 PROBLEMS 287

**11** Rolling, Torque, and Angular Momentum 295 **11-1** ROLLING AS TRANSLATION AND ROTATION COMBINED 295 What Is Physics? 295

Rolling as Translation and Rotation Combined 295

**11-2** FORCES AND KINETIC ENERGY OF ROLLING 298 The Kinetic Energy of Rolling 298

The Forces of Rolling 299

**11-3** THE YO-YO 301

The Yo-Yo 302

**11-4** TORQUE REVISITED 302

Torque Revisited 303

**11-5** ANGULAR MOMENTUM 305

Angular Momentum 305

**11-6** NEWTON’S SECOND LAW IN ANGULAR FORM 307 Newton’s Second Law in Angular Form 307

**11-7** ANGULAR MOMENTUM OF A RIGID BODY 310

The Angular Momentum of a System of Particles 310

The Angular Momentum of a Rigid Body Rotating About a Fixed Axis 311

**11-8** CONSERVATION OF ANGULAR MOMENTUM 312 Conservation of Angular Momentum 312

**11-9** PRECESSION OF A GYROSCOPE 317

Precession of a Gyroscope 317

REVIEW & SUMMARY 318 QUESTIONS 319 PROBLEMS 320

**12** Equilibrium and Elasticity 327

**12-1** EQUILIBRIUM 327

What Is Physics? 327

Equilibrium 327

The Requirements of Equilibrium 329

The Center of Gravity 330

**12-2** SOME EXAMPLES OF STATIC EQUILIBRIUM 332 Some Examples of Static Equilibrium 332

**12-3** ELASTICITY 338

Indeterminate Structures 338

Elasticity 339

REVIEW & SUMMARY 343 QUESTIONS 343 PROBLEMS 345

**13** Gravitation 354

**13-1** NEWTON’S LAW OF GRAVITATION 354

What Is Physics? 354

Newton’s Law of Gravitation 355

**13-2** GRAVITATION AND THE PRINCIPLE OF SUPERPOSITION 357 Gravitation and the Principle of Superposition 357

**13-3** GRAVITATION NEAR EARTH’S SURFACE 359

Gravitation Near Earth’s Surface 360

**13-4** GRAVITATION INSIDE EARTH 362

Gravitation Inside Earth 363

**13-5** GRAVITATIONAL POTENTIAL ENERGY 364

Gravitational Potential Energy 364

**13-6** PLANETS AND SATELLITES: KEPLER’S LAWS 368 Planets and Satellites: Kepler’s Laws 369

**13-7** SATELLITES: ORBITS AND ENERGY 371

Satellites: Orbits and Energy 371

**13-8** EINSTEIN AND GRAVITATION 374

Einstein and Gravitation 374

REVIEW & SUMMARY 376 QUESTIONS 377 PROBLEMS 378

**14** Fluids 386

**14-1** FLUIDS, DENSITY, AND PRESSURE 386

What Is Physics? 386

What Is a Fluid? 386

Density and Pressure 387

**14-2** FLUIDS AT REST 388

Fluids at Rest 389

**14-3** MEASURING PRESSURE 392

Measuring Pressure 392

CONTENTS ix

**14-4** PASCAL’S PRINCIPLE 393

**16-4** THE WAVE EQUATION 456

Pascal’s Principle 393

**14-5** ARCHIMEDES’ PRINCIPLE 394

Archimedes’ Principle 395

**14-6** THE EQUATION OF CONTINUITY 398

Ideal Fluids in Motion 398

The Equation of Continuity 399

**14-7** BERNOULLI’S EQUATION 401

Bernoulli’s Equation 401

REVIEW & SUMMARY 405 QUESTIONS 405 PROBLEMS 406

**15** Oscillations 413

**15-1** SIMPLE HARMONIC MOTION 413

What Is Physics? 414

Simple Harmonic Motion 414

The Force Law for Simple Harmonic Motion 419

**15-2** ENERGY IN SIMPLE HARMONIC MOTION 421

Energy in Simple Harmonic Motion 421

**15-3** AN ANGULAR SIMPLE HARMONIC OSCILLATOR 423 An Angular Simple Harmonic Oscillator 423

**15-4** PENDULUMS, CIRCULAR MOTION 424

Pendulums 425

Simple Harmonic Motion and Uniform Circular Motion 428

**15-5** DAMPED SIMPLE HARMONIC MOTION 430

Damped Simple Harmonic Motion 430

**15-6** FORCED OSCILLATIONS AND RESONANCE 432 Forced Oscillations and Resonance 432

REVIEW & SUMMARY 434 QUESTIONS 434 PROBLEMS 436

**16** Waves—I 444

**16-1** TRANSVERSE WAVES 444

What Is Physics? 445

Types of Waves 445

Transverse and Longitudinal Waves 445

Wavelength and Frequency 446

The Speed of a Traveling Wave 449

**16-2** WAVE SPEED ON A STRETCHED STRING 452

Wave Speed on a Stretched String 452

**16-3** ENERGY AND POWER OF A WAVE TRAVELING ALONG A STRING 454

Energy and Power of a Wave Traveling Along a String 454

The Wave Equation 456

**16-5** INTERFERENCE OF WAVES 458

The Principle of Superposition for Waves 458

Interference of Waves 459

**16-6** PHASORS 462

Phasors 462

**16-7** STANDING WAVES AND RESONANCE 465

Standing Waves 465

Standing Waves and Resonance 467

REVIEW & SUMMARY 470 QUESTIONS 471 PROBLEMS 472

**17** Waves—II 479

**17-1** SPEED OF SOUND 479

What Is Physics? 479

Sound Waves 479

The Speed of Sound 480

**17-2** TRAVELING SOUND WAVES 482

Traveling Sound Waves 482

**17-3** INTERFERENCE 485

Interference 485

**17-4** INTENSITY AND SOUND LEVEL 488

Intensity and Sound Level 489

**17-5** SOURCES OF MUSICAL SOUND 492

Sources of Musical Sound 493

**17-6** BEATS 496

Beats 497

**17-7** THE DOPPLER EFFECT 498

The Doppler Effect 499

**17-8** SUPERSONIC SPEEDS, SHOCK WAVES 503

Supersonic Speeds, Shock Waves 503

REVIEW & SUMMARY 504 QUESTIONS 505 PROBLEMS 506

**18** Temperature, Heat, and the First Law of Thermodynamics 514 **18-1** TEMPERATURE 514

What Is Physics? 514

Temperature 515

The Zeroth Law of Thermodynamics 515

Measuring Temperature 516

**18-2** THE CELSIUS AND FAHRENHEIT SCALES 518

The Celsius and Fahrenheit Scales 518

x CONTENTS

**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

CONTENTS xi

**23** Gauss’ Law 659

**25** Capacitance 717

**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

**25-1** 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

xii CONTENTS

**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

*B*:

**28-1** MAGNETIC FIELDS AND THE DEFINITION OF 803 What Is Physics? 803

What Produces a Magnetic Field? 804

*B*:

The Definition of 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

CONTENTS xiii

**31-5** POWER IN ALTERNATING-CURRENT CIRCUITS 927

**33-5** REFLECTION AND REFRACTION 990

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

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

xiv CONTENTS

**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

CONTENTS xv

**40** All About Atoms 1219

**42-2** SOME NUCLEAR PROPERTIES 1279

**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

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

xvi CONTENTS

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

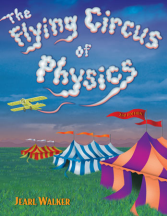
G Periodic Table of The Elements A-15

ANSWERS

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

**PREFACE**

**WHY I WROTE THIS BOOK**

Fun with a big challenge. That is how I have regarded physics since the day when Sharon, one of the students in a class I taught as a graduate student, suddenly demanded of me, “What has any of this got to do with my life?” Of course I immediately responded, “Sharon, this has everything to do with your life—this is physics.” 

She asked me for an example. I thought and thought but could not come up

with a single one.That night I began writing the book *The Flying Circus of Physics*

(John Wiley & Sons Inc., 1975) for Sharon but also for me because I realized her

complaint was mine. I had spent six years slugging my way through many dozens of

physics textbooks that were carefully written with the best of pedagogical plans, but

there was something missing. Physics is the most interesting subject in the world

because it is about how the world works, and yet the textbooks had been thor

oughly wrung of any connection with the real world.The fun was missing.

I have packed a lot of real-world physics into *Fundamentals of Physics*, con

necting it with the new edition of *The Flying Circus of Physics*. Much of the mate

rial comes from the introductory physics classes I teach, where I can judge from the

faces and blunt comments what material and presentations work and what do not.

The notes I make on my successes and failures there help form the basis of this

book. My message here is the same as I had with every student I’ve met since

Sharon so long ago: “Yes, you *can* reason from basic physics concepts all the way to

valid conclusions about the real world, and that understanding of the real world is

where the fun is.”

I have many goals in writing this book but the overriding one is to provide in

structors with tools by which they can teach students how to effectively read scientific material, iden tify fundamental concepts, reason through scientific questions, and solve quantitative problems. This process is not easy for either students or instructors. Indeed, the course associated with this book may be one of the most challenging of all the courses taken by a student. However, it can also be one of the most rewarding because it reveals the world’s fundamental clockwork from which all scientific and engineering applications spring.

Many users of the ninth edition (both instructors and students) sent in comments and suggestions to improve the book. These improvements are now incorporated into the narrative and problems throughout the book. The publisher John Wiley & Sons and I regard the book as an ongoing project and encourage more input from users. You can send suggestions, corrections, and positive or negative comments to John Wiley & Sons or Jearl Walker (mail address: Physics Department, Cleveland State University, Cleveland, OH 44115 USA; or the blog site at www.flyingcircusofphysics.com). We may not be able to respond to all suggestions, but we keep and study each of them.

**WHAT’S NEW?**

**Modules and Learning Objectives** “What was I supposed to learn from this section?” Students have asked me this question for decades, from the weakest student to the strongest. The problem is that even a thoughtful student may not feel confident that the important points were captured while read ing a section. I felt the same way back when I was using the first edition of Halliday and Resnick while taking first-year physics.

To ease the problem in this edition, I restructured the chapters into concept modules based on a primary theme and begin each module with a list of the module’s learning objectives. The list is an explicit statement of the skills and learning points that should be gathered in reading the module. Each list is following by a brief summary of the key ideas that should also be gathered. For example, check out the first module in Chapter 16, where a student faces a truck load of concepts and terms. Rather than depending on the student’s ability to gather and sort those ideas, I now provide an explicit checklist that functions somewhat like the checklist a pilot works through before taxiing out to the runway for takeoff.

xvii

xviii

**Links Between Homework Problems and Learning Objectives** In *WileyPLUS*, every question and prob lem at the end of the chapter is linked to a learning objective, to answer the (usually unspoken) ques tions, “Why am I working this problem? What am I supposed to learn from it?” By being explicit about a problem’s purpose, I believe that a student might better transfer the learning objective to other problems with a different wording but the same key idea. Such transference would help defeat the common trouble that a student learns to work a particular problem but cannot then apply its key idea to a problem in a different setting.

**Rewritten Chapters** My students have continued to be challenged by several key chapters and by spots in several other chapters and so, in this edition, I rewrote a lot of the material. For example, I redesigned the chapters on Gauss’ law and electric potential, which have proved to be tough-going for my students. The presentations are now smoother and more direct to the key points. In the quan tum chapters, I expanded the coverage of the Schrödinger equation, including reflection of matter waves from a step potential. At the request of several instructors, I decoupled the discussion of the Bohr atom from the Schrödinger solution for the hydrogen atom so that the historical account of Bohr’s work can be bypassed. Also, there is now a module on Planck’s blackbody radiation.

**New Sample Problems and Homework Questions and Problems** Sixteen new sample problems have been added to the chapters, written so as to spotlight some of the difficult areas for my students.Also, about 250 problems and 50 questions have been added to the homework sections of the chapters. Some of these problems come from earlier editions of the 

book, as requested by several instructors.

**Video Illustrations** In the eVersion of the text available in

*WileyPLUS*, David Maiullo of Rutgers University has

created video versions of approximately 30 of the photo

graphs and figures from the text. Much of physics is the

study of things that move and video can often provide a

better representation than a static photo or figure.

**Online Aid** *WileyPLUS* is not just an online grading pro

gram. Rather, it is a dynamic learning center stocked with many different learning aids, including just-in-time problem-solving tutorials, embedded reading quizzes to encourage reading, animated figures, hundreds of sample problems, loads of simulations and demonstrations, and over 1500 videos ranging from math reviews to mini-lectures to examples. More of these learning aids are added every semester. For this 10th edition of HRW, some of the photos involving motion have been converted into videos so that the motion can be slowed and analyzed.

These thousands of learning aids are available 24/7 and can be repeated as many times as de sired. Thus, if a student gets stuck on a homework problem at, say, 2:00 AM (which appears to be a popular time for doing physics homework), friendly and helpful resources are available at the click of a mouse.

**LEARNINGS TOOLS**

When I learned first-year physics in the first edition of

Halliday and Resnick, I caught on by repeatedly reread

ing a chapter. These days we better understand that

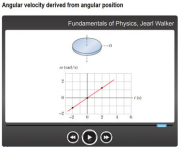
students have a wide range of learning styles. So, I have

produced a wide range of learning tools, both in this new

edition and online in *WileyPLUS*:

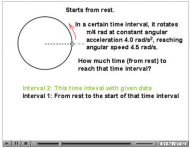
PREFACE

A

**Animations** of one of the key figures in each chapter. Here in the book, those figures are flagged with the swirling icon. In the online chapter in *WileyPLUS*, a mouse click begins the animation. I have chosen the fig ures that are rich in information so that a student can see the physics in action and played out over a minute or two 

PREFACE xix

instead of just being flat on a printed page. Not only does this give life to the physics, but the anima tion can be repeated as many times as a student wants.

**Videos** I have made well over 1500 instructional videos, with more coming each semester. Students can watch me draw or type on the screen as they hear me talk about a solution, tutorial, sample prob lem, or review, very much as they would experience were they sitting next to me in my office while I worked out something on a notepad. An instructor’s lectures and tutoring will always be the most valuable learning tools, but my videos are available 24 hours a day, 7 days a 

week, and can be repeated indefinitely.

• **Video tutorials on subjects in the chapters.** I chose the subjects that chal

lenge the students the most, the ones that my students scratch their heads

about.

• **Video reviews of high school math**, such as basic algebraic manipulations,

trig functions, and simultaneous equations.

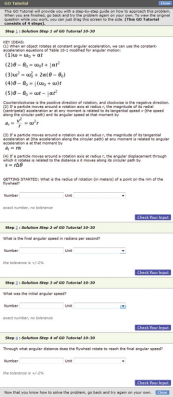
• **Video introductions to math**, such as vector multiplication, that will be new

to the students.

• **Video presentations of every Sample Problem** in the textbook chapters . My

intent is to work out the physics, starting with the Key Ideas instead of just

grabbing a formula. However, I also want to demonstrate how to read a sam

ple problem, that is, how to read technical material to learn problem-solving 

procedures that can be transferred to other types of problems.

• **Video solutions to 20% of the end-of chapter problems.** The availability and

timing of these solutions are controlled by the instructor. For example, they

might be available after a homework deadline or a quiz. Each solution is not

simply a plug-and-chug recipe. Rather I build a solution from the Key Ideas to

the first step of reasoning and to a final solution. The student learns not just

how to solve a particular problem but how to tackle any problem, even those

that require *physics courage*.

• **Video examples of how to read data from graphs** (more than simply reading

off a number with no comprehension of the physics).

**Problem-Solving Help** I have written a large number of resources for

*WileyPLUS* designed to help build the students’ problem-solving skills.

• **Every sample problem in the textbook** is available online in both reading

and video formats.

• **Hundreds of additional sample problems.** These are available as stand

alone resources but (at the discretion of the instructor) they are also linked

out of the homework problems. So, if a homework problem deals with, say,

forces on a block on a ramp, a link to a related sample problem is provided.

However, the sample problem is not just a replica of the homework problem

and thus does not provide a solution that can be merely duplicated without

comprehension.

• **GO Tutorials** for 15% of the end-of-chapter homework problems. In multi

ple steps, I lead a student through a homework problem, starting with the Key

Ideas and giving hints when wrong answers are submitted. However, I pur

posely leave the last step (for the final answer) to the student so that they are

responsible at the end. Some online tutorial systems trap a student when

wrong answers are given, which can generate a lot of frustration. My GO

Tutorials are not traps, because at any step along the way, a student can return

to the main problem.

• **Hints on every end-of-chapter homework problem** are available (at the

discretion of the instructor). I wrote these as true hints about the main ideas

and the general procedure for a solution, not as recipes that provide an answer without any comprehension.

xx

PREFACE

**Evaluation Materials**

• **Reading questions are available within each online section.** I wrote these so that they do not require analysis or any deep understanding; rather they simply test whether a student has read the section. When a student opens up a section, a randomly chosen reading question (from a bank of questions) appears at the end. The instructor can decide whether the question is part of the grading for that section or whether it is just for the benefit of the student.

• **Checkpoints are available within most sections.** I wrote these so that they require analysis and deci sions about the physics in the section. *Answers to all checkpoints are in the back of the book*.

**Checkpoint 1**

Here are three pairs of initial and final positions, respectively, along an *x* axis.Which

pairs give a negative displacement: (a) 3 m, 5 m; (b) 3 m, 7 m; (c) 7 m, 3 m?

• **All end-of-chapter homework Problems** in the book (and many more problems) are available in *WileyPLUS*. The instructor can construct a homework assignment and control how it is graded when the answers are submitted online. For example, the instructor controls the deadline for submission and how many attempts a student is allowed on an answer. The instructor also controls which, if any, learning aids are available with each homework problem. Such links can include hints, sample prob lems, in-chapter reading materials, video tutorials, video math reviews, and even video solutions (which can be made available to the students after, say, a homework deadline).

• **Symbolic notation problems** that require algebraic answers are available in every chapter.

• **All end-of-chapter homework Questions** in the book are available for assignment in *WileyPLUS*. These Questions (in a multiple choice format) are designed to evaluate the students’ conceptual un derstanding.

**Icons for Additional Help** When worked-out solutions are provided either in print or electronically for certain of the odd-numbered problems, the statements for those problems include an icon to alert both student and instructor as to where the solutions are located. There are also icons indicating which problems have GO Tutorial, an Interactive LearningWare, or a link to the *The Flying Circus of Physics*. An icon guide is provided here and at the beginning of each set of problems.

Tutoring problem available (at instructor’s discretion) in *WileyPLUS* and WebAssign

**SSM** Worked-out solution available in Student Solutions Manual **•** – **•••** Number of dots indicates level of problem difficulty

**WWW** Worked-out solution is at

**ILW** Interactive solution is at http://www.wiley.com/college/halliday

Additional information available in *The Flying Circus of Physics* and at flyingcircusofphysics.com

**VERSIONS OF THE TEXT**

To accommodate the individual needs of instructors and students, the ninth edition of *Fundamentals of Physics* is available in a number of different versions.

The **Regular Edition** consists of Chapters 1 through 37 (ISBN 9781118230718).

The **Extended Edition** contains seven additional chapters on quantum physics and cosmology, Chapters 1–44 (ISBN 9781118230725).

**Volume 1** –– Chapters 1–20 (Mechanics and Thermodynamics), hardcover,

ISBN 9781118233764

**Volume 2** –– Chapters 21–44 (E&M, Optics, and Quantum Physics), hardcover,

ISBN 9781118230732

PREFACE xxi

**INSTRUCTOR SUPPLEMENTS**

**Instructor’s Solutions Manual** by Sen-Ben Liao, Lawrence Livermore National Laboratory. This man ual provides worked-out solutions for all problems found at the end of each chapter. It is available in both MSWord and PDF.

**Instructor Companion Site** http://www.wiley.com/college/halliday

• **Instructor’s Manual** This resource contains lecture notes outlining the most important topics of each chapter; demonstration experiments; laboratory and computer projects; film and video sources; answers to all Questions, Exercises, Problems, and Checkpoints; and a correlation guide to the Questions, Exercises, and Problems in the previous edition. It also contains a complete list of all problems for which solutions are available to students (SSM,WWW, and ILW).

• **Lecture PowerPoint Slides** These PowerPoint slides serve as a helpful starter pack for instructors, outlining key concepts and incorporating figures and equations from the text.

• **Classroom Response Systems (“Clicker”) Questions** by David Marx, Illinois State University. There are two sets of questions available: Reading Quiz questions and Interactive Lecture ques tions.The Reading Quiz questions are intended to be relatively straightforward for any student who reads the assigned material.The Interactive Lecture questions are intended for use in an interactive lecture setting.

• **Wiley Physics Simulations** by Andrew Duffy, Boston University and John Gastineau, Vernier Software. This is a collection of 50 interactive simulations (Java applets) that can be used for class room demonstrations.

• **Wiley Physics Demonstrations** by David Maiullo, Rutgers University. This is a collection of digital videos of 80 standard physics demonstrations. They can be shown in class or accessed from *WileyPLUS*.There is an accompanying Instructor’s Guide that includes “clicker” questions.

• **Test Bank** For the 10th edition, the Test Bank has been completely over-hauled by Suzanne Willis, Northern Illinois University. The Test Bank includes more than 2200 multiple-choice questions. These items are also available in the Computerized Test Bank which provides full editing features to help you customize tests (available in both IBM and Macintosh versions).

• **All text illustrations** suitable for both classroom projection and printing.

**Online Homework and Quizzing.** In addition to *WileyPLUS*, *Fundamentals of Physics*, tenth edition, also supports WebAssignPLUS and LON-CAPA, which are other programs that give instructors the ability to deliver and grade homework and quizzes online. WebAssign PLUS also offers students an online version of the text.

**STUDENT SUPPLEMENTS**

**Student Companion Site.** The web site http://www.wiley.com/college/halliday was developed specifi cally for *Fundamentals of Physics*, tenth edition, and is designed to further assist students in the study of physics. It includes solutions to selected end-of-chapter problems (which are identified with a www icon in the text); simulation exercises; tips on how to make best use of a programmable calcu lator; and the Interactive LearningWare tutorials that are described below.

**Student Study Guide** (ISBN 9781118230787) by Thomas Barrett of Ohio State University. The Student Study Guide consists of an overview of the chapter’s important concepts, problem solving techniques and detailed examples.

**Student Solutions Manual** (ISBN 9781118230664) by Sen-Ben Liao, Lawrence Livermore National Laboratory. This manual provides students with complete worked-out solutions to 15 percent of the problems found at the end of each chapter within the text. The Student Solutions Manual for the 10th edition is written using an innovative approach called TEAL which stands for Think, Express, Analyze, and Learn.This learning strategy was originally developed at the Massachusetts Institute of Technology and has proven to be an effective learning tool for students. These problems with TEAL solutions are indicated with an SSM icon in the text.

xxii PREFACE

**Interactive Learningware.** This software guides students through solutions to 200 of the end-of-chapter problems. These problems are indicated with an ILW icon in the text. The solutions process is devel oped interactively, with appropriate feedback and access to error-specific help for the most common mistakes.

**Introductory Physics with Calculus as a Second Language:** (ISBN 9780471739104) *Mastering Problem Solving* by Thomas Barrett of Ohio State University. This brief paperback teaches the student how to approach problems more efficiently and effectively. The student will learn how to recognize common patterns in physics problems, break problems down into manageable steps, and apply appropriate techniques. The book takes the student step by step through the solutions to numerous examples.

**ACKNOWLEDGMENTS**

A great many people have contributed to this book. Sen-Ben Liao of Lawrence Livermore National Laboratory, James Whitenton of Southern Polytechnic State University, and Jerry Shi, of Pasadena City College, performed the Herculean task of working out solutions for every one of the homework problems in the book. At John Wiley publishers, the book received support from Stuart Johnson, Geraldine Osnato and Aly Rentrop, the editors who oversaw the entire project from start to finish. We thank Elizabeth Swain, the production editor, for pulling all the pieces together during the complex production process. We also thank Maddy Lesure for her design of the text and the cover; Lee Goldstein for her page make-up; Helen Walden for her copyediting; and Lilian Brady for her proofreading. Jennifer Atkins was inspired in the search for unusual and interesting photographs. Both the publisher John Wiley & Sons, Inc. and Jearl Walker would like to thank the following for comments and ideas about the recent editions:

Jonathan Abramson, *Portland State University*; Omar Adawi, *Parkland College*; Edward Adelson, *The Ohio State University*; Steven R. Baker, *Naval Postgraduate School*; George Caplan, *Wellesley College*; Richard Kass, *The Ohio State University*; M. R. Khoshbin-e-Khoshnazar, *Research Institution for Curriculum Development & Educational Innovations (Tehran)*; Craig Kletzing, *University of Iowa*, Stuart Loucks, *American River College*; Laurence Lurio, *Northern Illinois Universit*y; Ponn Maheswaranathan, *Winthrop University;* Joe McCullough, *Cabrillo College*; Carl E. Mungan, *U. S. Naval Academy*, Don N. Page, *University of Alberta*; Elie Riachi, *Fort Scott Community College*; Andrew G. Rinzler, *University of Florida*; Dubravka Rupnik, *Louisiana State University*; Robert Schabinger, *Rutgers University*; Ruth Schwartz, *Milwaukee School of Engineering*; Carol Strong, *University of Alabama at Huntsville*, Nora Thornber, *Raritan Valley Community College*; Frank Wang, *LaGuardia Community College*; Graham W. Wilson, *University of Kansas*; Roland Winkler, *Northern Illinois University*;William Zacharias, *Cleveland State University*; Ulrich Zurcher, *Cleveland State University*.

Finally, our external reviewers have been outstanding and we acknowledge here our debt to each member of that team.

Maris A.Abolins,*Michigan State University*

Edward Adelson, *Ohio State University*

Nural Akchurin,*Texas Tech*

Yildirim Aktas, *University of North Carolina-Charlotte* Barbara Andereck, *Ohio Wesleyan University* Tetyana Antimirova, *Ryerson University*

Mark Arnett, *Kirkwood Community College* Arun Bansil, *Northeastern University*

Richard Barber, *Santa Clara University*

Neil Basecu, *Westchester Community College* Anand Batra, *Howard University*

Kenneth Bolland,*The Ohio State University* Richard Bone, *Florida International University* Michael E. Browne, *University of Idaho*

Timothy J. Burns, *Leeward Community College* Joseph Buschi, *Manhattan College*

Philip A. Casabella, *Rensselaer Polytechnic Institute* Randall Caton, *Christopher Newport College* Roger Clapp, *University of South Florida*

W. R. Conkie, *Queen’s University*

Renate Crawford, *University of Massachusetts-Dartmouth* Mike Crivello, *San Diego State University*

Robert N. Davie, Jr., *St. Petersburg Junior College* Cheryl K. Dellai, *Glendale Community College* Eric R. Dietz, *California State University at Chico*

N. John DiNardo, *Drexel University*

Eugene Dunnam, *University of Florida*

Robert Endorf, *University of Cincinnati*

F. Paul Esposito, *University of Cincinnati*

Jerry Finkelstein, *San Jose State University*

Robert H. Good, *California State University-Hayward* Michael Gorman, *University of Houston*

Benjamin Grinstein, *University of California, San Diego* John B. Gruber, *San Jose State University*

Ann Hanks, *American River College*

Randy Harris, *University of California-Davis*

Samuel Harris,*Purdue University*

Harold B. Hart, *Western Illinois University*

Rebecca Hartzler, *Seattle Central Community College* John Hubisz, *North Carolina StateUniversity*

Joey Huston, *Michigan State University*

David Ingram, *Ohio University*

Shawn Jackson, *University of Tulsa*

Hector Jimenez, *University of Puerto Rico*

Sudhakar B. Joshi, *York University*

Leonard M. Kahn, *University of Rhode Island*

Sudipa Kirtley, *Rose-Hulman Institute*

Leonard Kleinman, *University of Texas at Austin* Craig Kletzing, *University of Iowa*

Peter F. Koehler, *University of Pittsburgh*

xxiii

xxiv

ACKNOWLEDGMENTS

Arthur Z. Kovacs, *Rochester Institute of Technology* Kenneth Krane, *Oregon State University* Hadley Lawler, *Vanderbilt University*

Priscilla Laws, *Dickinson College*

Edbertho Leal, *Polytechnic University of Puerto Rico* Vern Lindberg, *Rochester Institute of Technology* Peter Loly, *University of Manitoba*

James MacLaren,*Tulane University*

Andreas Mandelis, *University of Toronto* Robert R. Marchini, *Memphis State University* Andrea Markelz, *University at Buffalo, SUNY* Paul Marquard, *Caspar College*

David Marx, *Illinois State University*

Dan Mazilu, *Washington and LeeUniversity* James H. McGuire, *Tulane University*

David M. McKinstry, *Eastern Washington University* Jordon Morelli, *Queen’s University*

Eugene Mosca, *United States Naval Academy*

Eric R. Murray, *Georgia Institute of Technology, School of Physics*

James Napolitano, *Rensselaer Polytechnic Institute* Blaine Norum, *University of Virginia*

Michael O’Shea, *Kansas State University*

Patrick Papin, *San Diego State University*

Kiumars Parvin, *San Jose State University*

Robert Pelcovits, *Brown University*

Oren P. Quist, *South Dakota State University*

Joe Redish, *University of Maryland*

Timothy M. Ritter, *University of North Carolina at Pembroke* Dan Styer, *Oberlin College*

Frank Wang, *LaGuardia Community College*

Robert Webb, *Texas A&M University*

Suzanne Willis, *Northern Illinois University*

Shannon Willoughby, *Montana State University*

**CHAPTER 1**

Measurement

**1-1 MEASURING THINGS, INCLUDING LENGTHS** Learning Objectives

*After reading this module, you should be able to . . .* **1.01** Identify the base quantities in the SI system. **1.02** Name the most frequently used prefixes for SI units.

Key Ideas

● Physics is based on measurement of physical quantities. Certain physical quantities have been chosen as base quanti ties (such as length, time, and mass); each has been defined in terms of a standard and given a unit of measure (such as meter, second, and kilogram). Other physical quantities are defined in terms of the base quantities and their standards and units. ● The unit system emphasized in this book is the International System of Units (SI). The three physical quantities displayed in Table 1-1 are used in the early chapters. Standards, which must be both accessible and invariable, have been estab lished for these base quantities by international agreement.

**What Is Physics?**

**1.03** Change units (here for length, area, and volume) by using chain-link conversions.

**1.04** Explain that the meter is defined in terms of the speed of light in vacuum.

These standards are used in all physical measurement, for both the base quantities and the quantities derived from them. Scientific notation and the prefixes of Table 1-2 are used to simplify measurement notation.

● Conversion of units may be performed by using chain-link conversions in which the original data are multiplied succes sively by conversion factors written as unity and the units are

manipulated like algebraic quantities until only the desired units remain.

● The meter is defined as the distance traveled by light during a precisely specified time interval.

Science and engineering are based on measurements and comparisons. Thus, we need rules about how things are measured and compared, and we need experiments to establish the units for those measurements and comparisons. One purpose of physics (and engineering) is to design and conduct those experiments.

For example, physicists strive to develop clocks of extreme accuracy so that any time or time interval can be precisely determined and compared. You may wonder whether such accuracy is actually needed or worth the effort. Here is one example of the worth: Without clocks of extreme accuracy, the Global Positioning System (GPS) that is now vital to worldwide navigation would be useless.

**Measuring Things**

We discover physics by learning how to measure the quantities involved in physics. Among these quantities are length, time, mass, temperature, pressure, and electric current.

We measure each physical quantity in its own units, by comparison with a **standard**. The **unit** is a unique name we assign to measures of that quantity—for example, meter (m) for the quantity length. The standard corresponds to exactly 1.0 unit of the quantity. As you will see, the standard for length, which corresponds

1

2 CHAPTER 1 MEASUREMENT

to exactly 1.0 m, is the distance traveled by light in a vacuum during a certain

fraction of a second. We can define a unit and its standard in any way we care to.

However, the important thing is to do so in such a way that scientists around the

world will agree that our definitions are both sensible and practical.

Once we have set up a standard—say, for length—we must work out proce

dures by which any length whatever, be it the radius of a hydrogen atom, the

wheelbase of a skateboard, or the distance to a star, can be expressed in terms of

the standard. Rulers, which approximate our length standard, give us one such

procedure for measuring length. However, many of our comparisons must be

indirect. You cannot use a ruler, for example, to measure the radius of an atom

or the distance to a star.

***Base Quantities.*** There are so many physical quantities that it is a problem to

organize them. Fortunately, they are not all independent; for example, speed is the

ratio of a length to a time. Thus, what we do is pick out—by international agree

ment—a small number of physical quantities, such as length and time, and assign

standards to them alone. We then define all other physical quantities in terms of

these *base quantitie*s and their standards (called *base standards*). Speed, for example,

is defined in terms of the base quantities length and time and their base standards.

Base standards must be both accessible and invariable. If we define the

length standard as the distance between one’s nose and the index finger on an

outstretched arm, we certainly have an accessible standard—but it will, of course,

vary from person to person.The demand for precision in science and engineering

**Table 1-1** Units for Three SI

Base Quantities

Quantity Unit Name Unit Symbol

Length meter m Time second s Mass kilogram kg

**Table 1-2** Prefixes for SI Units

Factor Prefix*a* Symbol

1024 yotta- Y 1021 zetta- Z 1018 exa- E 1015 peta- P 1012 tera- T **109 giga- G 106 mega- M**

**103 kilo- k** 102 hecto- h 101 deka- da 10 1 deci- d **10****2 centi- c 10****3 milli- m 10****6 micro-** m **10****9 nano- n 10****12 pico- p** 10 15 femto- f 10 18 atto- a 10 21 zepto- z 10 24 yocto- y

*a*The most frequently used prefixes are shown in bold type.

pushes us to aim first for invariability. We then exert great effort to make dupli cates of the base standards that are accessible to those who need them.

**The International System of Units**

In 1971, the 14th General Conference on Weights and Measures picked seven quantities as base quantities, thereby forming the basis of the International System of Units, abbreviated SI from its French name and popularly known as the *metric system*.Table 1-1 shows the units for the three base quantities—length, mass, and time—that we use in the early chapters of this book. These units were defined to be on a “human scale.”

Many SI *derived units* are defined in terms of these base units. For example, the SI unit for power, called the **watt** (W), is defined in terms of the base units for mass, length, and time.Thus, as you will see in Chapter 7,

1 watt 1 W 1 kg m2/s3, (1-1)

where the last collection of unit symbols is read as kilogram-meter squared per second cubed.

To express the very large and very small quantities we often run into in physics, we use *scientific notation*, which employs powers of 10. In this notation,

3 560 000 000 m 3.56 109 m (1-2)

and 0.000 000 492 s 4.92 10 7 s. (1-3)

Scientific notation on computers sometimes takes on an even briefer look, as in 3.56 E9 and 4.92 E–7, where E stands for “exponent of ten.” It is briefer still on some calculators, where E is replaced with an empty space.

As a further convenience when dealing with very large or very small mea surements, we use the prefixes listed in Table 1-2. As you can see, each prefix represents a certain power of 10, to be used as a multiplication factor. Attaching a prefix to an SI unit has the effect of multiplying by the associated factor. Thus, we can express a particular electric power as

1.27 109 watts 1.27 gigawatts 1.27 GW (1-4)

1-1 MEASURING THINGS, INCLUDING LENGTHS 3

or a particular time interval as

2.35 10 9 s 2.35 nanoseconds 2.35 ns. (1-5)

Some prefixes, as used in milliliter, centimeter, kilogram, and megabyte, are probably familiar to you.

**Changing Units**

We often need to change the units in which a physical quantity is expressed. We do so by a method called *chain-link conversion*. In this method, we multiply the original measurement by a **conversion factor** (a ratio of units that is equal to unity). For example, because 1 min and 60 s are identical time intervals, we have

60 s 1 and 60 s

1 min

1 min  1.

Thus, the ratios (1 min)/(60 s) and (60 s)/(1 min) can be used as conversion 1

factors. This is *not* the same as writing or 60 1; each *number* and its *unit*

must be treated together.

60  1

Because multiplying any quantity by unity leaves the quantity unchanged, we can introduce conversion factors wherever we find them useful. In chain-link conversion, we use the factors to cancel unwanted units. For example, to convert 2 min to seconds, we have

2 min (2 min)(1) (2 min) 60 s

1 min  120 s.

(1-6)

If you introduce a conversion factor in such a way that unwanted units do *not* cancel, invert the factor and try again. In conversions, the units obey the same algebraic rules as variables and numbers.

Appendix D gives conversion factors between SI and other systems of units, including non-SI units still used in the United States. However, the conversion factors are written in the style of “1 min 60 s” rather than as a ratio. So, you need to decide on the numerator and denominator in any needed ratio.

**Length**

In 1792, the newborn Republic of France established a new system of weights and measures. Its cornerstone was the meter, defined to be one ten-millionth of the distance from the north pole to the equator. Later, for practical reasons, this Earth standard was abandoned and the meter came to be defined as the distance between two fine lines engraved near the ends of a platinum–iridium bar, the **standard meter bar**, which was kept at the International Bureau of Weights and Measures near Paris. Accurate copies of the bar were sent to standardizing labo ratories throughout the world. These **secondary standards** were used to produce other, still more accessible standards, so that ultimately every measuring device derived its authority from the standard meter bar through a complicated chain of comparisons.

Eventually, a standard more precise than the distance between two fine scratches on a metal bar was required. In 1960, a new standard for the meter, based on the wavelength of light, was adopted. Specifically, the standard for the meter was redefined to be 1 650 763.73 wavelengths of a particular orange-red light emitted by atoms of krypton-86 (a particular isotope, or type, of krypton) in a gas discharge tube that can be set up anywhere in the world. This awkward number of wavelengths was chosen so that the new standard would be close to the old meter-bar standard.

4 CHAPTER 1 MEASUREMENT

By 1983, however, the demand for higher precision had reached such a point

**Table 1-3** Some Approximate Lengths Measurement Length in Meters

Distance to the first

galaxies formed 2 1026 Distance to the

Andromeda galaxy 2 1022 Distance to the nearby

star Proxima Centauri 4 1016 Distance to Pluto 6 1012 Radius of Earth 6 106 Height of Mt. Everest 9 103 Thickness of this page 1 10 4 Length of a typical virus 1 10 8 Radius of a hydrogen atom 5 10 11 Radius of a proton 1 10 15

that even the krypton-86 standard could not meet it, and in that year a bold step was taken. The meter was redefined as the distance traveled by light in a specified time interval. In the words of the 17th General Conference on Weights and Measures:

The meter is the length of the path traveled by light in a vacuum during a time interval of 1/299 792 458 of a second.

This time interval was chosen so that the speed of light *c* is exactly *c*  299 792 458 m/s.

Measurements of the speed of light had become extremely precise, so it made sense to adopt the speed of light as a defined quantity and to use it to redefine the meter.

Table 1-3 shows a wide range of lengths, from that of the universe (top line) to those of some very small objects.

**Significant Figures and Decimal Places**

Suppose that you work out a problem in which each value consists of two digits. Those digits are called **significant figures** and they set the number of digits that you can use in reporting your final answer. With data given in two significant figures, your final answer should have only two significant figures. However, depending on the mode setting of your calculator, many more digits might be displayed.Those extra digits are meaningless.

In this book, final results of calculations are often rounded to match the least number of significant figures in the given data. (However, sometimes an extra significant figure is kept.) When the leftmost of the digits to be discarded is 5 or more, the last remaining digit is rounded up; otherwise it is retained as is. For

example, 11.3516 is rounded to three significant figures as 11.4 and 11.3279 is rounded to three significant figures as 11.3. (The answers to sample problems in this book are usually presented with the symbol instead of even if rounding is involved.)

When a number such as 3.15 or 3.15 103 is provided in a problem, the number of significant figures is apparent, but how about the number 3000? Is it known to only one significant figure (3 103)? Or is it known to as many as four significant figures (3.000 103)? In this book, we assume that all the zeros in such given num bers as 3000 are significant, but you had better not make that assumption elsewhere.

Don’t confuse *significant figures* with *decimal places*. Consider the lengths 35.6 mm, 3.56 m, and 0.00356 m. They all have three significant figures but they have one, two, and five decimal places, respectively.

Sample Problem 1.01 Estimating order of magnitude, ball of string

The world’s largest ball of string is about 2 m in radius. To the nearest order of magnitude, what is the total length *L* of the string in the ball?

KEY IDEA

We could, of course, take the ball apart and measure the to tal length *L*, but that would take great effort and make the

ball’s builder most unhappy. Instead, because we want only the nearest order of magnitude, we can estimate any quanti ties required in the calculation.

*Calculations:* Let us assume the ball is spherical with radius *R*  2 m. The string in the ball is not closely packed (there are uncountable gaps between adjacent sections of string). To allow for these gaps, let us somewhat overestimate

the cross-sectional area of the string by assuming the cross section is square, with an edge length *d*  4 mm. Then, with a cross-sectional area of *d*2 and a length *L*, the or

string occupies a total volume of

1-2 TIME 5

*d*2*L*  4*R*3,

*L* 4*R*3

*d* 2 4(2 m)3

(4 10 3 m)2

*V*  (cross-sectional area)(length) *d*2*L*.

This is approximately equal to the volume of the ball, given 4

by , which is about 4*R*3 because p is about 3. Thus, we

3*R*3

have the following

2 106 m 106 m 103 km.

(Answer)

(Note that you do not need a calculator for such a simplified calculation.) To the nearest order of magnitude, the ball contains about 1000 km of string!

Additional examples, video, and practice available at *WileyPLUS*

**1-2 TIME**

Learning Objectives

*After reading this module, you should be able to . . .* **1.05** Change units for time by using chain-link conversions.

Key Idea

● The second is defined in terms of the oscillations of light emitted by an atomic (cesium-133) source. Accurate time

**Time**

**1.06** Use various measures of time, such as for motion or as determined on different clocks.

signals are sent worldwide by radio signals keyed to atomic clocks in standardizing laboratories.

Time has two aspects. For civil and some scientific purposes, we want to know the time of day so that we can order events in sequence. In much scientific work, we want to know how long an event lasts. Thus, any time standard must be able to answer two questions: “*When* did it happen?” and “What is its *duration*?” Table 1-4 shows some time intervals. 

Any phenomenon that repeats itself is a possible time standard. Earth’s rotation, which determines the length of the day, has been used in this way for centuries; Fig. 1-1 shows one novel example of a watch based on that rotation. A quartz clock, in which a quartz ring is made to vibrate continuously, can be calibrated against Earth’s rotation via astronomical observations and used to measure time intervals in the laboratory. However, the calibration cannot be carried out with the accuracy called for by modern scientific and engineering technology.

**Table 1-4** Some Approximate Time Intervals

Time Interval

Measurement in Seconds

Lifetime of the

proton (predicted) 3 1040 Age of the universe 5 1017 Age of the pyramid of Cheops 1 1011 Human life expectancy 2 109

Length of a day 9 104

Time Interval

Measurement in Seconds

Time between human heartbeats 8 10 1 Lifetime of the muon 2 10 6 Shortest lab light pulse 1 10 16 Lifetime of the most

unstable particle 1 10 23 The Planck time*a* 1 10 43

Steven Pitkin

**Figure 1-1** When the metric system was proposed in 1792, the hour was redefined to provide a 10-hour day. The idea did not catch on. The maker of this 10-hour watch wisely provided a small dial that kept con ventional 12-hour time. Do the two dials

*a*This is the earliest time after the big bang at which the laws of physics as we know them can be applied.

indicate the same time?

6 CHAPTER 1 MEASUREMENT +4

To meet the need for a better time standard, atomic clocks have been developed. An atomic clock at the National Institute of Standards and Technology (NIST) in Boulder, Colorado, is the stan

f

o

h

t

g

n

e

l

n

e

e

w

t

e

b

e

c

n

e

r

e

f

f

i

D

)

s

m

(

+3

s

r

u

o

h

4

2

y

l

t

c

a

x

+2

e

d

n

a

y

a

d

1980 1981 1982 1983 +1

dard for Coordinated Universal Time (UTC) in the United States. Its time signals are available by shortwave radio (stations WWV and WWVH) and by telephone (303-499-7111). Time signals (and related information) are also available from the United States Naval Observatory at website http://tycho.usno.navy.mil/time.html. (To set a clock extremely accurately at your particular location, you would have to account for the travel time required for these signals to reach you.)

Figure 1-2 shows variations in the length of one day on Earth over a 4-year period, as determined by comparison with a cesium (atomic) clock. Because the variation displayed by Fig. 1-2 is sea sonal and repetitious, we suspect the rotating Earth when there is a difference between Earth and atom as timekeepers. The variation is

**Figure 1-2** Variations in the length of the day over a 4-year period. Note that the entire vertical scale amounts to only 3 ms ( 0.003 s).

**1-3 MASS**

Learning Objectives

due to tidal effects caused by the Moon and to large-scale winds. The 13th General Conference on Weights and Measures in 1967 adopted a standard second based on the cesium clock:

One second is the time taken by 9 192 631 770 oscillations of the light (of a specified wavelength) emitted by a cesium-133 atom.

Atomic clocks are so consistent that, in principle, two cesium clocks would have to run for 6000 years before their readings would differ by more than 1 s. Even such accuracy pales in comparison with that of clocks currently being developed; their precision may be 1 part in 1018—that is, 1 s in 1 1018 s (which is about 3 1010 y).

*After reading this module, you should be able to . . .* **1.07** Change units for mass by using chain-link conversions.

Key Ideas

● The kilogram is defined in terms of a platinum–iridium standard mass kept near Paris. For measurements on an atomic scale, the atomic mass unit, defined in terms of the atom carbon-12, is usually used.

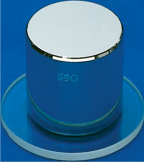
**Mass**

**1.08** Relate density to mass and volume when the mass is uniformly distributed.

● The density of a material is the mass per unit volume:

*mV* .

.

**The Standard Kilogram** 

e

M

P

M

I

t

B

The SI standard of mass is a cylinder of

e

e

s

h

d

t

i

platinum and iridium (Fig. 1-3) that is kept

f

o

o

P

s

at the International Bureau of Weights

n

e

o

i

d

s

l

s

and Measures near Paris and assigned, by

i

a

n

m

r

o

i

e

t

p

a

n

h

r

t

i

e

t

w

n

I

d

e

u

c

a

u

e

d

r

o

u

r

**Figure 1-3** The international 1 kg standard of

B

p

e

y

s

mass, a platinum–iridium cylinder 3.9 cm in

R

e

t

.

r

s

height and in diameter.

e

u

r

o

u

C

s

international agreement, a mass of 1 kilogram. Accurate copies have been sent to standardizing laboratories in other countries, and the masses of other bodies can be determined by balancing them against a copy. Table 1-5 shows some masses expressed in kilograms, ranging over about 83 orders of magnitude.

The U.S. copy of the standard kilogram is housed in a vault at NIST. It is removed, no more than once a year, for the purpose of checking duplicate copies that are used elsewhere. Since 1889, it has been taken to France twice for recomparison with the primary standard.

**A Second Mass Standard**

The masses of atoms can be compared with one another more precisely than they can be compared with the standard kilogram. For this reason, we have a second mass standard. It is the carbon-12 atom, which, by international agree ment, has been assigned a mass of 12 **atomic mass units** (u).The relation between the two units is

1 u 1.660 538 86 10 27 kg, (1-7)

with an uncertainty of 10 in the last two decimal places. Scientists can, with reasonable precision, experimentally determine the masses of other atoms rela tive to the mass of carbon-12. What we presently lack is a reliable means of extending that precision to more common units of mass, such as a kilogram.

**Density**

As we shall discuss further in Chapter 14, **density** r (lowercase Greek letter rho) is the mass per unit volume:

1-3 MASS 7

**Table 1-5** Some Approximate Masses

Mass in

Object Kilograms

Known universe 1 1053 Our galaxy 2 1041 Sun 2 1030 Moon 7 1022 Asteroid Eros 5 1015 Small mountain 1 1012 Ocean liner 7 107

Elephant 5 103 Grape 3 10 3 Speck of dust 7 10 10 Penicillin molecule 5 10 17 Uranium atom 4 10 25 Proton 2 10 27 Electron 9 10 31

*mV* .

(1-8)

Densities are typically listed in kilograms per cubic meter or grams per cubic centimeter.The density of water (1.00 gram per cubic centimeter) is often used as a comparison. Fresh snow has about 10% of that density; platinum has a density that is about 21 times that of water.

Sample Problem 1.02 Density and liquefaction

A heavy object can sink into the ground during an earthquake if the shaking causes the ground to undergo *liquefaction,* in which the soil grains experience little friction as they slide over one another. The ground is then effectively quicksand. The possibility of liquefaction in sandy ground can be pre dicted in terms of the *void ratio e* for a sample of the ground:

KEY IDEA

The density of the sand rsand in a sample is the mass per unit volume—that is, the ratio of the total mass *m*sand of the sand grains to the total volume *V*total of the sample:

sand *m*sand

*e* *V*voids *V*grains.

(1-9)

*V*total.

(1-10)

Here, *V*grains is the total volume of the sand grains in the sam ple and *V*voids is the total volume between the grains (in the *voids*). If *e* exceeds a critical value of 0.80, liquefaction can occur during an earthquake.What is the corresponding sand density rsand? Solid silicon dioxide (the primary component of sand) has a density of 2.600 103 kg/m3   
 . SiO2 

*Calculations:* The total volume *V*total of a sample is *V*total  *V*grains  *V*voids.

Substituting for *V*voids from Eq. 1-9 and solving for *V*grains lead to

*V* (1-11) grains *V*total

1 *e*.

8 CHAPTER 1 MEASUREMENT

From Eq. 1-8, the total mass *m*sand of the sand grains is the product of the density of silicon dioxide and the total vol ume of the sand grains:

Substituting 2.600 103 kg/m3 and the critical value

SiO2

of *e* 0.80, we find that liquefaction occurs when the sand

density is less than

*m*sand    
SiO2*V*grains.

(1-12)

sand 2.600 103 kg/m3

Substituting this expression into Eq. 1-10 and then substitut ing for *V*grains from Eq. 1-11 lead to

(1-13) sand  SiO2 1 *e*  SiO2

1.80  1.4 103 kg/m3.

(Answer)

A building can sink several meters in such liquefaction.

*V*total

*V*total

1 *e*.

Additional examples, video, and practice available at *WileyPLUS* Review & Summary

**Measurement in Physics** Physics is based on measurement of physical quantities. Certain physical quantities have been cho sen as **base quantities** (such as length, time, and mass); each has been defined in terms of a **standard** and given a **unit** of measure (such as meter, second, and kilogram). Other physical quantities are defined in terms of the base quantities and their standards and units.

**SI Units** The unit system emphasized in this book is the International System of Units (SI). The three physical quantities displayed in Table 1-1 are used in the early chapters. Standards, which must be both accessible and invariable, have been estab lished for these base quantities by international agreement. These standards are used in all physical measurement, for both the base quantities and the quantities derived from them. Scientific notation and the prefixes of Table 1-2 are used to sim plify measurement notation.

**Changing Units** Conversion of units may be performed by us ing *chain-link conversions* in which the original data are multiplied

Problems

successively by conversion factors written as unity and the units are manipulated like algebraic quantities until only the desired units remain.

**Length** The meter is defined as the distance traveled by light during a precisely specified time interval.

**Time** The second is defined in terms of the oscillations of light emitted by an atomic (cesium-133) source. Accurate time signals are sent worldwide by radio signals keyed to atomic clocks in stan dardizing laboratories.

**Mass** The kilogram is defined in terms of a platinum– iridium standard mass kept near Paris. For measurements on an atomic scale, the atomic mass unit, defined in terms of the atom carbon-12, is usually used.

**Density** The density r of a material is the mass per unit volume:   
 (1-8) *mV* .

Tutoring problem available (at instructor’s discretion) in *WileyPLUS* and WebAssign

**SSM** Worked-out solution available in Student Solutions Manual **•** – **•••** Number of dots indicates level of problem difficulty

**WWW** Worked-out solution is at

**ILW** Interactive solution is at http://www.wiley.com/college/halliday

Additional information available in *The Flying Circus of Physics* and at flyingcircusofphysics.com

**Module 1-1 Measuring Things, Including Lengths •1** Earth is approximately a sphere of radius 6.37 106 m.

**SSM**

What are (a) its circumference in kilometers, (b) its surface area in square kilometers, and (c) its volume in cubic kilometers?

**•2** A *gry* is an old English measure for length, defined as 1/10 of a line, where *line* is another old English measure for length, defined as 1/12 inch. A common measure for length in the publishing busi ness is a *point,* defined as 1/72 inch. What is an area of 0.50 gry2 in points squared (points2)?

**•3** The micrometer (1 mm) is often called the *micron.* (a) How

many microns make up 1.0 km? (b) What fraction of a centimeter equals 1.0 mm? (c) How many microns are in 1.0 yd?

**•4** Spacing in this book was generally done in units of points and picas: 12 points 1 pica, and 6 picas 1 inch. If a figure was mis placed in the page proofs by 0.80 cm, what was the misplacement in (a) picas and (b) points?

**•5** Horses are to race over a certain English meadow

**SSM WWW**

for a distance of 4.0 furlongs. What is the race distance in (a) rods and (b) chains? (1 furlong 201.168 m, 1 rod 5.0292 m, and 1 chain 20.117 m.)

PROBLEMS 9

**••6** You can easily convert common units and measures electroni

**Module 1-2 Time**

cally, but you still should be able to use a conversion table, such as those in Appendix D. Table 1-6 is part of a conversion table for a system of volume measures once common in Spain; a volume of 1 fanega is equivalent to 55.501 dm3 (cubic decimeters). To complete the table, what numbers (to three significant figures) should be en tered in (a) the cahiz column, (b) the fanega column, (c) the cuar tilla column, and (d) the almude column, starting with the top blank? Express 7.00 almudes in (e) medios, (f) cahizes, and (g) cu bic centimeters (cm3).

**Table 1-6** Problem 6

cahiz fanega cuartilla almude medio

1 cahiz 1 12 48 144 288 1 fanega 1 4 12 24 1 cuartilla 13 6 1 almude 1 2 1 medio 1

**••7** Hydraulic engineers in the United States often use, as a

**ILW**

unit of volume of water, the *acre-foot,* defined as the volume of wa ter that will cover 1 acre of land to a depth of 1 ft. A severe thun derstorm dumped 2.0 in. of rain in 30 min on a town of area 26 km2.What volume of water, in acre-feet, fell on the town?

**••8** Harvard Bridge, which connects MIT with its fraternities across the Charles River, has a length of 364.4 Smoots plus one ear. The unit of one Smoot is based on the length of Oliver Reed Smoot, Jr., class of 1962, who was carried or dragged length by length across the bridge so that other pledge members of the Lambda Chi Alpha fraternity could mark off (with paint) 

1-Smoot lengths along the bridge.The marks have been repainted biannually by fraternity pledges since the initial measurement, usually during times of traffic congestion so that the police can not easily interfere. (Presumably, the police were originally up set because the Smoot is not an SI base unit, but these days they seem to have accepted the unit.) Figure 1-4 shows three parallel paths, measured in Smoots (S), Willies (W), and Zeldas (Z).

**•10** Until 1883, every city and town in the United States kept its own local time. Today, travelers reset their watches only when the time change equals 1.0 h. How far, on the average, must you travel in degrees of longitude between the time-zone boundaries at which your watch must be reset by 1.0 h? (*Hint:* Earth rotates 360° in about 24 h.)

**•11** For about 10 years after the French Revolution, the French government attempted to base measures of time on multiples of ten: One week consisted of 10 days, one day consisted of 10 hours, one hour consisted of 100 minutes, and one minute consisted of 100 seconds. What are the ratios of (a) the French decimal week to the standard week and (b) the French decimal second to the standard second?

**•12** The fastest growing plant on record is a *Hesperoyucca whip plei* that grew 3.7 m in 14 days. What was its growth rate in micro meters per second?

**•13** Three digital clocks *A, B,* and *C* run at different rates and do not have simultaneous readings of zero. Figure 1-6 shows si multaneous readings on pairs of the clocks for four occasions. (At the earliest occasion, for example, *B* reads 25.0 s and *C* reads 92.0 s.) If two events are 600 s apart on clock *A,* how far apart are they on (a) clock *B* and (b) clock *C*? (c) When clock *A* reads 400 s, what does clock *B* read? (d) When clock *C* reads 15.0 s, what does clock *B* read? (Assume negative readings for prezero times.) 

312 512

*A* (s)

25.0 125 200 290

*B* (s)

92.0 142

*C* (s)

**Figure 1-6** Problem 13.

**•14** A lecture period (50 min) is close to 1 microcentury. (a) How long is a microcentury in minutes? (b) Using

percentage difference  actual approximation

What is the length of 50.0 Smoots in (a) Willies and (b) Zeldas?

actual  100 ,

0 32

0

60

**Figure 1-4** Problem 8.

212 258 216

find the percentage difference from the approximation.

S

**•15** A fortnight is a charming English measure of time equal to W

2.0 weeks (the word is a contraction of “fourteen nights”).That is a nice amount of time in pleasant company but perhaps a painful Z

string of microseconds in unpleasant company. How many mi croseconds are in a fortnight?

**•16** Time standards are now based on atomic clocks. A promis

**••9** Antarctica is roughly semicircular, with a radius of 2000 km (Fig. 1-5). The average thickness of its ice cover is 3000 m. How many cubic centimeters of ice does Antarctica contain? (Ignore the curvature of Earth.)

2000 km

3000 m

**Figure 1-5** Problem 9.

ing second standard is based on *pulsars,* which are rotating neu tron stars (highly compact stars consisting only of neutrons). Some rotate at a rate that is highly stable, sending out a radio beacon that sweeps briefly across Earth once with each rotation, like a lighthouse beacon. Pulsar PSR 1937 21 is an example; it rotates once every 1.557 806 448 872 75 3 ms, where the trailing 3 indicates the uncertainty in the last decimal place (it does *not* mean 3 ms). (a) How many rotations does PSR 1937 21 make in 7.00 days? (b) How much time does the pulsar take to rotate ex actly one million times and (c) what is the associated uncertainty?

10 CHAPTER 1 MEASUREMENT

**•17** Five clocks are being tested in a laboratory. Exactly at

**SSM** that range, give the lower value and the higher value, respectively,

noon, as determined by the WWV time signal, on successive days of a week the clocks read as in the following table. Rank the five clocks according to their relative value as good timekeepers, best to worst. Justify your choice.

Clock Sun. Mon. Tues. Wed. Thurs. Fri. Sat.

A 12:36:40 12:36:56 12:37:12 12:37:27 12:37:44 12:37:59 12:38:14 B 11:59:59 12:00:02 11:59:57 12:00:07 12:00:02 11:59:56 12:00:03 C 15:50:45 15:51:43 15:52:41 15:53:39 15:54:37 15:55:35 15:56:33 D 12:03:59 12:02:52 12:01:45 12:00:38 11:59:31 11:58:24 11:57:17 E 12:03:59 12:02:49 12:01:54 12:01:52 12:01:32 12:01:22 12:01:12

**••18** Because Earth’s rotation is gradually slowing, the length of each day increases:The day at the end of 1.0 century is 1.0 ms longer than the day at the start of the century. In 20 centuries, what is the total of the daily increases in time?

**•••19** Suppose that, while lying on a beach near the equator watching the Sun set over a calm ocean, you start a stopwatch just as the top of the Sun disappears. You then stand, elevating your eyes by a height *H*  1.70 m, and stop the watch when the top of the Sun again disappears. If the elapsed time is *t*  11.1 s, what is the radius *r* of Earth?

**Module 1-3 Mass**

**•20** The record for the largest glass bottle was set in 1992 by a team in Millville, New Jersey—they blew a bottle with a volume of 193 U.S. fluid gallons. (a) How much short of 1.0 million cubic cen timeters is that? (b) If the bottle were filled with water at the leisurely rate of 1.8 g/min, how long would the filling take? Water has a density of 1000 kg/m3. 

**•21** Earth has a mass of 5.98 1024 kg.The average mass of the atoms that make up Earth is 40 u. How many atoms are there in Earth?

**•22** Gold, which has a density of 19.32 g/cm3, is the most ductile metal and can be pressed into a thin leaf or drawn out into a long fiber. (a) If a sample of gold, with a mass of 27.63 g, is pressed into a leaf of 1.000 mm thickness, what is the area of the leaf? (b) If, instead, the gold is drawn out into a cylindrical fiber of radius 2.500 mm, what is the length of the fiber?

**•23** (a) Assuming that water has a density of exactly 1 g/cm3,

**SSM**

find the mass of one cubic meter of water in kilograms. (b) Suppose that it takes 10.0 h to drain a container of 5700 m3 of water.What is the “mass flow rate,” in kilograms per second, of wa ter from the container?

**••24** Grains of fine California beach sand are approximately spheres with an average radius of 50 m and are made of silicon 

dioxide, which has a density of 2600 kg/m3.What mass of sand grains would have a total surface area (the total area of all the individual

for the following. (a) How many cubic meters of water are in a cylindrical cumulus cloud of height 3.0 km and radius 1.0 km? (b) How many 1-liter pop bottles would that water fill? (c) Water has a density of 1000 kg/m3. How much mass does the water in the cloud have?

**••27** Iron has a density of 7.87 g/cm3, and the mass of an iron atom is 9.27 10 26 kg. If the atoms are spherical and tightly packed, (a) what is the volume of an iron atom and (b) what is the distance be tween the centers of adjacent atoms?

**••28** A mole of atoms is 6.02 1023 atoms. To the nearest order of magnitude, how many moles of atoms are in a large domestic cat? The masses of a hydrogen atom, an oxygen atom, and a carbon atom are 1.0 u, 16 u, and 12 u, respectively. (*Hint:* Cats are some times known to kill a mole.)

**••29** On a spending spree in Malaysia, you buy an ox with a weight of 28.9 piculs in the local unit of weights: 1 picul 100 gins, 1 gin 16 tahils, 1 tahil 10 chees, and 1 chee 10 hoons. The weight of 1 hoon corresponds to a mass of 0.3779 g. When you arrange to ship the ox home to your astonished family, how much mass in kilograms must you declare on the shipping manifest? (*Hint:* Set up multiple chain-link conversions.)

**••30** Water is poured into a container that has a small leak. The mass *m* of the water is given as a function of time *t* by *m*  5.00*t*0.8  3.00*t*  20.00, with *t* 0, *m* in grams, and *t* in sec onds. (a) At what time is the water mass greatest, and (b) what is that greatest mass? In kilograms per minute, what is the rate of mass change at (c) *t*  2.00 s and (d) *t*  5.00 s? 

**•••31** A vertical container with base area measuring 14.0 cm by 17.0 cm is being filled with identical pieces of candy, each with a volume of 50.0 mm3 and a mass of 0.0200 g.Assume that the volume of the empty spaces between the candies is negligible. If the height of the candies in the container increases at the rate of 0.250 cm/s, at what rate (kilograms per minute) does the mass of the candies in the container increase?

**Additional Problems**

**32** In the United States, a doll house has the scale of 1 12 of a 1

real house (that is, each length of the doll house is that of the real

12

house) and a miniature house (a doll house to fit within a doll house) has the scale of 1 144 of a real house. Suppose a real house (Fig. 1-7) has a front length of 20 m, a depth of 12 m, a height of 6.0 m, and a standard sloped roof (vertical triangular faces on the ends) of height 3.0 m. In cubic meters, what are the volumes of the corre sponding (a) doll house and (b) miniature house?

spheres) equal to the surface area of a cube 1.00 m on an edge?

**••25** During heavy rain, a section of a mountainside mea suring 2.5 km horizontally, 0.80 km up along the slope, and 2.0 m deep slips into a valley in a mud slide.Assume that the mud ends up uniformly distributed over a surface area of the valley measuring 0.40 km 0.40 km and that mud has a density of 1900 kg/m3. What is the mass of the mud sitting above a 4.0 m2 area of the valley floor? 

3.0 m 6.0 m

|  |
| --- |
|  |

|  |
| --- |
|  |

|  |
| --- |
|  |

|  |
| --- |
|  |

|  |
| --- |
|  |

20 m

**••26** One cubic centimeter of a typical cumulus cloud contains 50 to 500 water drops, which have a typical radius of 10 mm. For

12 m

**Figure 1-7** Problem 32.

PROBLEMS 11

**SSM** The tourist does not realize that the U.K. gallon differs from the **33** A ton is a measure of volume frequently used in ship

ping, but that use requires some care because there are at least three types of tons: A *displacement ton* is equal to 7 barrels bulk, a *freight ton* is equal to 8 barrels bulk, and a *register ton* is equal to 20 barrels bulk. A *barrel bulk* is another measure of vol ume: 1 barrel bulk 0.1415 m3. Suppose you spot a shipping order for “73 tons” of M&M candies, and you are certain that the client who sent the order intended “ton” to refer to volume (instead of weight or mass, as discussed in Chapter 5). If the client actually meant displacement tons, how many extra U.S. bushels of the can dies will you erroneously ship if you interpret the order as (a) 73 freight tons and (b) 73 register tons? (1 m3  28.378 U.S. bushels.)

**34** Two types of *barrel* units were in use in the 1920s in the United States.The apple barrel had a legally set volume of 7056 cu bic inches; the cranberry barrel, 5826 cubic inches. If a merchant sells 20 cranberry barrels of goods to a customer who thinks he is receiving apple barrels, what is the discrepancy in the shipment volume in liters?

**35** An old English children’s rhyme states, “Little Miss Muffet sat on a tuffet, eating her curds and whey, when along came a spi der who sat down beside her. . . .” The spider sat down not because of the curds and whey but because Miss Muffet had a stash of 11 tuffets of dried flies. The volume measure of a tuffet is given by 1 tuffet 2 pecks 0.50 Imperial bushel, where 1 Imperial bushel 36.3687 liters (L). What was Miss Muffet’s stash in (a) pecks, (b) Imperial bushels, and (c) liters?

**36** Table 1-7 shows some old measures of liquid volume. To complete the table, what numbers (to three significant figures) should be entered in (a) the wey column, (b) the chaldron column, (c) the bag column, (d) the pottle column, and (e) the gill column, starting from the top down? (f) The volume of 1 bag is equal to 0.1091 m3. If an old story has a witch cooking up some vile liquid in a cauldron of volume 1.5 chaldrons, what is the volume in cubic meters?

**Table 1-7** Problem 36

wey chaldron bag pottle gill

1 wey 1 10/9 40/3 640 120 240 1 chaldron

1 bag

1 pottle

1 gill

**37** A typical sugar cube has an edge length of 1 cm. If you had a cubical box that contained a mole of sugar cubes, what would its edge length be? (One mole 6.02 1023 units.)

**38** An old manuscript reveals that a landowner in the time of King Arthur held 3.00 acres of plowed land plus a live stock area of 25.0 perches by 4.00 perches. What was the total area in (a) the old unit of roods and (b) the more modern unit of square meters? Here, 1 acre is an area of 40 perches by 4 perches, 1 rood is an area of 40 perches by 1 perch, and 1 perch is the length 16.5 ft.

**39** A tourist purchases a car in England and ships it home to

**SSM**

the United States.The car sticker advertised that the car’s fuel con sumption was at the rate of 40 miles per gallon on the open road.

U.S. gallon:

1 U.K. gallon 4.546 090 0 liters

1 U.S. gallon 3.785 411 8 liters.

For a trip of 750 miles (in the United States), how many gallons of fuel does (a) the mistaken tourist believe she needs and (b) the car actually require?

**40** Using conversions and data in the chapter, determine the number of hydrogen atoms required to obtain 1.0 kg of hydrogen.A hydrogen atom has a mass of 1.0 u.

**41** A *cord* is a volume of cut wood equal to a stack 8 ft

**SSM**

long, 4 ft wide, and 4 ft high. How many cords are in 1.0 m3?

**42** One molecule of water (H2O) contains two atoms of hydrogen and one atom of oxygen.A hydrogen atom has a mass of 1.0 u and an atom of oxygen has a mass of 16 u, approximately. (a) What is the mass in kilograms of one molecule of water? (b) How many mole cules of water are in the world’s oceans, which have an estimated total mass of 1.4 1021 kg?

**43** A person on a diet might lose 2.3 kg per week. Express the mass loss rate in milligrams per second, as if the dieter could sense the second-by-second loss.

**44** What mass of water fell on the town in Problem 7? Water has a density of 1.0 103 kg/m3.

**45** (a) A unit of time sometimes used in microscopic physics is the *shake.* One shake equals 10 8 s. Are there more shakes in a second than there are seconds in a year? (b) Humans have ex isted for about 106 years, whereas the universe is about 1010 years old. If the age of the universe is defined as 1 “universe day,” where a universe day consists of “universe seconds” as a normal day consists of normal seconds, how many universe seconds have humans existed?

**46** A unit of area often used in measuring land areas is the *hectare,* defined as 104 m2. An open-pit coal mine consumes 75 hectares of land, down to a depth of 26 m, each year. What volume of earth, in cubic kilometers, is removed in this time?

**47** An astronomical unit (AU) is the average distance

**SSM**

between Earth and the Sun, approximately 1.50 108 km. The speed of light is about 3.0 108 m/s. Express the speed of light in astronomical units per minute.

**48** The common Eastern mole, a mammal, typically has a mass of 75 g, which corresponds to about 7.5 moles of atoms. (A mole of atoms is 6.02 1023 atoms.) In atomic mass units (u), what is the average mass of the atoms in the common Eastern mole?

**49** A traditional unit of length in Japan is the ken (1 ken 1.97 m). What are the ratios of (a) square kens to square meters and (b) cubic kens to cubic meters? What is the volume of a cylin drical water tank of height 5.50 kens and radius 3.00 kens in (c) cu bic kens and (d) cubic meters?

**50** You receive orders to sail due east for 24.5 mi to put your sal vage ship directly over a sunken pirate ship. However, when your divers probe the ocean floor at that location and find no evidence of a ship, you radio back to your source of information, only to discover that the sailing distance was supposed to be 24.5 *nautical miles,* not regular miles. Use the Length table in Appendix D to calculate how far horizontally you are from the pirate ship in kilometers.

12 CHAPTER 1 MEASUREMENT

**51** The cubit is an ancient unit of length based on the distance between the elbow and the tip of the middle finger of the mea surer. Assume that the distance ranged from 43 to 53 cm, and suppose that ancient drawings indicate that a cylindrical pillar was to have a length of 9 cubits and a diameter of 2 cubits. For the stated range, what are the lower value and the upper value, respectively, for (a) the cylinder’s length in meters, (b) the cylin der’s length in millimeters, and (c) the cylinder’s volume in cubic meters?

**52** As a contrast between the old and the modern and between the large and the small, consider the following: In old rural England 1 hide (between 100 and 120 acres) was the area of land needed to sustain one family with a single plough for one year. (An area of 1 acre is equal to 4047 m2.) Also, 1 wapentake was the area of land needed by 100 such families. In quantum physics, the cross-sectional area of a nucleus (defined in terms of the chance of a particle hitting and being absorbed by it) is measured in units of barns, where 1 barn is 1 10 28 m2. (In nuclear physics jargon, if a nucleus is “large,” then shooting a particle at it is like shooting a bullet at a barn door, which can hardly be missed.) What is the ratio of 25 wapentakes to 11 barns?

**53** An *astronomical unit* (AU) is equal to the average

**SSM**

distance from Earth to the Sun, about 92.9 106 mi. A *parsec*

(pc) is the distance at which a length of 1 AU would subtend an angle of exactly 1 second of

**56** The *corn–hog ratio* is a financial term used in the pig market and presumably is related to the cost of feeding a pig until it is large enough for market. It is defined as the ratio of the market price of a pig with a mass of 3.108 slugs to the market price of a U.S. bushel of corn. (The word “slug” is derived from an old German word that means “to hit”; we have the same meaning for “slug” as a verb in modern English.) A U.S. bushel is equal to 35.238 L. If the corn–hog ratio is listed as 5.7 on the market ex change, what is it in the metric units of

price of 1 kilogram of pig

price of 1 liter of corn?

(*Hint:* See the Mass table in Appendix D.)

**57** You are to fix dinners for 400 people at a convention of Mexican food fans. Your recipe calls for 2 jalapeño peppers per serving (one serving per person). However, you have only ha banero peppers on hand. The spiciness of peppers is measured in terms of the *scoville heat unit* (SHU). On average, one jalapeño pepper has a spiciness of 4000 SHU and one habanero pepper has a spiciness of 300 000 SHU. To get the desired spiciness, how many habanero peppers should you substitute for the jalapeño peppers in the recipe for the 400 dinners?

**58** A standard interior staircase has steps each with a rise (height) of 19 cm and a run (horizontal depth) of 23 cm. Research

arc (Fig. 1-8). A *light-year* (ly) is the distance that light, trav eling through a vacuum with a speed of 186 000 mi/s, would cover in 1.0 year. Express the Earth–Sun distance in (a) parsecs and (b) light-years.

An angle of

exactly 1 second

1 pc

1 AU 1 pc

**Figure 1-8** Problem 53.

suggests that the stairs would be safer for descent if the run were, instead, 28 cm. For a particular staircase of total height 4.57 m, how much farther into the room would the staircase extend if this change in run were made?

**59** In purchasing food for a political rally, you erroneously order shucked medium-size Pacific oysters (which come 8 to 12 per U.S. pint) instead of shucked medium-size Atlantic oysters (which

**54** The description for a certain brand of house paint claims a cov erage of 460 ft2/gal. (a) Express this quantity in square meters per liter. (b) Express this quantity in an SI unit (see Appendices A and D). (c) What is the inverse of the original quantity, and (d) what is its physical significance?

**55** Strangely, the wine for a large wedding reception is to be served in a stunning cut-glass receptacle with the interior dimen sions of 40 cm 40 cm 30 cm (height). The receptacle is to be initially filled to the top. The wine can be purchased in bottles of the sizes given in the following table. Purchasing a larger bottle in stead of multiple smaller bottles decreases the overall cost of the wine. To minimize the cost, (a) which bottle sizes should be pur chased and how many of each should be purchased and, once the receptacle is filled, how much wine is left over in terms of (b) stan dard bottles and (c) liters?

1 standard bottle

1 magnum 2 standard bottles

1 jeroboam 4 standard bottles

1 rehoboam 6 standard bottles

1 methuselah 8 standard bottles

1 salmanazar 12 standard bottles

1 balthazar 16 standard bottles 11.356 L

1 nebuchadnezzar 20 standard bottles

come 26 to 38 per U.S. pint).The filled oyster container shipped to you has the interior measure of 1.0 m 12 cm 20 cm, and a U.S. pint is equivalent to 0.4732 liter. By how many oysters is the order short of your anticipated count?

**60** An old English cookbook carries this recipe for cream of net tle soup: “Boil stock of the following amount: 1 breakfastcup plus 1 teacup plus 6 tablespoons plus 1 dessertspoon. Using gloves, separate nettle tops until you have 0.5 quart; add the tops to the boiling stock. Add 1 tablespoon of cooked rice and 1 saltspoon of salt. Simmer for 15 min.” The following table gives some of the conversions among old (premetric) British measures and among common (still premetric) U.S. measures. (These measures just scream for metrication.) For liquid measures, 1 British teaspoon 1 U.S. teaspoon. For dry measures, 1 British teaspoon 2 U.S. tea spoons and 1 British quart 1 U.S. quart. In U.S. measures, how much (a) stock, (b) nettle tops, (c) rice, and (d) salt are required in the recipe?

Old British Measures U.S. Measures

teaspoon 2 saltspoons tablespoon 3 teaspoons dessertspoon 2 teaspoons half cup 8 tablespoons tablespoon 2 dessertspoons cup 2 half cups teacup 8 tablespoons

breakfastcup 2 teacups

**CHAPTER 2**

Motion Along a Straight Line

**2-1 POSITION, DISPLACEMENT, AND AVERAGE VELOCITY** Learning Objectives

*After reading this module, you should be able to …* **2.01** Identify that if all parts of an object move in the same di rection and at the same rate, we can treat the object as if it were a (point-like) particle. (This chapter is about the mo tion of such objects.)

**2.02** Identify that the position of a particle is its location as read on a scaled axis, such as an *x* axis.

**2.03** Apply the relationship between a particle’s displacement and its initial and final positions.

Key Ideas

● The position *x* of a particle on an *x* axis locates the particle with respect to the origin, or zero point, of the axis.

**2.04** Apply the relationship between a particle’s average velocity, its displacement, and the time interval for that displacement.

**2.05** Apply the relationship between a particle’s average speed, the total distance it moves, and the time interval for the motion.

**2.06** Given a graph of a particle’s position versus time, determine the average velocity between any two particular times.

● When a particle has moved from position *x*1 to position *x*2 during a time interval *t*  *t*2  *t*1, its average velocity during

● The position is either positive or negative, according to which side of the origin the particle is on, or zero if

that interval is

.

*v*avg  *x*

*t* *x*2  *x*1

the particle is at the origin. The positive direction on an axis is the direction of increasing positive numbers; the opposite direction is the negative direction on the axis.

● The displacement *x* of a particle is the change in its position:

*x*  *x*2  *x*1.

● Displacement is a vector quantity. It is positive if the particle has moved in the positive direction of the *x* axis

*t*2  *t*1

● The algebraic sign of *v*avg indicates the direction of motion (*v*avg is a vector quantity). Average velocity does not depend on the actual distance a particle moves, but instead depends on its original and final positions.

● On a graph of *x* versus *t*, the average velocity for a time in terval *t* is the slope of the straight line connecting the points on the curve that represent the two ends of the interval.

● The average speed *s*avg of a particle during a time interval *t* depends on the total distance the particle moves in that time

and negative if the particle has moved in the negative direction.

**What Is Physics?**

interval:

*s*avg total distance *t* .

One purpose of physics is to study the motion of objects—how fast they move, for

example, and how far they move in a given amount of time. NASCAR engineers

are fanatical about this aspect of physics as they determine the performance of

their cars before and during a race. Geologists use this physics to measure

tectonic-plate motion as they attempt to predict earthquakes. Medical

researchers need this physics to map the blood flow through a patient when

diagnosing a partially closed artery, and motorists use it to determine how they

might slow sufficiently when their radar detector sounds a warning. There are

countless other examples. In this chapter, we study the basic physics of motion

where the object (race car, tectonic plate, blood cell, or any other object) moves

along a single axis. Such motion is called *one-dimensional motion*.

13

14 CHAPTER 2 MOTION ALONG A STRAIGHT LINE

**Motion**

The world, and everything in it, moves. Even seemingly stationary things, such as a

roadway, move with Earth’s rotation, Earth’s orbit around the Sun, the Sun’s orbit

around the center of the Milky Way galaxy, and that galaxy’s migration relative to

other galaxies.The classification and comparison of motions (called **kinematics**) is

often challenging.What exactly do you measure, and how do you compare?

Before we attempt an answer, we shall examine some general properties of

motion that is restricted in three ways.

**1.** The motion is along a straight line only.The line may be vertical, horizontal, or

slanted, but it must be straight.

**2.** Forces (pushes and pulls) cause motion but will not be discussed until

Chapter 5. In this chapter we discuss only the motion itself and changes in the

motion. Does the moving object speed up, slow down, stop, or reverse

direction? If the motion does change, how is time involved in the change?

**3.** The moving object is either a **particle** (by which we mean a point-like object

such as an electron) or an object that moves like a particle (such that every

portion moves in the same direction and at the same rate). A stiff pig slipping

down a straight playground slide might be considered to be moving like a par

ticle; however, a tumbling tumbleweed would not.

**Position and Displacement**

Positive direction

Negative direction

–3 0

–2 –1 1 2 3 Origin

To locate an object means to find its position relative to some reference point, of ten the **origin** (or zero point) of an axis such as the *x* axis in Fig. 2-1. The **positive direction** of the axis is in the direction of increasing numbers (coordinates), which *x* (m)

is to the right in Fig. 2-1.The opposite is the **negative direction.**

For example, a particle might be located at *x*  5 m, which means it is 5 m in the positive direction from the origin. If it were at *x*  5 m, it would be just as

**Figure 2-1** Position is determined on an axis that is marked in units of length (here meters) and that extends indefinitely in opposite directions. The axis name, here *x*, is always on the positive side of the origin.

far from the origin but in the opposite direction. On the axis, a coordinate of 5 m is less than a coordinate of 1 m, and both coordinates are less than a coordinate of 5 m. A plus sign for a coordinate need not be shown, but a minus sign must always be shown.

A change from position *x*1 to position *x*2 is called a **displacement**  *x*, where *x*  *x*2  *x*1. (2-1)

(The symbol , the Greek uppercase delta, represents a change in a quantity, and it means the final value of that quantity minus the initial value.) When numbers are inserted for the position values *x*1 and *x*2 in Eq. 2-1, a displacement in the positive direction (to the right in Fig. 2-1) always comes out positive, and a displacement in the opposite direction (left in the figure) always comes out negative. For example, if the particle moves from *x*1  5 m to *x*2  12 m, then the displacement is *x*  (12 m) (5 m) 7 m. The positive result indicates that the motion is in the positive direction. If, instead, the particle moves from *x*1  5 m to *x*2  1 m, then *x*  (1 m) (5 m) 4 m. The negative result in dicates that the motion is in the negative direction.

The actual number of meters covered for a trip is irrelevant; displacement in volves only the original and final positions. For example, if the particle moves from *x*  5 m out to *x*  200 m and then back to *x*  5 m, the displacement from start to finish is *x*  (5 m) (5 m) 0.

***Signs.*** A plus sign for a displacement need not be shown, but a minus sign must always be shown. If we ignore the sign (and thus the direction) of a displace ment, we are left with the **magnitude** (or absolute value) of the displacement. For example, a displacement of *x*  4 m has a magnitude of 4 m.

This is a graph of position *x* versus time *t* for a *stationary*

2-1 POSITION, DISPLACEM ENT, AND AVERAGE VELOCITY 15

*x* (m)

+1

**Figure 2-2** The graph of *x*(*t*) for an armadillo that is stationary at *x*  2 m. The value of *x* is 2 m for all times *t*.

object.

Same position

for any time.

–1

0

~~–1~~

*t* (s) 1234 *x*(*t*)

Displacement is an example of a **vector quantity**, which is a quantity that has both a direction and a magnitude.We explore vectors more fully in Chapter 3, but here all we need is the idea that displacement has two features: (1) Its *magnitude* is the distance (such as the number of meters) between the original and final po sitions. (2) Its *direction*, from an original position to a final position, can be repre sented by a plus sign or a minus sign if the motion is along a single axis.

*Here is the first of many checkpoints where you can check your understanding with a bit of reasoning. The answers are in the back of the book.*

**Checkpoint 1**

Here are three pairs of initial and final positions, respectively, along an *x* axis.Which pairs give a negative displacement: (a) 3 m, 5 m; (b) 3 m, 7 m; (c) 7 m, 3 m?

**Average Velocity and Average Speed**

A compact way to describe position is with a graph of position *x* plotted as a func tion of time *t*—a graph of *x*(*t*). (The notation *x*(*t*) represents a function *x* of *t*, not the product *x* times *t*.) As a simple example, Fig. 2-2 shows the position function *x*(*t*) for a stationary armadillo (which we treat as a particle) over a 7 s time inter val.The animal’s position stays at *x*  2 m.

Figure 2-3 is more interesting, because it involves motion. The armadillo is apparently first noticed at *t*  0 when it is at the position *x*  5 m. It moves

*x* (m)

A

This is a graph of position *x* versus time *t* for a *moving*

At *x* = 2 m when *t* = 4 s.

4

Plotted here.

3

2

*x*(*t*) –5 2 0 *x* (m) 1

object.

It is at position *x* = –5 m when time *t* = 0 s.

Those data are plotted here.

0

–1 –2 –3 –4 –5

*t* (s) 1 2 3 4

At *x* = 0 m when *t* = 3 s. Plotted here.

4 s

–5 2 0 *x* (m) 0 s

–5 2 0 *x* (m) 3 s

**Figure 2-3** The graph of *x*(*t*) for a moving armadillo. The path associated with the graph is also shown, at three times.

16 CHAPTER 2 MOTION ALONG A STRAIGHT LINE

toward *x*  0, passes through that point at *t*  3 s, and then moves on to increas

ingly larger positive values of *x*. Figure 2-3 also depicts the straight-line motion of

the armadillo (at three times) and is something like what you would see. The

graph in Fig. 2-3 is more abstract, but it reveals how fast the armadillo moves.

Actually, several quantities are associated with the phrase “how fast.” One of

them is the **average velocity** *v*avg, which is the ratio of the displacement *x* that

occurs during a particular time interval *t* to that interval:

*v*avg  *x*

*t* *x*2  *x*1

*t*2  *t*1.

(2-2)

The notation means that the position is *x*1 at time *t*1 and then *x*2 at time *t*2. A com mon unit for *v*avg is the meter per second (m/s). You may see other units in the problems, but they are always in the form of length/time.

***Graphs.*** On a graph of *x* versus *t*, *v*avg is the **slope** of the straight line that connects two particular points on the *x*(*t*) curve: one is the point that corresponds to *x*2 and *t*2, and the other is the point that corresponds to *x*1 and *t*1. Like displace ment, *v*avg has both magnitude and direction (it is another vector quantity). Its magnitude is the magnitude of the line’s slope. A positive *v*avg (and slope) tells us that the line slants upward to the right; a negative *v*avg (and slope) tells us that the line slants downward to the right. The average velocity *v*avg always has the same sign as the displacement *x* because *t* in Eq. 2-2 is always positive.

Figure 2-4 shows how to find *v*avg in Fig. 2-3 for the time interval *t*  1 s to *t*  4 s. We draw the straight line that connects the point on the position curve at the begin ning of the interval and the point on the curve at the end of the interval.Then we find the slope *x*/ *t* of the straight line. For the given time interval, the average velocity is

*v*avg 6 m

3 s  2 m/s.

**Average speed** *s*avg is a different way of describing “how fast” a particle moves. Whereas the average velocity involves the particle’s displacement *x*, the average speed involves the total distance covered (for example, the number of meters moved), independent of direction; that is,

*s*avg total distance *t* .

(2-3)

Because average speed does *not* include direction, it lacks any algebraic sign.

Sometimes *s*avg is the same (except for the absence of a sign) as *v*avg. However, the

two can be quite different.

A

*x* (m)

This is a graph

of position *x* versus time *t.*

4

*v*avg = slope of this line

3

2

To find average velocity, 1

rise \_\_\_

run = =

Δ\_\_*x* Δ*t*

End of interval

**Figure 2-4** Calculation of the average velocity between *t*  1 s and *t*  4 s as the slope of the line that connects the points on the *x*(*t*) curve representing those times. The swirling icon indicates that a figure is available in *WileyPLUS*

first draw a straight line, start to end, and then find the slope of the line.

0

–1 –2 –3 –4 –5

*t* (s)

*x*(*t*)

1 2 34

This vertical distance is how *far* it moved, start to end:

Δ*x* = 2 m – (–4 m) = 6 m

This horizontal distance is how *long* it took, start to end:

as an animation with voiceover.

Start of interval Δ*t* = 4 s – 1 s = 3 s

2-1 POSITION, DISPLACEM ENT, AND AVERAGE VELOCITY 17

Sample Problem 2.01 Average velocity, beat-up pickup truck

You drive a beat-up pickup truck along a straight road for 8.4 km at 70 km/h, at which point the truck runs out of gaso

*Calculation:* Here we find *t* 10.4 km

line and stops. Over the next 30 min, you walk another

*v*avg  *x*

0.62 h

2.0 km farther along the road to a gasoline station. (a) What is your overall displacement from the beginning

16.8 km/h 17 km/h.

(Answer)

of your drive to your arrival at the station?

KEY IDEA

Assume, for convenience, that you move in the positive di rection of an *x* axis, from a first position of *x*1  0 to a second position of *x*2 at the station. That second position must be at *x*2  8.4 km 2.0 km 10.4 km. Then your displacement *x* along the *x* axis is the second position minus the first position.

*Calculation:* From Eq. 2-1, we have

*x*  *x*2  *x*1  10.4 km 0 10.4 km. (Answer) Thus, your overall displacement is 10.4 km in the positive direction of the *x* axis.

(b) What is the time interval *t* from the beginning of your drive to your arrival at the station?

KEY IDEA

We already know the walking time interval *t*wlk ( 0.50 h), but we lack the driving time interval *t*dr. However, we know that for the drive the displacement *x*dr is 8.4 km and the average velocity *v*avg,dr is 70 km/h. Thus, this average velocity is the ratio of the displacement for the drive to the time interval for the drive.

*Calculations:* We first write

To find *v*avg graphically, first we graph the function *x*(*t*) as shown in Fig. 2-5, where the beginning and arrival points on the graph are the origin and the point labeled as “Station.”Your average velocity is the slope of the straight line connecting those points; that is, *v*avg is the ratio of the *rise* ( *x*  10.4 km) to the *run* ( *t*  0.62 h), which gives us *v*avg  16.8 km/h.

(d) Suppose that to pump the gasoline, pay for it, and walk back to the truck takes you another 45 min. What is your average speed from the beginning of your drive to your return to the truck with the gasoline?

KEY IDEA

Your average speed is the ratio of the total distance you move to the total time interval you take to make that move.

*Calculation:* The total distance is 8.4 km 2.0 km 2.0 km 12.4 km. The total time interval is 0.12 h 0.50 h 0.75 h 1.37 h.Thus, Eq. 2-3 gives us

*s* (Answer) avg 12.4 km 1.37 h  9.1 km/h.

Driving ends, walking starts.

*x*

12

*v*avg,dr  *x*dr

10

*t*dr.

)

8

m

k

Rearranging and substituting data then give us

(

g

n

6

in

o

i

iv

*t*dr  *x*dr

*v*avg,dr 8.4 km

t

i

r

s

70 km/h  0.12 h.

D

o

4

P

Walking

Station

Slope of this line gives

average

velocity.

How far:

Δ*x* = 10.4 km

So,

(Answer)

*t*  *t*dr  *t*wlk

0.12 h 0.50 h 0.62 h.

2

*t*

00 0.2 0.4 0.6

(c) What is your average velocity *v*avg from the beginning of your drive to your arrival at the station? Find it both numer ically and graphically.

Time (h)

How long:

Δ*t* = 0.62 h

KEY IDEA

From Eq. 2-2 we know that *v*avg *for the entire trip* is the ratio of the displacement of 10.4 km *for the entire trip* to the time interval of 0.62 h *for the entire trip.*

**Figure 2-5** The lines marked “Driving” and “Walking” are the position–time plots for the driving and walking stages. (The plot for the walking stage assumes a constant rate of walking.) The slope of the straight line joining the origin and the point labeled “Station” is the average velocity for the trip, from the beginning to the station.

Additional examples, video, and practice available at *WileyPLUS*

18 CHAPTER 2 MOTION ALONG A STRAIGHT LINE **2-2 INSTANTANEOUS VELOCITY AND SPEED** Learning Objectives

*After reading this module, you should be able to . . .* **2.07** Given a particle’s position as a function of time, calculate the instantaneous velocity for any particular time.

Key Ideas

● The instantaneous velocity (or simply velocity) *v* of a moving

**2.08** Given a graph of a particle’s position versus time, deter mine the instantaneous velocity for any particular time. **2.09** Identify speed as the magnitude of the instantaneous velocity.

● The instantaneous velocity (at a particular time) may be

particle is

*v*  lim

*t* : 0

*x*

*t* *dxdt* ,

found as the slope (at that particular time) of the graph of *x* versus *t*.

● Speed is the magnitude of instantaneous velocity.

where *x*  *x*2  *x*1 and *t*  *t*2  *t*1.

**Instantaneous Velocity and Speed**

You have now seen two ways to describe how fast something moves: average

velocity and average speed, both of which are measured over a time interval *t*.

However, the phrase “how fast” more commonly refers to how fast a particle is

moving at a given instant—its **instantaneous velocity** (or simply **velocity**) *v*.

The velocity at any instant is obtained from the average velocity by shrinking

the time interval *t* closer and closer to 0. As *t* dwindles, the average velocity

approaches a limiting value, which is the velocity at that instant:

*x*

*v*  lim *t* : 0

*t* *dxdt* .

(2-4)

Note that *v* is the rate at which position *x* is changing with time at a given instant;

that is, *v* is the derivative of *x* with respect to *t*. Also note that *v* at any instant is

the slope of the position–time curve at the point representing that instant.

Velocity is another vector quantity and thus has an associated direction.

**Speed** is the magnitude of velocity; that is, speed is velocity that has been

stripped of any indication of direction, either in words or via an algebraic sign.

(*Caution:* Speed and average speed can be quite different.) A velocity of 5 m/s

and one of 5 m/s both have an associated speed of 5 m/s. The speedometer in a

car measures speed, not velocity (it cannot determine the direction).

**Checkpoint 2**

The following equations give the position *x*(*t*) of a particle in four situations (in each

equation, *x* is in meters, *t* is in seconds, and *t*  0): (1) *x*  3*t*  2; (2) *x*  4*t* 2  2;

(3) *x*  2/*t* 2; and (4) *x*  2. (a) In which situation is the velocity *v* of the particle con

stant? (b) In which is *v* in the negative *x* direction?

Sample Problem 2.02 Velocity and slope of *x* versus *t*, elevator cab

Figure 2-6*a* is an *x*(*t*) plot for an elevator cab that is initially stationary, then moves upward (which we take to be the pos itive direction of *x*), and then stops. Plot *v*(*t*).

KEY IDEA

We can find the velocity at any time from the slope of the *x*(*t*) curve at that time.

*Calculations:* The slope of *x*(*t*), and so also the velocity, is zero in the intervals from 0 to 1 s and from 9 s on, so then the cab is stationary. During the interval *bc*, the slope is con stant and nonzero, so then the cab moves with constant ve locity.We calculate the slope of *x*(*t*) then as

(2-5)  *x* *t* *v* 24 m 4.0 m

8.0 s 3.0 s 4.0 m/s.

2-2 INSTANTANEOUS VELOCITY AND SPEED 19

)

m

(

n

o

i

t

is

o

P

*x*

25

20

15

10

5

*x* = 24 m

at *t* = 8.0 s

*x* = 4.0 m

at *t* = 3.0 s

*x*(*t*)

*c d* Δ*x*

*a b*

Δ*t*

0

*t*

0 9 1 2 3 4 5 6 7 8

Time (s)

(*a*)

*v*

Slope of *x*(*t*)

Slopes on the *x* versus *t* graph are the values on the *v* versus *t* graph.

) s

/

m

(

y

t

i

c

o

l

e

V

*b c v*(*t*)

4

3

2

1

*a d* 0

*t*

9

0

1 2 3 4 5 6 7 8

)

2

s

/m

3 2 1

Time (s)

(*b*)

*a*

Acceleration

Slopes on the *v* versus *t* graph are the values on the *a* versus *t* graph.

(

0

**Figure 2-6** (*a*) The *x*(*t*) curve for an elevator cab

n

o

i

–1

that moves upward along an *x* axis. (*b*) The *v*(*t*)

t

a

r

–2

curve for the cab. Note that it is the derivative

e

l

e

–3

c

of the *x*(*t*) curve (*v*  *dx*/*dt*). (*c*) The *a*(*t*) curve

c

–4

A

for the cab. It is the derivative of the *v*(*t*) curve (*a*  *dv*/*dt*). The stick figures along the bottom suggest how a passenger’s body might feel dur ing the accelerations.

*a d b c*

*a*(*t*)

*t*

1 2 3 4 5 6 7 8 9 Deceleration

(*c*)

What you would feel.

The plus sign indicates that the cab is moving in the posi tive *x* direction. These intervals (where *v*  0 and *v*  4 m/s) are plotted in Fig. 2-6*b.* In addition, as the cab ini tially begins to move and then later slows to a stop, *v* varies as indicated in the intervals 1 s to 3 s and 8 s to 9 s. Thus, Fig. 2-6*b* is the required plot. (Figure 2-6*c* is consid ered in Module 2-3.)

Given a *v*(*t*) graph such as Fig. 2-6*b*, we could “work backward” to produce the shape of the associated *x*(*t*) graph (Fig. 2-6*a*). However, we would not know the actual values for *x* at various times, because the *v*(*t*) graph indicates only *changes* in *x.* To find such a change in *x* during any in

terval, we must, in the language of calculus, calculate the area “under the curve” on the *v*(*t*) graph for that interval. For example, during the interval 3 s to 8 s in which the cab has a velocity of 4.0 m/s, the change in *x* is

*x*  (4.0 m/s)(8.0 s 3.0 s) 20 m. (2-6)

(This area is positive because the *v*(*t*) curve is above the *t* axis.) Figure 2-6*a* shows that *x* does indeed increase by 20 m in that interval. However, Fig. 2-6*b* does not tell us the *values* of *x* at the beginning and end of the interval. For that, we need additional information, such as the value of *x* at some instant.

Additional examples, video, and practice available at *WileyPLUS*

20 CHAPTER 2 MOTION ALONG A STRAIGHT LINE **2-3 ACCELERATION**

Learning Objectives

*After reading this module, you should be able to . . .*

**2.10** Apply the relationship between a particle’s average acceleration, its change in velocity, and the time interval for that change.

**2.11** Given a particle’s velocity as a function of time, calcu late the instantaneous acceleration for any particular time.

Key Ideas

● Average acceleration is the ratio of a change in velocity *v* to the time interval *t* in which the change occurs:

*a*avg *v**t*.

**2.12** Given a graph of a particle’s velocity versus time, deter mine the instantaneous acceleration for any particular time and the average acceleration between any two particular times.

● Instantaneous acceleration (or simply acceleration) *a* is the first time derivative of velocity *v*(*t*) and the second time deriv ative of position *x*(*t*):

*a* *dvdt* *d*2*x*

.

*dt*2

The algebraic sign indicates the direction of *a*avg. **Acceleration**

● On a graph of *v* versus *t*, the acceleration *a* at any time *t* is the slope of the curve at the point that represents *t*.

When a particle’s velocity changes, the particle is said to undergo **acceleration** (or to accelerate). For motion along an axis, the **average acceleration** *a*avg over a time interval *t* is

*a*avg *v*2  *v*1

*t*2  *t*1 *v**t*,

(2-7)

where the particle has velocity *v*1 at time *t*1 and then velocity *v*2 at time *t*2. The **instantaneous acceleration** (or simply **acceleration**) is

*a* *dvdt* .

(2-8)

In words, the acceleration of a particle at any instant is the rate at which its velocity is changing at that instant. Graphically, the acceleration at any point is the slope of the curve of *v*(*t*) at that point.We can combine Eq. 2-8 with Eq. 2-4 to write

*a* *dvdt* *ddt*  *dxdt* *d*2*x dt* 2 .

(2-9)

In words, the acceleration of a particle at any instant is the second derivative of its position *x*(*t*) with respect to time.

A common unit of acceleration is the meter per second per second: m/(s s) or m/s2. Other units are in the form of length/(time time) or length/time2. Acceleration has both magnitude and direction (it is yet another vector quan tity). Its algebraic sign represents its direction on an axis just as for displacement and velocity; that is, acceleration with a positive value is in the positive direction of an axis, and acceleration with a negative value is in the negative direction.

Figure 2-6 gives plots of the position, velocity, and acceleration of an ele vator moving up a shaft. Compare the *a*(*t*) curve with the *v*(*t*) curve—each point on the *a*(*t*) curve shows the derivative (slope) of the *v*(*t*) curve at the corresponding time. When *v* is constant (at either 0 or 4 m/s), the derivative is zero and so also is the acceleration. When the cab first begins to move, the *v*(*t*)

2-3 ACCELERATION 21

curve has a positive derivative (the slope is positive), which means that *a*(*t*) is

positive. When the cab slows to a stop, the derivative and slope of the *v*(*t*)

curve are negative; that is, *a*(*t*) is negative.

Next compare the slopes of the *v*(*t*) curve during the two acceleration peri

ods. The slope associated with the cab’s slowing down (commonly called “decel

eration”) is steeper because the cab stops in half the time it took to get up to

speed. The steeper slope means that the magnitude of the deceleration is larger

than that of the acceleration, as indicated in Fig. 2-6*c*.

***Sensations.*** The sensations you would feel while riding in the cab of

Fig. 2-6 are indicated by the sketched figures at the bottom. When the cab first

accelerates, you feel as though you are pressed downward; when later the cab is

braked to a stop, you seem to be stretched upward. In between, you feel nothing

special. In other words, your body reacts to accelerations (it is an accelerometer)

but not to velocities (it is not a speedometer). When you are in a car traveling at

90 km/h or an airplane traveling at 900 km/h, you have no bodily awareness of

the motion. However, if the car or plane quickly changes velocity, you may be

come keenly aware of the change, perhaps even frightened by it. Part of the thrill

of an amusement park ride is due to the quick changes of velocity that you un

dergo (you pay for the accelerations, not for the speed).A more extreme example

is shown in the photographs of Fig. 2-7, which were taken while a rocket sled was

rapidly accelerated along a track and then rapidly braked to a stop. 

***g Units.*** Large accelerations are sometimes expressed in terms of *g* units, with

1*g*  9.8 m/s2 (*g* unit). (2-10)

(As we shall discuss in Module 2-5, *g* is the magnitude of the acceleration of a

falling object near Earth’s surface.) On a roller coaster, you may experience brief

accelerations up to 3*g*, which is (3)(9.8 m/s2), or about 29 m/s2, more than enough

to justify the cost of the ride.

***Signs.*** In common language, the sign of an acceleration has a nonscientific

meaning: positive acceleration means that the speed of an object is increasing, and

negative acceleration means that the speed is decreasing (the object is decelerat

ing). In this book, however, the sign of an acceleration indicates a direction, not

**Figure 2-7** 

Colonel J. P. Stapp in

a rocket sled as it is

brought up to high

speed (acceleration

out of the page) and

then very rapidly

braked (acceleration

into the page).

Courtesy U.S. Air Force

22 CHAPTER 2 MOTION ALONG A STRAIGHT LINE

whether an object’s speed is increasing or decreasing. For example, if a car with an

initial velocity *v*  25 m/s is braked to a stop in 5.0 s, then *a*avg  5.0 m/s2. The

acceleration is *positive*, but the car’s speed has decreased. The reason is the differ

ence in signs: the direction of the acceleration is opposite that of the velocity.

Here then is the proper way to interpret the signs:

If the signs of the velocity and acceleration of a particle are the same, the speed

of the particle increases. If the signs are opposite, the speed decreases.

**Checkpoint 3**

A wombat moves along an *x* axis.What is the sign of its acceleration if it is moving

(a) in the positive direction with increasing speed, (b) in the positive direction with

decreasing speed, (c) in the negative direction with increasing speed, and (d) in the

negative direction with decreasing speed?

Sample Problem 2.03 Acceleration and *dv*/*dt*

A particle’s position on the *x* axis of Fig. 2-1 is given by *x*  4 27*t*  *t* 3,

with *x* in meters and *t* in seconds.

(a) Because position *x* depends on time *t*, the particle must be moving. Find the particle’s velocity function *v*(*t*) and ac celeration function *a*(*t*).

KEY IDEAS

(1) To get the velocity function *v*(*t*), we differentiate the po sition function *x*(*t*) with respect to time. (2) To get the accel eration function *a*(*t*), we differentiate the velocity function *v*(*t*) with respect to time.

*Calculations:* Differentiating the position function, we find *v*  27 3*t* 2, (Answer)

with *v* in meters per second. Differentiating the velocity function then gives us

*a*  6*t*, (Answer)

*Reasoning:* We need to examine the expressions for *x*(*t*), *v*(*t*), and *a*(*t*).

At *t*  0, the particle is at *x*(0) 4 m and is moving with a velocity of *v*(0) 27 m/s—that is, in the negative direction of the *x* axis. Its acceleration is *a*(0) 0 because just then the particle’s velocity is not changing (Fig. 2-8*a*).

For 0 *t* 3 s, the particle still has a negative velocity, so it continues to move in the negative direction. However, its acceleration is no longer 0 but is increasing and positive. Because the signs of the velocity and the acceleration are opposite, the particle must be slowing (Fig. 2-8*b*).

Indeed, we already know that it stops momentarily at *t*  3 s. Just then the particle is as far to the left of the origin in Fig. 2-1 as it will ever get. Substituting *t*  3 s into the expression for *x*(*t*), we find that the particle’s position just then is *x*  50 m (Fig. 2-8*c*). Its acceleration is still positive.

For *t*  3 s, the particle moves to the right on the axis. Its acceleration remains positive and grows progressively larger in magnitude. The velocity is now positive, and it too grows progressively larger in magnitude (Fig. 2-8*d*).

with *a* in meters per second squared.

(b) Is there ever a time when *v*  0?

*Calculation:* Setting *v*(*t*) 0 yields

0 27 3*t* 2,

which has the solution

*t*  3 s. (Answer)

Thus, the velocity is zero both 3 s before and 3 s after the clock reads 0.

*t* = 3 s

*v* = 0

*a* pos

reversing (*c*)

−50 m

*t* = 4 s

*v* pos

*a* pos

speeding up (*d*)

*t* = 1 s

*v* neg

*a* pos

slowing

(*b*)

*x*

0 4 m*t* = 0 *v* neg

*a* = 0

leftward

motion

(*a*)

(c) Describe the particle’s motion for *t* 0. **Figure 2-8** Four stages of the particle’s motion. Additional examples, video, and practice available at *WileyPLUS*

2-4 CONSTANT ACCELERATION 23

**2-4 CONSTANT ACCELERATION**

Learning Objectives

*After reading this module, you should be able to . . .* **2.13** For constant acceleration, apply the relationships be tween position, displacement, velocity, acceleration, and elapsed time (Table 2-1).

Key Ideas

**2.14** Calculate a particle’s change in velocity by integrating its acceleration function with respect to time. **2.15** Calculate a particle’s change in position by integrating its velocity function with respect to time.

● The following five equations describe the motion of a particle with constant acceleration: *x*  *x*0  *v*0*t* 12 *~~a~~t*2 *v*  *v* , 0  *at*,

*x*  *x*0 *vt* 12 *~~a~~t*2 *x*  *x* . 0 12 *v* (*v*0  *v*)*t*, 2  *v*02  2*a*(*x*  *x*0), These are *not* valid when the acceleration is not constant.

**Constant Acceleration: A Special Case**

*x*

In many types of motion, the acceleration is either constant or approximately so. For example, you might accelerate a car at an approximately constant rate when a traffic light turns from red to green. Then graphs of your position, velocity, n

and acceleration would resemble those in Fig. 2-9. (Note that *a*(*t*) in Fig. 2-9*c* is

o

i

t

i

constant, which requires that *v*(*t*) in Fig. 2-9*b* have a constant slope.) Later when

s

o

P

you brake the car to a stop, the acceleration (or deceleration in common *x*0

*x*(*t*)

Slope varies

language) might also be approximately constant.

(*a*)

Such cases are so common that a special set of equations has been derived for dealing with them. One approach to the derivation of these equations is given

*t*

0

Slopes of the position graph

in this section. A second approach is given in the next section. Throughout both sections and later when you work on the homework problems, keep in mind that *these equations are valid only for constant acceleration (or situations in which you can approximate the acceleration as being constant)*.

***First Basic Equation.*** When the acceleration is constant, the average accel eration and instantaneous acceleration are equal and we can write Eq. 2-7, with

are plotted on the velocity graph.

*v*

*v*(*t*)

y

t

i

c

some changes in notation, as

o

l

e

V

*v*0

*a*  *a*avg *v*  *v*0

*t*  0 .

0

(*b*)

Slope = *a*

*t*

Here *v*0 is the velocity at time *t*  0 and *v* is the velocity at any later time *t*.We can recast this equation as

*v*  *v*0  *at*. (2-11)

Slope of the velocity graph is plotted on the acceleration graph.

*a*

n

o

i

t

a

r

As a check, note that this equation reduces to *v*  *v*0 for *t*  0, as it must.As a fur

e

l

e

*a*(*t*)

Slope = 0

ther check, take the derivative of Eq. 2-11. Doing so yields *dv*/*dt*  *a*, which is the

(*c*) *t*

c

c

0

A

definition of *a*. Figure 2-9*b* shows a plot of Eq. 2-11, the *v*(*t*) function; the function

is linear and thus the plot is a straight line.

***Second Basic Equation.*** In a similar manner, we can rewrite Eq. 2-2 (with a few changes in notation) as

*v*avg *x*  *x*0

*t*  0

**Figure 2-9** (*a*) The position *x*(*t*) of a particle moving with constant acceleration. (*b*) Its velocity *v*(*t*), given at each point by the slope of the curve of *x*(*t*). (*c*) Its (constant) acceleration, equal to the (constant) slope of the curve of *v*(*t*).

24 CHAPTER 2 MOTION ALONG A STRAIGHT LINE

and then as

*x*  *x*0  *v*avg*t*, (2-12)

in which *x*0 is the position of the particle at *t*  0 and *v*avg is the average velocity

between *t*  0 and a later time *t*.

For the linear velocity function in Eq. 2-11, the *average* velocity over any time

interval (say, from *t*  0 to a later time *t*) is the average of the velocity at the be

ginning of the interval ( *v*0) and the velocity at the end of the interval ( *v*). For

the interval from *t*  0 to the later time *t* then, the average velocity is

*v*avg  12 (*v*0  *v*).

(2-13)

Substituting the right side of Eq. 2-11 for *v* yields, after a little rearrangement,

*v*avg  *v*0  12 *at*.

Finally, substituting Eq. 2-14 into Eq. 2-12 yields *x*  *x*0  *v*0*t*  12 *at* 2.

(2-14) (2-15)

As a check, note that putting *t*  0 yields *x*  *x*0, as it must. As a further check, taking the derivative of Eq. 2-15 yields Eq. 2-11, again as it must. Figure 2-9*a* shows a plot of Eq. 2-15; the function is quadratic and thus the plot is curved.

***Three Other Equations.*** Equations 2-11 and 2-15 are the *basic equations for constant acceleration;* they can be used to solve any constant acceleration prob lem in this book. However, we can derive other equations that might prove useful in certain specific situations. First, note that as many as five quantities can possi bly be involved in any problem about constant acceleration—namely, *x*  *x*0, *v*, *t*, *a*, and *v*0. Usually, one of these quantities is *not* involved in the problem, *either as a given or as an unknown.* We are then presented with three of the remaining quantities and asked to find the fourth.

Equations 2-11 and 2-15 each contain four of these quantities, but not the same four. In Eq. 2-11, the “missing ingredient” is the displacement *x*  *x*0. In Eq. 2-15, it is the velocity *v.* These two equations can also be combined in three ways to yield three additional equations, each of which involves a different “missing variable.” First, we can eliminate *t* to obtain

*v*2  *v*02  2*a*(*x*  *x*0).

(2-16)

This equation is useful if we do not know *t* and are not required to find it. Second, we can eliminate the acceleration *a* between Eqs. 2-11 and 2-15 to produce an equation in which *a* does not appear:

**Table 2-1** Equations for Motion with Constant Acceleration*a*

Equation Missing Number Equation Quantity

*x*  *x*0  12(*v*0  *v*)*t*.

Finally, we can eliminate *v*0, obtaining

*x*  *x*0  *vt*  12 *at* 2.

(2-17) (2-18)

2-11 *v*  *v*0  *at x*  *x*0 *x*  *x*0  *v*0*t*  12*at*2

2-15 *v* 2-16 *t*

*v*2  *v*02  2*a*(*x*  *x*0)

*x*  *x*0  12(*v*0  *v*)*t*

2-17 *a x*  *x*0  *vt*  12*at*2

2-18 *v*0

*a*Make sure that the acceleration is indeed constant before using the equations in this table.

Note the subtle difference between this equation and Eq. 2-15. One involves the initial velocity *v*0; the other involves the velocity *v* at time *t*.

Table 2-1 lists the basic constant acceleration equations (Eqs. 2-11 and 2-15) as well as the specialized equations that we have derived.To solve a simple constant ac celeration problem, you can usually use an equation from this list (*if* you have the list with you). Choose an equation for which the only unknown variable is the vari able requested in the problem. A simpler plan is to remember only Eqs. 2-11 and 2-15, and then solve them as simultaneous equations whenever needed.

2-4 CONSTANT ACCELERATION 25

**Checkpoint 4**

The following equations give the position *x*(*t*) of a particle in four situations: (1) *x*

3*t*  4; (2) *x*  5*t* 3  4*t* 2  6; (3) *x*  2/*t* 2  4/*t*; (4) *x*  5*t* 2  3.To which of these

situations do the equations of Table 2-1 apply?

Sample Problem 2.04 Drag race of car and motorcycle

A popular web video shows a jet airplane, a car, and a mo torcycle racing from rest along a runway (Fig. 2-10). Initially the motorcycle takes the lead, but then the jet takes the lead, and finally the car blows past the motorcycle. Here let’s focus on the car and motorcycle and assign some reasonable values to the motion. The motorcycle first takes the lead because its (constant) acceleration *am*  8.40 m/s2 is greater than the car’s (constant) acceleration *ac*  5.60 m/s2, but it soon loses to the

choose any initial numbers because we are looking for the elapsed time, not a particular time in, say, the afternoon, but let’s stick with these easy numbers.) We want the car to pass the motorcycle, but what does that mean mathematically?

It means that at some time *t*, the side-by-side vehicles are at the same coordinate: *xc* for the car and the sum *xm*1  *xm*2 for the motorcycle. We can write this statement mathe matically as

car because it reaches its greatest speed *vm*  58.8 m/s before the car reaches its greatest speed *vc*  106 m/s. How long does

*xc*  *xm*1  *xm*2.

(2-19)

the car take to reach the motorcycle?

KEY IDEAS

We can apply the equations of constant acceleration to both vehicles, but for the motorcycle we must consider the mo tion in two stages: (1) First it travels through distance *xm*1 with zero initial velocity and acceleration *am*  8.40 m/s2, reaching speed *vm*  58.8 m/s. (2) Then it travels through dis tance *xm*2 with constant velocity *vm*  58.8 m/s and zero ac

(Writing this first step is the hardest part of the problem. That is true of most physics problems. How do you go from the problem statement (in words) to a mathematical expres sion? One purpose of this book is for you to build up that ability of writing the first step — it takes lots of practice just as in learning, say, tae-kwon-do.)

Now let’s fill out both sides of Eq. 2-19, left side first. To reach the passing point at *xc*, the car accelerates from rest. From (*x*  *x*0  *v*0*t*  12*at*2)

Eq. 2-15 , with *x*0 and *v*0  0, we have

celeration (that, too, is a constant acceleration). (Note that we symbolized the distances even though we do not know

*xc*  12*act*2.

(2-20)

their values. Symbolizing unknown quantities is often help ful in solving physics problems, but introducing such un knowns sometimes takes *physics courage*.)

*Calculations:* So that we can draw figures and do calcula

To write an expression for *xm*1 for the motorcycle, we first find the time *tm* it takes to reach its maximum speed *vm*, using Eq. 2-11 (*v*  *v*0  *at*). Substituting *v*0  0, *v*  *vm*  58.8 m/s, and *a*  *am*  8.40 m/s2, that time is

tions, let’s assume that the vehicles race along the positive di rection of an *x* axis, starting from *x*  0 at time *t*  0. (We can

*tm* *vm*

*am*

58.8 m/s

8.40 m/s2  7.00 s.

(2-21)

To get the distance *xm*1 traveled by the motorcycle during the first stage, we again use Eq. 2-15 with *x*0  0 and *v*0  0, but we also substitute from Eq. 2-21 for the time.We find

*xm*1  12*amtm*2  12*am* *vm*

*am*  212*vm*2 *am*.

(2-22)





**Figure 2-10** A jet airplane, a car, and a motorcycle just after accelerating from rest.

For the remaining time of , the motorcycle travels

*t*  *tm*

at its maximum speed with zero acceleration. To get the distance, we use Eq. 2-15 for this second stage of the motion, but now the initial velocity is (the speed at the end *v*0  *vm* of the first stage) and the acceleration is *a*  0. So, the dis tance traveled during the second stage is

*xm* (2-23) 2  *vm*(*t*  *tm*) *vm*(*t*  7.00 s).

26 CHAPTER 2 MOTION ALONG A STRAIGHT LINE

To finish the calculation, we substitute Eqs. 2-20, 2-22, and 2-23 into Eq. 2-19, obtaining

2*act*2 12*vm*2

that at *t*  7.00 s the plot for the motorcycle switches from being curved (because the speed had been increasing) to be ing straight (because the speed is thereafter constant).

1

*am* *vm*(*t*  7.00 s).

(2-24)

This is a quadratic equation. Substituting in the given data, we solve the equation (by using the usual quadratic-equa tion formula or a polynomial solver on a calculator), finding *t*  4.44 s and *t*  16.6 s.

But what do we do with two answers? Does the car pass the motorcycle twice? No, of course not, as we can see in the

)

video. So, one of the answers is mathematically correct but m

(

not physically meaningful. Because we know that the car

*x*

passes the motorcycle *after* the motorcycle reaches its maxi mum speed at *t*  7.00 s, we discard the solution with *t* 7.00 s as being the unphysical answer and conclude that the passing occurs at

1000 800 600 400 200

Acceleration ends

Car passes

motorcycle

Motorcycle

Car

*t*  16.6 s.

(Answer)

0

0 5 10 15 20

Figure 2-11 is a graph of the position versus time for the two vehicles, with the passing point marked. Notice

*t* (s)

**Figure 2-11** Graph of position versus time for car and motorcycle.

Additional examples, video, and practice available at *WileyPLUS*

**Another Look at Constant Acceleration\***

The first two equations in Table 2-1 are the basic equations from which the others

are derived. Those two can be obtained by integration of the acceleration with

the condition that *a* is constant. To find Eq. 2-11, we rewrite the definition of ac

celeration (Eq. 2-8) as

*dv*  *a dt*.

We next write the *indefinite integral* (or *antiderivative*) of both sides:

*dv*  *a dt*.

Since acceleration *a* is a constant, it can be taken outside the integration.We obtain

*dv*  *a*  *dt*

or *v*  *at*  *C*. (2-25)

To evaluate the constant of integration *C*, we let *t*  0, at which time *v*  *v*0.

Substituting these values into Eq. 2-25 (which must hold for all values of *t*,

including *t*  0) yields

*v*0  (*a*)(0) *C*  *C.*

Substituting this into Eq. 2-25 gives us Eq. 2-11.

To derive Eq. 2-15, we rewrite the definition of velocity (Eq. 2-4) as

*dx*  *v dt*

and then take the indefinite integral of both sides to obtain

*dx*  *v dt*.

\*This section is intended for students who have had integral calculus.

2-5 FREE-FALL ACCELERATION 27

Next, we substitute for *v* with Eq. 2-11:

*dx*  (*v*0  *at*) *dt*.

Since *v*0 is a constant, as is the acceleration *a*, this can be rewritten as

*dx*  *v*0 *dt*  *a* *t dt*.

Integration now yields

*x*  *v*0*t*  12 *at* 2  *C* ,

(2-26)

where *C* is another constant of integration. At time *t*  0, we have *x*  *x*0. Substituting these values in Eq. 2-26 yields *x*0  *C* . Replacing *C* with *x*0 in Eq. 2-26 gives us Eq. 2-15.

**2-5 FREE-FALL ACCELERATION**

Learning Objectives

*After reading this module, you should be able to . . .* **2.16** Identify that if a particle is in free flight (whether upward or downward) and if we can neglect the effects of air on its motion, the particle has a constant

Key Ideas

● An important example of straight-line motion with constant acceleration is that of an object rising or falling freely near Earth’s surface. The constant acceleration equations de scribe this motion, but we make two changes in notation:

**Free-Fall Acceleration**

downward acceleration with a magnitude *g* that we take to be 9.8 m/s2.

**2.17** Apply the constant-acceleration equations (Table 2-1) to free-fall motion.

(1) we refer the motion to the vertical *y* axis with *y* vertically up; (2) we replace *a* with *g*, where *g* is the magnitude of the free-fall acceleration. Near Earth’s surface,

*g*  9.8 m/s2  32 ft/s2.

If you tossed an object either up or down and could somehow eliminate the effects of air on its flight, you would find that the object accelerates downward at a certain constant rate.That rate is called the **free-fall acceleration,** and its magni tude is represented by *g*. The acceleration is independent of the object’s charac teristics, such as mass, density, or shape; it is the same for all objects.

Two examples of free-fall acceleration are shown in Fig. 2-12, which is a series of stroboscopic photos of a feather and an apple. As these objects fall, they accelerate downward—both at the same rate *g*. Thus, their speeds increase at the same rate, and they fall together.

The value of *g* varies slightly with latitude and with elevation. At sea level in Earth’s midlatitudes the value is 9.8 m/s2 (or 32 ft/s2), which is what you should use as an exact number for the problems in this book unless otherwise noted.

The equations of motion in Table 2-1 for constant acceleration also apply to free fall near Earth’s surface; that is, they apply to an object in vertical flight, either up or down, when the effects of the air can be neglected. However, note that for free fall: (1) The directions of motion are now along a vertical *y* axis instead of the *x* axis, with the positive direction of *y* upward. (This is important for later chapters when combined horizontal and vertical motions are examined.) (2) The free-fall acceleration is negative—that is, downward on the *y* axis, toward Earth’s center—and so it has the value *g* in the equations.

© Jim Sugar/CORBIS

**Figure 2-12** A feather and an apple free fall in vacuum at the same magnitude of acceleration *g*. The acceleration increases the distance between successive images. In the absence of air, the feather and apple fall together.

28 CHAPTER 2 MOTION ALONG A STRAIGHT LINE

The free-fall acceleration near Earth’s surface is *a*  *g*  9.8 m/s2, and the

*magnitude* of the acceleration is *g*  9.8 m/s2. Do not substitute 9.8 m/s2 for *g*.

Suppose you toss a tomato directly upward with an initial (positive) velocity *v*0

and then catch it when it returns to the release level. During its *free-fall flight* (from

just after its release to just before it is caught), the equations of Table 2-1 apply to its

motion. The acceleration is always *a*  *g*  9.8 m/s2, negative and thus down

ward. The velocity, however, changes, as indicated by Eqs. 2-11 and 2-16: during the

ascent, the magnitude of the positive velocity decreases, until it momentarily be

comes zero. Because the tomato has then stopped, it is at its maximum height.

During the descent, the magnitude of the (now negative) velocity increases.

**Checkpoint 5**

(a) If you toss a ball straight up, what is the sign of the ball’s displacement for the ascent,

from the release point to the highest point? (b) What is it for the descent, from the high

est point back to the release point? (c) What is the ball’s acceleration at its highest point?

Sample Problem 2.05 Time for full up-down flight, baseball toss In Fig. 2-13, a pitcher tosses a baseball up along a *y* axis, with

*y*

*v* = 0 at

Ball

an initial speed of 12 m/s. (a) How long does the ball take to reach its maximum height?

KEY IDEAS

(1) Once the ball leaves the pitcher and before it returns to his hand, its acceleration is the free-fall acceleration *a*  *g*. Because this is constant, Table 2-1 applies to the motion. (2) The velocity *v* at the maximum height must be 0.

*Calculation:* Knowing *v*, *a*, and the initial velocity *v*0  12 m/s, and seeking *t*, we solve Eq. 2-11, which contains those four variables.This yields

*a* 0 12 m/s

highest point

During ascent,

*a* = –*g,*

speed decreases,

and velocity

becomes less

positive

**Figure 2-13** A pitcher tosses a

baseball straight up into the air.

During

descent,

*a* = –*g,*

speed

increases, and velocity becomes

more

negative

*y* = 0

*t* *v*  *v*0

9.8 m/s2  1.2 s.

(Answer)

The equations of free fall apply for rising as well as for falling objects, provided any effects

(b) What is the ball’s maximum height above its release point?

*Calculation:* We can take the ball’s release point to be *y*0  0. We can then write Eq.2-16 in *y* notation,set *y*  *y*0  *y* and *v*  0 (at the maximum height),and solve for *y*.We get

*y* *v*2  *v*02

2*a* 0 (12 m/s)2

from the air can be neglected.

5.0 m (12 m/s)*t*  (12)(9.8 m/s2)*t*2.

or

If we temporarily omit the units (having noted that they are consistent), we can rewrite this as

2( 9.8 m/s2)  7.3 m.

(Answer)

4.9*t* 2  12*t*  5.0 0.

(c) How long does the ball take to reach a point 5.0 m above its release point?

*Calculations:* We know *v*0, *a*  *g*, and displacement *y*  *y*0  5.0 m, and we want *t*, so we choose Eq. 2-15. Rewriting it for *y* and setting *y*0  0 give us

*y*  *v*0*t*  12 *gt*2,

Solving this quadratic equation for *t* yields

*t*  0.53 s and *t*  1.9 s. (Answer)

There are two such times! This is not really surprising because the ball passes twice through *y*  5.0 m, once on the way up and once on the way down.

Additional examples, video, and practice available at *WileyPLUS*

2-6 GRAPHICAL INTEGRATION IN MOTION ANALYSIS 29

**2-6 GRAPHICAL INTEGRATION IN MOTION ANALYSIS**

Learning Objectives

*After reading this module, you should be able to . . .*

**2.18** Determine a particle’s change in velocity by graphical integration on a graph of acceleration versus time.

Key Ideas

● On a graph of acceleration *a* versus time *t*, the change in the velocity is given by

**2.19** Determine a particle’s change in position by graphical integration on a graph of velocity versus time.

● On a graph of velocity *v* versus time *t*, the change in the position is given by

*v*1  *v*0  *t*1 *t*0

*a dt*.

*x*1  *x*0  *t*1 *t*0

*v dt*,

The integral amounts to finding an area on the graph:

where the integral can be taken from the graph as

*t*1 *t*0

*a dt*  area between acceleration curve and time axis, from *t*0 to *t*1  .

*t*1 *t*0

and time axis, from *t*0 to *t*1  .

*v dt*  area between velocity curve

**Graphical Integration in Motion Analysis**

***Integrating Acceleration.*** When we have a graph of an object’s acceleration *a* ver sus time *t*, we can integrate on the graph to find the velocity at any given time. Because *a* is defined as *a*  *dv*/*dt*, the Fundamental Theorem of Calculus tells us that

*v*1  *v*0  *t*1 *t*0

*a dt*.

(2-27)

The right side of the equation is a definite integral (it gives a numerical result rather than a function),*v*0 is the velocity at time *t*0,and *v*1 is the velocity at later time *t*1.The def inite integral can be evaluated from an *a*(*t*) graph,such as in Fig.2-14*a*.In particular,

*t*1 *t*0

*a dt*  area between acceleration curve and time axis, from *t*0 to *t*1  .

(2-28)

If a unit of acceleration is 1 m/s2 and a unit of time is 1 s, then the correspon ding unit of area on the graph is

(1 m/s2)(1 s) 1 m/s,

which is (properly) a unit of velocity.When the acceleration curve is above the time axis, the area is positive; when the curve is below the time axis, the area is negative. ***Integrating Velocity.*** Similarly, because velocity *v* is defined in terms of the posi *a*

Area

tion *x* as *v*  *dx*/*dt*, then

(2-29)

*x*1  *x*0  *t*1

*v dt*,

This area gives the change in velocity.

*t*0

where *x*0 is the position at time *t*0 and *x*1 is the position at time *t*1. The definite integral on the right side of Eq. 2-29 can be evaluated from a *v*(*t*) graph, like that shown in Fig. 2-14*b*. In particular,

*t*0*t t*1 (*a*)

*v*

*t*1 *t*0

and time axis, from *t*0 to *t*1  .

*v dt*  area between velocity curve

(2-30)

Area

*t*0*t t*1

This area gives the change in position.

If the unit of velocity is 1 m/s and the unit of time is 1 s, then the corre sponding unit of area on the graph is

(1 m/s)(1 s) 1 m,

which is (properly) a unit of position and displacement.Whether this area is posi tive or negative is determined as described for the *a*(*t*) curve of Fig. 2-14*a*.

(*b*)

**Figure 2-14** The area between a plotted curve and the horizontal time axis, from time *t*0 to time *t*1, is indicated for (*a*) a graph of acceleration *a* versus *t* and (*b*) a graph of velocity *v* versus *t.*

30 CHAPTER 2 MOTION ALONG A STRAIGHT LINE Sample Problem 2.06 Graphical integration *a* versus *t*, whiplash injury

“Whiplash injury” commonly occurs in a rear-end collision where a front car is hit from behind by a second car. In the 1970s, researchers concluded that the injury was due to the occupant’s head being whipped back over the top of the seat

Combining Eqs. 2-27 and 2-28, we can write and time axis, from *t*0 to *t*1  .

*v*1  *v*0  area between acceleration curve

(2-31)

as the car was slammed forward. As a result of this finding, head restraints were built into cars, yet neck injuries in rear end collisions continued to occur.

In a recent test to study neck injury in rear-end collisions, a volunteer was strapped to a seat that was then moved abruptly to simulate a collision by a rear car moving at 10.5 km/h. Figure 2-15*a* gives the accelerations of the volun teer’s torso and head during the collision, which began at time *t*  0. The torso acceleration was delayed by 40 ms because during that time interval the seat back had to compress against the volunteer. The head acceleration was delayed by an additional 70 ms. What was the torso speed when the head began to accelerate? 

KEY IDEA

We can calculate the torso speed at any time by finding an area on the torso *a*(*t*) graph.

*Calculations:* We know that the initial torso speed is *v*0  0 at time *t*0  0, at the start of the “collision.” We want the torso speed *v*1 at time *t*1  110 ms, which is when the head begins to accelerate.

100

For convenience, let us separate the area into three regions (Fig. 2-15*b*). From 0 to 40 ms, region *A* has no area:

area*A*  0.

From 40 ms to 100 ms,region *B* has the shape of a triangle,with area

area*B*  12(0.060 s)(50 m/s2) 1.5 m/s.

From 100 ms to 110 ms, region *C* has the shape of a rectan gle, with area

area*C*  (0.010 s)(50 m/s2) 0.50 m/s.

Substituting these values and *v*0  0 into Eq. 2-31 gives us *v*1  0 0 1.5 m/s 0.50 m/s,

or *v*1  2.0 m/s 7.2 km/h. (Answer)

*Comments:* When the head is just starting to move forward, the torso already has a speed of 7.2 km/h. Researchers argue that it is this difference in speeds during the early stage of a rear-end collision that injures the neck. The backward whip ping of the head happens later and could, especially if there is no head restraint, increase the injury.

*a*

)

2

s

/

m

(

*a*

50

Head

Torso

50

(*b*) *A*

*B C*

*t* 40 100 110

The total area gives the change in velocity.

0 40 80 120 160 *t* (ms) (*a*)

**Figure 2-15** (*a*) The *a*(*t*) curve of the torso and head of a volunteer in a simulation of a rear-end collision. (*b*) Breaking up the region between the plotted curve and the time axis to calculate the area.

Additional examples, video, and practice available at *WileyPLUS* Review & Summary

**Position** The *position x* of a particle on an *x* axis locates the par ticle with respect to the **origin,** or zero point, of the axis.The position is either positive or negative, according to which side of the origin the particle is on, or zero if the particle is at the origin. The **positive**

**Average Velocity** When a particle has moved from position *x*1 to position *x*2 during a time interval *t*  *t*2  *t*1, its *average velocity* during that interval is

*t* *x*2  *x*1

**direction** on an axis is the direction of increasing positive numbers; the opposite direction is the **negative direction** on the axis.

*v*avg  *x*

*t*2  *t*1.

(2-2)

**Displacement** The *displacement*  *x* of a particle is the change in its position:

*x*  *x*2  *x*1. (2-1)

Displacement is a vector quantity. It is positive if the particle has moved in the positive direction of the *x* axis and negative if the particle has moved in the negative direction.

The algebraic sign of *v*avg indicates the direction of motion (*v*avg is a vector quantity). Average velocity does not depend on the actual distance a particle moves, but instead depends on its original and final positions.

On a graph of *x* versus *t*, the average velocity for a time interval *t* is the slope of the straight line connecting the points on the curve that represent the two ends of the interval.

**Average Speed** The *average speed s*avg of a particle during a time interval *t* depends on the total distance the particle moves in

QUESTIONS 31

and the second time derivative of position *x*(*t*):

*a* *dvdt* *d*2*x*

that time interval:

(2-3)

*s*avg total distance

*dt*2 .

(2-8, 2-9)

*t* .

**Instantaneous Velocity** The *instantaneous velocity* (or sim ply **velocity**) *v* of a moving particle is

*x*

On a graph of *v* versus *t*, the acceleration *a* at any time *t* is the slope of the curve at the point that represents *t*.

**Constant Acceleration** The five equations in Table 2-1 describe the motion of a particle with constant acceleration:

*v*  lim

*t* *dxdt* ,

(2-4)

*v*  *v*0  *at*, (2-11)

*t* : 0

where *x* and *t* are defined by Eq. 2-2.The instantaneous velocity (at a particular time) may be found as the slope (at that particular time) of the graph of *x* versus *t*. **Speed** is the magnitude of instanta neous velocity.

**Average Acceleration** *Average acceleration* is the ratio of a change in velocity *v* to the time interval *t* in which the change occurs:

*x*  *x*0  *v*0*t*  12*at*2,

*v*2  *v*02  2*a*(*x*  *x*0),

*x*  *x*0  12(*v*0  *v*)*t*,

*x*  *x*0  *vt*  12*at*2.

These are *not* valid when the acceleration is not constant.

(2-15) (2-16) (2-17) (2-18)

*a*avg *v**t*.

The algebraic sign indicates the direction of *a*avg.

(2-7)

**Free-Fall Acceleration** An important example of straight line motion with constant acceleration is that of an object rising or falling freely near Earth’s surface. The constant acceleration equa tions describe this motion, but we make two changes in notation:

**Instantaneous Acceleration** *Instantaneous acceleration* (or simply **acceleration**) *a* is the first time derivative of velocity *v*(*t*)

Questions

(1) we refer the motion to the vertical *y* axis with *y* vertically *up*; (2) we replace *a* with *g*, where *g* is the magnitude of the free-fall acceleration. Near Earth’s surface, *g*  9.8 m/s2 ( 32 ft/s2).

*v*

**1** Figure 2-16 gives the velocity of a

particle moving on an *x* axis. What

are (a) the initial and (b) the final di

rections of travel? (c) Does the parti

*t*

cle stop momentarily? (d) Is the ac

celeration positive or negative? (e) Is

it constant or varying?

**2** Figure 2-17 gives the accelera

is the sign of the particle’s position? Is the particle’s velocity positive, negative, or 0 at (b) *t*  1 s, (c) *t*  2 s, and (d) *t*  3 s? (e) How many times does the particle go through the point *x*  0?

**5** Figure 2-20 gives the velocity of

*x*

0 1 2 3 4

*t* (s)

tion *a*(*t*) of a Chihuahua as it chases a German shepherd along an axis. In which of the time periods indicated

**Figure 2-16** Question 1.

*v*

a particle moving along an axis. Point 1 is at the highest point on the curve; point 4 is at the lowest point;

**Figure 2-19** Question 4.

does the Chihuahua move at constant speed?

*a*

*t*

and points 2 and 6 are at the same height. What is the direction of travel at (a) time *t*  0 and (b) point 4? (c) At which of the six numbered points does the particle reverse its direction of travel? (d) Rank the six points according to the magnitude of the acceleration, greatest first.

1

2 6

*t*

3 5

4

**Figure 2-20** Question 5.

**Figure 2-17** Question 2.

*AB C D E F G H*

**6** At *t*  0, a particle moving along an

*v*

*x* axis is at position *x*0  20 m. The

*B A*

**3** Figure 2-18 shows four paths along which objects move from a starting point to a final point, all in the same time interval. The paths pass over a grid of equally spaced straight lines. Rank the paths according to (a) the av erage velocity of the objects and (b) the average speed of the objects, great

1

4

2

3

signs of the particle’s initial velocity *v*0 (at time *t*0) and constant acceleration *a* are, respectively, for four situations: (1) , ; (2) , ; (3) , ; (4) , . In which situations will the particle (a) stop momentarily, (b) pass through the origin, and (c) never pass through the origin?

**7** Hanging over the railing of a

0 *t*

*C*

*D*

est first.

**4** Figure 2-19 is a graph of a parti

**Figure 2-18** Question 3.

bridge, you drop an egg (no initial ve locity) as you throw a second egg

*G F E*

cle’s position along an *x* axis versus time. (a) At time *t*  0, what

downward. Which curves in Fig. 2-21

**Figure 2-21** Question 7.

32 CHAPTER 2 MOTION ALONG A STRAIGHT LINE

give the velocity *v*(*t*) for (a) the dropped egg and (b) the thrown egg? (Curves *A* and *B* are parallel; so are *C*, *D*, and *E*; so are *F* and *G*.)

1

**8** The following equations give the velocity *v*(*t*) of a particle in four situations: (a) *v*  3; (b) *v*  4*t* 2  2*t*  6; (c) *v*  3*t*  4; (d) *v*  5*t* 2  3. To which of these situations do the equations of Table 2-1 apply?

2

**9** In Fig. 2-22, a cream tangerine is thrown di rectly upward past three evenly spaced windows of equal heights. Rank the windows according to (a) the average speed of the cream tangerine while passing them, (b) the time the cream tan 3

gerine takes to pass them, (c) the magnitude of the acceleration of the cream tangerine while passing them, and (d) the change *v* in the

apple’s release, the balloon is accelerating upward with a magni tude of 4.0 m/s2 and has an upward velocity of magnitude 2 m/s. What are the (a) magnitude and (b) direction of the acceleration of the apple just after it is released? (c) Just then, is the apple moving upward or downward, or is it stationary? (d) What is the magni tude of its velocity just then? (e) In the next few moments, does the speed of the apple increase, decrease, or remain constant?

**11** Figure 2-23 shows that a particle moving along an *x* axis un dergoes three periods of acceleration. Without written computa tion, rank the acceleration periods according to the increases they produce in the particle’s velocity, greatest first.

(3)

*a*

n

o

i

t

a

speed of the cream tangerine during the pas sage, greatest first.

**Figure 2-22**

r

e

l

e

c

c

(1)

(2)

**10** Suppose that a passenger intent on lunch

Question 9.A

during his first ride in a hot-air balloon accidently drops an apple over the side during the balloon’s liftoff. At the moment of the

Problems

Tutoring problem available (at instructor’s discretion) in *WileyPLUS* and WebAssign

Time *t*

**Figure 2-23** Question 11.

**SSM** Worked-out solution available in Student Solutions Manual **•** – **•••** Number of dots indicates level of problem difficulty

**WWW** Worked-out solution is at

**ILW** Interactive solution is at http://www.wiley.com/college/halliday

Additional information available in *The Flying Circus of Physics* and at flyingcircusofphysics.com

**Module 2-1 Position, Displacement, and Average Velocity •1** While driving a car at 90 km/h, how far do you move while your eyes shut for 0.50 s during a hard sneeze?

**•2** Compute your average velocity in the following two cases: (a) You walk 73.2 m at a speed of 1.22 m/s and then run 73.2 m at a speed of 3.05 m/s along a straight track. (b) You walk for 1.00 min at a speed of 1.22 m/s and then run for 1.00 min at 3.05 m/s along a straight track. (c) Graph *x* versus *t* for both cases and indicate how the average velocity is found on the graph.

**•3** An automobile travels on a straight road for

**SSM WWW**

40 km at 30 km/h. It then continues in the same direction for an other 40 km at 60 km/h. (a) What is the average velocity of the car during the full 80 km trip? (Assume that it moves in the positive *x* direction.) (b) What is the average speed? (c) Graph *x* versus *t* and

“Cogito ergo zoom!” (I think, therefore I go fast!). In 2001, Sam Whittingham beat Huber’s record by 19.0 km/h. What was Whittingham’s time through the 200 m?

**••7** Two trains, each having a speed of 30 km/h, are headed at each other on the same straight track. A bird that can fly 60 km/h flies off the front of one train when they are 60 km apart and heads directly for the other train. On reaching the other train, the (crazy) bird flies directly back to the first train, and so forth.What is the to tal distance the bird travels before the trains collide?

**••8** *Panic escape*. Figure 2-24 shows a general situation in which a stream of people attempt to escape through an exit door that turns out to be locked. The people move toward the door at speed *vs*  3.50 m/s, are each *d*  0.25 m in depth, and are sepa rated by *L*  1.75 m. The 

indicate how the average velocity is found on the graph.

**•4** A car moves uphill at 40 km/h and then back downhill at 60 km/h.What is the average speed for the round trip?

**•5** The position of an object moving along an *x* axis is given

**SSM**

by *x* 3*t* 4*t*2 *t*3, where *x* is in meters and *t* in seconds. Find the

position of the object at the following values of *t*: (a) 1 s, (b) 2 s, (c) 3 s, and (d) 4 s. (e) What is the object’s displacement between *t*  0 and *t*  4 s? (f) What is its average velocity for the time interval

arrangement in Fig. 2-24 occurs at time *t*  0. (a) At what average rate does the layer of people at the door increase? (b) At what time does the layer’s depth reach 5.0 m? (The answers reveal how quickly such a situation becomes dangerous.)

*L L L*

*ddd*

Locked

door

**Figure 2-24** Problem 8.

from *t*  2 s to *t*  4 s? (g) Graph *x* versus *t* for 0 *t*  4 s and indi cate how the answer for (f) can be found on the graph.

**•6** The 1992 world speed record for a bicycle (human-powered vehicle) was set by Chris Huber. His time through the measured 200 m stretch was a sizzling 6.509 s, at which he commented,

**••9** In 1 km races, runner 1 on track 1 (with time 2 min, 27.95 s)

**ILW**

appears to be faster than runner 2 on track 2 (2 min, 28.15 s). However, length *L*2 of track 2 might be slightly greater than length *L*1 of track 1. How large can *L*2  *L*1 be for us still to conclude that runner 1 is faster?

**••10** To set a speed record in a measured (straight-line) distance *d*, a race car must be driven first in one direction (in time *t*1) and then in the opposite direction (in time *t*2). (a) To eliminate the ef fects of the wind and obtain the car’s speed *vc* in a windless situation, should we find the average of *d/t*1 and *d/t*2 (method 1) or should we di vide *d* by the average of *t*1 and *t*2? (b) What is the fractional difference in the two methods when a steady wind blows along the car’s route and the ratio of the wind speed *vw* to the car’s speed *vc* is 0.0240? 

**••11 **You are to drive 300 km to an interview. The interview is at 11 15 A.M. You plan to drive at 100 km/h, so you leave at 8 00 A.M. to allow some extra time. You drive at that speed for the first 100 km, but then construction work forces you to slow to 40 km/h for 40 km.What would be the least speed needed for the rest of the trip to arrive in time for the interview?

**•••12** *Traffic shock wave*. An abrupt slowdown in concen trated traffic can travel as a pulse, termed a *shock wave,* along the line of cars, either downstream (in the traffic direction) or up stream, or it can be stationary. Figure 2-25 shows a uniformly spaced line of cars moving at speed *v*  25.0 m/s toward a uni formly spaced line of slow cars moving at speed *vs*  5.00 m/s. Assume that each faster car adds length *L*  12.0 m (car length plus buffer zone) to the line of slow cars when it joins the line, and as sume it slows abruptly at the last instant. (a) For what separation dis tance *d* between the faster cars does the shock wave remain stationary? If the separation is twice that amount, what are the (b) speed and (c) direction (upstream or downstream) of the shock wave?

*~~L d L d L L L~~*

*v vs*

Car Buffer

**Figure 2-25** Problem 12.

**•••13** You drive on Interstate 10 from San Antonio to Houston,

**ILW**

half the *time* at 55 km/h and the other half at 90 km/h. On the way back you travel half the *distance* at 55 km/h and the other half at 90 km/h. What is your average speed (a) from San Antonio to Houston, (b) from Houston back to San Antonio, and (c) for the entire trip? (d) What is your average velocity for the entire trip? (e) Sketch *x* versus *t* for (a), assuming the motion is all in the positive *x* direc tion.Indicate how the average velocity can be found on the sketch.

**Module 2-2 Instantaneous Velocity and Speed •14** An electron moving along the *x* axis has a position given by *x* 16*te**t* m, where *t* is in seconds. How far is the electron from 

the origin when it momentarily stops?



**•15** (a) If a particle’s position is given by *x* 4 12*t* 3*t* 2 (where *t* is in seconds and *x* is in meters), what is its velocity at

PROBLEMS 33

term 20*t* or the term 20*t* in *x*(*t*)? (g) Does that inclusion increase or decrease the value of *x* at which the particle momentarily stops?

**••17** The position of a particle moving along the *x* axis is given in centimeters by *x*  9.75 1.50*t*3, where *t* is in seconds. Calculate (a) the average velocity during the time interval *t*  2.00 s to *t*  3.00 s; (b) the instantaneous velocity at *t*  2.00 s; (c) the instantaneous ve locity at *t*  3.00 s; (d) the instantaneous velocity at *t*  2.50 s; and (e) the instantaneous velocity when the particle is midway between its positions at *t*  2.00 s and *t*  3.00 s. (f) Graph *x* versus *t* and in dicate your answers graphically.

**Module 2-3 Acceleration**

**•18** The position of a particle moving along an *x* axis is given by *x*  12*t*2  2*t*3, where *x* is in meters and *t* is in seconds. Determine (a) the position, (b) the velocity, and (c) the acceleration of the particle at *t*  3.0 s. (d) What is the maximum positive coordinate reached by the particle and (e) at what time is it reached? (f) What is the maxi mum positive velocity reached by the particle and (g) at what time is it reached? (h) What is the acceleration of the particle at the instant the particle is not moving (other than at *t*  0)? (i) Determine the av erage velocity of the particle between *t*  0 and *t*  3 s.

**•19** At a certain time a particle had a speed of 18 m/s in

**SSM**

the positive *x* direction, and 2.4 s later its speed was 30 m/s in the opposite direction. What is the average acceleration of the particle during this 2.4 s interval?

**•20** (a) If the position of a particle is given by *x*  20*t*  5*t* 3, where *x* is in meters and *t* is in seconds, when, if ever, is the parti cle’s velocity zero? (b) When is its acceleration *a* zero? (c) For what time range (positive or negative) is *a* negative? (d) Positive? (e) Graph *x*(*t*), *v*(*t*), and *a*(*t*).

**••21** From *t*  0 to *t*  5.00 min, a man stands still, and from *t*  5.00 min to *t*  10.0 min, he walks briskly in a straight line at a constant speed of 2.20 m/s. What are (a) his average velocity *v*avg and (b) his average acceleration *a*avg in the time interval 2.00 min to 8.00 min? What are (c) *v*avg and (d) *a*avg in the time interval 3.00 min to 9.00 min? (e) Sketch *x* versus *t* and *v* versus *t*, and indicate how the answers to (a) through (d) can be obtained from the graphs.

**••22** The position of a particle moving along the *x* axis depends on the time according to the equation *x*  *ct*2  *bt*3, where *x* is in me ters and *t* in seconds.What are the units of (a) constant *c* and (b) con stant *b*? Let their numerical values be 3.0 and 2.0, respectively. (c) At what time does the particle reach its maximum positive *x* position? From *t*  0.0 s to *t*  4.0 s, (d) what distance does the particle move and (e) what is its displacement? Find its velocity at times (f) 1.0 s, (g) 2.0 s, (h) 3.0 s, and (i) 4.0 s. Find its acceleration at times (j) 1.0 s, (k) 2.0 s, (l) 3.0 s, and (m) 4.0 s.

*t*  1

s? (b) Is it moving in the positive or negative direction of *x*

**Module 2-4 Constant Acceleration**

just then? (c) What is its speed just then? (d) Is the speed increasing or decreasing just then? (Try answering the next two questions without further calculation.) (e) Is there ever an instant

**•23** An electron with an initial velocity *v*0 1.50 105 m/s

**SSM**

enters a region of length *L* 1.00

when the velocity is zero? If so, give the time *t*; if not, answer no. (f) Is there a time after *t*  3 s when the particle is moving in the negative direction of *x*? If so, give the time *t*; if not, answer no. **•16** The position function *x*(*t*) of a particle moving along an *x* axis is *x*  4.0 6.0*t* 2, with *x* in meters and *t* in seconds. (a) At what time and (b) where does the particle (momentarily) stop? At what (c) negative time and (d) positive time does the particle pass through the origin? (e) Graph *x* versus *t* for the range 5 s to 5 s.

cm where it is electrically acceler ated (Fig. 2-26). It emerges with *v* 5.70 106 m/s. What is its ac

celeration, assumed constant?

**•24** *Catapulting mush rooms*. Certain mushrooms launch their spores by a catapult mecha nism.As water condenses from the 

Nonaccelerating region

Path of

electron

Accelerating region

*L*

(f) To shift the curve rightward on the graph, should we include the

air onto a spore that is attached to

**Figure 2-26** Problem 23.

34 CHAPTER 2 MOTION ALONG A STRAIGHT LINE

the mushroom, a drop grows on one side of the spore and a film *xr*

grows on the other side.The spore is bent over by the drop’s weight,

Green car

*x*

but when the film reaches the drop, the drop’s water suddenly spreads into the film and the spore springs upward so rapidly that it is slung off into the air. Typically, the spore reaches a speed of 1.6 m/s in a 5.0 mm launch; its speed is then reduced to zero in 1.0 mm

Red

car *xg* **Figure 2-27** Problems 34 and 35.

by the air. Using those data and assuming constant accelerations, find the acceleration in terms of *g* during (a) the launch and (b) the speed reduction.

**•25** An electric vehicle starts from rest and accelerates at a rate of 2.0 m/s2 in a straight line until it reaches a speed of 20 m/s. The vehicle then slows at a constant rate of 1.0 m/s2 until it stops. (a) How much time elapses from start to stop? (b) How far does the

**••35** Figure 2-27 shows a red car and a green car that move toward each other. Figure 2-28 is a graph of )

their motion, showing the positions

m

(

*xg*0  270 m and *xr*0  35.0 m at *x*

time *t*  0. The green car has a con stant speed of 20.0 m/s and the red car begins from rest. What is the ac

*xg* 0 *xr* 00

0 12 *t* (s)

vehicle travel from start to stop?

**•26** A muon (an elementary particle) enters a region with a speed

**Figure 2-28** Problem 35.

celeration magnitude of the red car?

of 5.00 106 m/s and then is slowed at the rate of 1.25 1014 m/s2. (a) How far does the muon take to stop? (b) Graph *x* versus *t* and *v* versus*t* for the muon.

**•27** An electron has a constant acceleration of 3.2 m/s2. At a certain instant its velocity is 9.6 m/s. What is its velocity (a) 2.5 s earlier and (b) 2.5 s later?

**••36** A car moves along an *x* axis through a distance of 900 m, starting at rest (at *x*  0) and ending at rest (at *x*  900 m). 1

Through the first of that distance, its acceleration is 2.25 m/s2.

4

Through the rest of that distance, its acceleration is 0.750 m/s2. What are (a) its travel time through the 900 m and (b) its maxi mum speed? (c) Graph position *x*, velocity *v*, and acceleration *a* versus time *t* for the trip.

**•28** On a dry road, a car with good tires may be able to brake with a constant deceleration of 4.92 m/s2. (a) How long does such a car, initially traveling at 24.6 m/s, take to stop? (b) How far does it travel in this time? (c) Graph *x* versus *t* and *v* versus *t* for the deceleration.

**•29** A certain elevator cab has a total run of 190 m and a max

**ILW**

imum speed of 305 m/min, and it accelerates from rest and then back to rest at 1.22 m/s2. (a) How far does the cab move while ac celerating to full speed from rest? (b) How long does it take to

**••37** Figure 2-29 depicts the motion of a particle moving along an *x* axis with a constant acceleration. The fig ure’s vertical scaling is set by *xs*  6.0 m. What are the (a) magnitude and (b) di rection of the particle’s acceleration?

**••38** (a) If the maximum acceleration that is tolerable for passengers in a subway train is 1.34 m/s2 and subway

*x* (m)

*xs*

1 2 0

*t* (s)

make the nonstop 190 m run, starting and ending at rest?

**•30** The brakes on your car can slow you at a rate of 5.2 m/s2. (a) If you are going 137 km/h and suddenly see a state trooper, what is

stations are located 806 m apart, what is the maximum speed a subway train can attain between stations? (b) What

**Figure 2-29** Problem 37.

the minimum time in which you can get your car under the 90 km/h speed limit? (The answer reveals the futility of braking to keep your high speed from being detected with a radar or laser gun.) (b) Graph *x* versus *t* and *v* versus *t* for such a slowing.

**•31** Suppose a rocket ship in deep space moves with con

is the travel time between stations? (c) If a subway train stops for 20 s at each station, what is the maximum average speed of the train, from one start-up to the next? (d) Graph *x*, *v*, and *a* versus*t* for the interval from one start-up to the next.

**••39** Cars *A* and *B* move in

**SSM**

stant acceleration equal to 9.8 m/s2, which gives the illusion of nor mal gravity during the flight. (a) If it starts from rest, how long will it take to acquire a speed one-tenth that of light, which travels at 3.0 108 m/s? (b) How far will it travel in so doing?

**•32 **A world’s land speed record was set by Colonel John P. Stapp when in March 1954 he rode a rocket-propelled sled that moved along a track at 1020 km/h. He and the sled were brought to

the same direction in adjacent lanes.The position *x* of car *A* is given in Fig. 2-30, from time *t*  0 to *t*  7.0 s. The figure’s vertical scaling is set by *xs*  32.0 m.At *t*  0, car *B* is at *x*  0, with a velocity of 12 m/s and

)

m

(*x*

*xs*

0 123 *t* (s)

4567

a stop in 1.4 s. (See Fig. 2-7.) In terms of *g*, what acceleration did he experience while stopping?

a negative constant accelera tion *aB*. (a) What must *aB* be such that the cars are (momen

**Figure 2-30** Problem 39.

**•33** A car traveling 56.0 km/h is 24.0 m from a barrier

**SSM ILW**

when the driver slams on the brakes. The car hits the barrier 2.00 s later. (a) What is the magnitude of the car’s constant acceleration before impact? (b) How fast is the car traveling at impact?

**••34** In Fig. 2-27, a red car and a green car, identical except for the color, move toward each other in adjacent lanes and parallel to an *x* axis. At time *t*  0, the red car is at *xr*  0 and the green car is at *xg*  220 m. If the red car has a constant velocity of 20 km/h, the cars pass each other at *x*  44.5 m, and if it has a constant velocity of 40 km/h, they pass each other at *x*  76.6 m. What are (a) the initial velocity and (b) the constant acceleration of the green car? 

tarily) side by side (momentarily at the same value of *x*) at *t*  4.0 s? (b) For that value of *aB*, how many times are the cars side by side? (c) Sketch the position *x* of car *B* versus time *t* on Fig. 2-30. How many times will the cars be side by side if the magnitude of accelera tion *aB* is (d) more than and (e) less than the answer to part (a)?

**••40** You are driving toward a traffic signal when it turns yel 

low. Your speed is the legal speed limit of *v*0 55 km/h; your best deceleration rate has the magnitude *a*  5.18 m/s2.Your best reaction time to begin braking is *T*  0.75 s.To avoid having the front of your car enter the intersection after the light turns red, should you brake to a stop or continue to move at 55 km/h if the distance to

the intersection and the duration of the yellow light are (a) 40 m and 2.8 s, and (b) 32 m and 1.8 s? Give an answer of brake, continue, either (if either strategy works), or neither (if neither strategy works and the yellow duration is inappropriate).

PROBLEMS 35

**•46** Raindrops fall 1700 m from a cloud to the ground. (a) If they were not slowed by air resistance, how fast would the drops be moving when they struck the ground? (b) Would it be safe to walk outside during a rainstorm?

**••41** As two trains move along a track, their conductors suddenly notice that they are headed toward each other. Figure 2-31 gives their velocities *v* as functions of time *t* as the conductors slow the trains. The figure’s vertical scaling is set by *vs*  40.0 m/s. The slowing 

) s

/

m

(

*v*

*vs* 0

*t* (s) 2 4 6

**Figure 2-31** Problem 41.

**•47** At a construction site a pipe wrench struck the ground

**SSM**

with a speed of 24 m/s. (a) From what height was it inadvertently dropped? (b) How long was it falling? (c) Sketch graphs of *y*, *v*, and *a* versus *t* for the wrench.

**•48** A hoodlum throws a stone vertically downward with an ini tial speed of 12.0 m/s from the roof of a building, 30.0 m above the ground. (a) How long does it take the stone to reach the ground? (b) What is the speed of the stone at impact?

**•49** A hot-air balloon is ascending at the rate of 12 m/s and

processes begin when the trains are 200 m apart.What is their separa tion when both trains have stopped?

**•••42** You are arguing over a cell phone while trailing an unmarked police car by 25 m; both your car and the police car are traveling at 110 km/h. Your argument diverts your attention from the police car for 2.0 s (long enough for you to look at the phone and yell, “I won’t do that!”). At the beginning of that 2.0 s, the po lice officer begins braking suddenly at 5.0 m/s2. (a) What is the sep aration between the two cars when your attention finally returns? Suppose that you take another 0.40 s to realize your danger and begin braking. (b) If you too brake at 5.0 m/s2, what is your speed when you hit the police car? 

**•••43** When a high-speed passenger train traveling at 161 km/h rounds a bend, the engineer is shocked to see that a locomotive has improperly entered onto the track from a siding and is a distance *D*  676 m ahead (Fig. 2-32). The locomotive is moving at 29.0 km/h. The engineer of the high-speed train imme diately applies the brakes. (a) What must be the magnitude of the resulting constant deceleration if a collision is to be just avoided? (b) Assume that the engineer is at *x*  0 when, at *t*  0, he first 

**SSM**

is 80 m above the ground when a package is dropped over the side. (a) How long does the package take to reach the ground? (b) With what speed does it hit the ground?

**••50** At time *t*  0, apple 1 is dropped from a bridge onto a road way beneath the bridge; somewhat later, apple 2 is thrown down from the same height. Figure 2-33 gives the vertical positions *y* of the apples versus *t* during the falling, until both apples have hit the roadway. The scaling is set by *ts*  2.0 s. With approximately what speed is apple 2 thrown down?

*y*

0 *ts*

**Figure 2-33** Problem 50.

spots the locomotive. Sketch *x*(*t*) curves for the locomotive and high-speed train for the cases in which a collision is just avoided and is not quite avoided.

*~~D~~*

**••51** As a runaway scientific bal loon ascends at 19.6 m/s, one of its instrument packages breaks free of a harness and free-falls. Figure 2-34 gives the vertical velocity of the package versus time, from before it breaks free to when it reaches the ground. (a) What maximum height

*v*

0468 2

*t* (s)

High-speed

above the break-free point does it rise? (b) How high is the break-free point above the ground?

**Figure 2-34** Problem 51.

train Locomotive

**Figure 2-32** Problem 43.

**Module 2-5 Free-Fall Acceleration**

**•44** When startled, an armadillo will leap upward. Suppose it rises 0.544 m in the first 0.200 s. (a) What is its initial speed as it leaves the ground? (b) What is its speed at the height of 0.544 m? (c) How much higher does it go?

**•45** (a) With what speed must a ball be thrown verti

**SSM WWW**

cally from ground level to rise to a maximum height of 50 m? (b) How long will it be in the air? (c) Sketch graphs of *y*, *v*, and *a* versus *t* for the ball. On the first two graphs, indicate the time at which 50 m is reached.

**••52** A bolt is dropped from a bridge under construction, falling 90 m to the valley below the bridge. (a) In how much time does it pass through the last 20% of its fall? What is its speed (b) when it begins that last 20% of its fall and (c) when it reaches the valley beneath the bridge? 

**••53** A key falls from a bridge that is 45 m above the

**SSM ILW**

water. It falls directly into a model boat, moving with constant velocity, that is 12 m from the point of impact when the key is re leased.What is the speed of the boat?

**••54** A stone is dropped into a river from a bridge 43.9 m above the water. Another stone is thrown vertically down 1.00 s after the first is dropped. The stones strike the water at the same time. (a) What is the initial speed of the second stone? (b) Plot velocity versus time on a graph for each stone, taking zero time as the instant the first stone is released. 

36 CHAPTER 2 MOTION ALONG A STRAIGHT LINE

**SSM Module 2-6 Graphical Integration in Motion Analysis ••55** A ball of moist clay falls 15.0 m to the ground. It is

in contact with the ground for 20.0 ms before stopping. (a) What is the magnitude of the average acceleration of the ball during the time it is in contact with the ground? (Treat the ball as a particle.) (b) Is the average acceleration up or down?

**•65** Figure 2-15*a* gives the acceleration of a volunteer’s head and torso during a rear-end collision. At maximum head ac celeration, what is the speed of (a) the head and (b) the torso? 

**••66 **In a forward punch in karate, the fist begins at rest at

**••56** Figure 2-35 shows the speed *v* versus height *y* of a ball tossed directly upward, along a *y* axis. Distance *d* is 0.40 m. The speed at height *yA* is *vA*.The speed at height *yB* 1 

is *vA*. What is speed *vA*?

*v*

\_1\_3

*vA*

*vA*

*y*

the waist and is brought rapidly forward until the arm is fully ex tended. The speed *v*(*t*) of the fist is given in Fig. 2-37 for someone skilled in karate. The vertical scaling is set by *vs*  8.0 m/s. How far has the fist moved at (a) time *t*  50 ms and (b) when the speed of the fist is maximum?

*vs*

3

**••57** To test the quality of a tennis ball, you drop it onto the floor from a height of 4.00 m. It re

*d* 0

*yA yB*

**Figure 2-35** Problem 56.

) s

/

m

(

*v*

bounds to a height of 2.00 m. If the ball is in contact with the floor for 12.0 ms, (a) what is the magnitude of its average acceleration during that contact and (b) is the average acceleration up or down?

**••58** An object falls a distance *h* from rest. If it travels 0.50*h* in the last 1.00 s, find (a) the time and (b) the height of its fall. (c) Explain the physically unacceptable solution of the quadratic

0 50 100 140 *t* (ms)

**Figure 2-37** Problem 66.

**••67** When a soccer

equation in *t* that you obtain.

**••59** Water drips from the nozzle of a shower onto the floor 200 cm below. The drops fall at regular (equal) intervals of time, the first drop striking the floor at the instant the fourth drop begins to fall. When the first drop strikes the floor, how far below the nozzle are the (a) second and (b) third drops?

**••60 **A rock is thrown vertically upward from ground level at time *t*  0.At *t*  1.5 s it passes the top of a tall tower, and 1.0 s later it reaches its maximum height.What is the height of the tower?

**•••61 **A steel ball is dropped from a building’s roof and passes

ball is kicked to ward a player and the player deflects the ball by “head ing” it, the accelera tion of the head dur ing the collision can be significant. Figure 2-38 gives the meas ured acceleration

)

2

s

/

m

(

*a*

*as*

Bare

Helmet

246

0

*t* (ms)

**Figure 2-38** Problem 67.

a window, taking 0.125 s to fall from the top to the bottom of the window, a distance of 1.20 m. It then falls to a sidewalk and bounces back past the window, moving from bottom to top in 0.125 s. Assume that the upward flight is an exact reverse of the fall. The time the ball spends below the bottom of the window is 2.00 s. How tall is the building?

*a*(*t*) of a soccer player’s head for a bare head and a helmeted head, starting from rest. The scaling on the vertical axis is set by *as*  200 m/s2. At time *t*  7.0 ms, what is the difference in the speed acquired by the bare head and the speed acquired by the helmeted head?

**••68** A salamander of the genus *Hydromantes* captures prey by launching its tongue 

**•••62** A basketball player grabbing a rebound jumps 76.0 cm vertically. How much total time (ascent and descent) does the player spend (a) in the top 15.0 cm of this jump and (b) in the bottom 15.0 cm? (The player seems to hang in the air at the top.) 

**•••63** A drowsy cat spots a flowerpot that sails first up and then down past an open window.The pot is in view for a total of 0.50 s, and the top-to-bottom height of the window is 2.00 m. How high above the 

as a projectile: The skeletal part of the tongue is shot for ward, unfolding the rest of the tongue, until the outer portion lands on the prey, sticking to it. Figure 2-39 shows the acceleration mag nitude *a* versus time *t* for the

)

2

s

/

m

(*a*

*a*2

*a*1 0

10 20 30 40 *t* (ms)

window top does the flowerpot go?

**•••64** A ball is shot vertically up ward from the surface of another planet. A plot of *y* versus *t* for the ball is shown in Fig. 2-36, where *y* is the height of the ball above its start ing point and *t*  0 at the instant the ball is shot. The figure’s vertical scal ing is set by *ys*  30.0 m.What are the magnitudes of (a) the free-fall accel eration on the planet and (b) the ini tial velocity of the ball?

)

m

(*y*

*ys*

0012345 *t* (s)

**Figure 2-36** Problem 64.

acceleration phase of the launch in a typical situation. The indicated accelerations are *a*2  400 m/s2 and *a*1  100 m/s2. What is the outward speed of the tongue at the end of the acceleration phase?

**••69** How far does the run

**ILW**

ner whose velocity–time graph is shown in Fig. 2-40 travel in 16 s? The figure’s vertical scaling is set by *vs*  8.0 m/s.

) s

/

m

(*v*

**Figure 2-39** Problem 68. *vs*

0 4 8 12 16 *t* (s)

**Figure 2-40** Problem 69.

**•••70** Two particles move along an *x* axis. The position of particle 1 is given by *x*  6.00*t*2  3.00*t*  2.00 (in meters and seconds); the ac celeration of particle 2 is given by *a*  8.00*t* (in meters per second squared and seconds) and, at *t*  0, its velocity is 20 m/s. When the velocities of the particles match, what is their velocity?

**Additional Problems**

**71** In an arcade video game, a spot is programmed to move across the screen according to *x*  9.00*t*  0.750*t*3, where *x* is dis tance in centimeters measured from the left edge of the screen and *t* is time in seconds. When the spot reaches a screen edge, at either

*x*  0 or *x*  15.0 cm, *t* is reset to 0 and the spot starts moving again according to *x*(*t*). (a) At what time after starting is the spot instan taneously at rest? (b) At what value of *x* does this occur? (c) What is the spot’s acceleration (including sign) when this occurs? (d) Is it moving right or left just prior to coming to rest? (e) Just after? (f) At what time *t*  0 does it first reach an edge of the screen?

**72** A rock is shot vertically upward from the edge of the top of a tall building. The rock reaches its maximum height above the top of the building 1.60 s after being shot. Then, after barely missing the edge of the building as it falls downward, the rock strikes the ground 6.00 s after it is launched. In SI units: (a) with what upward velocity is the rock shot, (b) what maximum height above the top of the building is reached by the rock, and (c) how tall is the building?

**73** At the instant the traffic light turns green, an automobile starts with a constant acceleration *a* of 2.2 m/s2.At the same instant a truck, traveling with a constant speed of 9.5 m/s, overtakes and passes the automobile. (a) How far beyond the traffic signal will the automobile overtake the truck? (b) How fast will the automo bile be traveling at that instant? 

**74** A pilot flies horizontally at 1300 km/h, at height *h*  35 m

PROBLEMS 37

reached intersection 2, where the green appeared when they were distance *d* from the intersection. They continue to travel at a cer tain speed *vp* (the speed limit) to reach intersection 3, where the green appears when they are distance *d* from it. The intersections are separated by distances *D*23 and *D*12. (a) What should be the time delay of the onset of green at intersection 3 relative to that at intersection 2 to keep the platoon moving smoothly?

Suppose, instead, that the platoon had been stopped by a red light at intersection 1. When the green comes on there, the leaders require a certain time *tr* to respond to the change and an additional time to accelerate at some rate *a* to the cruising speed *vp*. (b) If the green at intersection 2 is to appear when the leaders are distance *d* from that intersection, how long after the light at intersection 1 turns green should the light at intersection 2 turn green?

**77** A hot rod can accelerate from 0 to 60 km/h in 5.4 s.

**SSM**

(a) What is its average acceleration, in m/s2, during this time? (b) How far will it travel during the 5.4 s, assuming its acceleration is con stant? (c) From rest, how much time would it require to go a distance of 0.25 km if its acceleration could be maintained at the value in (a)?

**78** A red train traveling at 72 km/h and a green train traveling at 144 km/h are headed toward each other along a straight, level track. When they are 950 m apart, each engineer sees the other’s train and applies the brakes. The brakes slow each train at the rate of 1.0 m/s2. Is there a collision? If so, answer yes and give the speed of the red train and the speed of the green train at impact, respec tively. If not, answer no and give the separation between the trains when they stop. 

**79** At time *t*  0, a rock 

climber accidentally allows a

piton to fall freely from a high

above initially level ground. However, at time *t*  0, the pilot be gins to fly over ground sloping upward at angle u 4.3° (Fig. 2-41). If the pilot does not change the airplane’s heading, at what time *t* does the plane strike the ground?

θ

*h*

point on the rock wall to the *y*

valley below him.Then, after a short delay, his climbing part ner, who is 10 m higher on the wall, throws a piton down ward. The positions *y* of the pitons versus *t* during the falling are given in Fig. 2-43.

0123 *t* (s)

**Figure 2-43** Problem 79.

**Figure 2-41** Problem 74.

**75** To stop a car, first you require a certain reaction time to be gin braking; then the car slows at a constant rate. Suppose that the total distance moved by your car during these two phases is 56.7 m when its initial speed is 80.5 km/h, and 24.4 m when its initial speed is 48.3 km/h. What are (a) your reaction time and (b) the magni tude of the acceleration? 

**76 **Figure 2-42 shows part of a street where traffic flow

With what speed is the second piton thrown?

**80** A train started from rest and moved with constant accelera tion. At one time it was traveling 30 m/s, and 160 m farther on it was traveling 50 m/s. Calculate (a) the acceleration, (b) the time re quired to travel the 160 m mentioned, (c) the time required to at tain the speed of 30 m/s, and (d) the distance moved from rest to the time the train had a speed of 30 m/s. (e) Graph *x* versus *t* and *v* versus *t* for the train, from rest.

**81** A particle’s acceleration along an *x* axis is *a*  5.0*t*, with *t*

**SSM**

in seconds and *a* in meters per

second squared. At *t* 2.0 s,

is to be controlled to allow a *platoon* of cars to move smoothly along the street. Suppose that the platoon leaders have just

ONE WAY

1 2 3

*D*~~12~~ *D*23

**Figure 2-42** Problem 76.

its velocity is 17 m/s. What is its velocity at *t*  4.0 s?

**82** Figure 2-44 gives the ac celeration *a* versus time *t* for a particle moving along an *x* axis. The *a*-axis scale is set by *as*  12.0 m/s2. At *t*  2.0 s, the particle’s velocity is 7.0 m/s. What is its velocity at *t*  6.0 s?

*a* (m/s2)

*as*

*t* (s) –2 0 246 **Figure 2-44** Problem 82.

38 CHAPTER 2 MOTION ALONG A STRAIGHT LINE

**83** Figure 2-45 shows a simple device for measuring your reaction time. It consists of a cardboard strip marked with a scale and two large dots. A friend holds the strip *vertically,* with thumb and forefinger at the dot on the right in Fig. 2-45. You then posi tion your thumb and forefinger at the other dot (on the left in Fig. 2-45), being careful not to touch the strip. Your friend re leases the strip, and you try to pinch it as soon as possible after you see it begin to fall. The mark at the place where you pinch the strip gives your reaction time. (a) How far from the lower dot should you place the 50.0 ms mark? How much higher should you place the marks for (b) 100, (c) 150, (d) 200, and (e) 250 ms? (For example, should the 100 ms marker be 2 times as far from the dot as the 50 ms marker? If so, give an answer of 2 times. Can

the acceleration of the particle at *t* 5.0 s? (d) What is the average ve

locity of the particle between *t* 1.0 s and *t* 5.0 s? (e) What is the

average acceleration of the particle between *t* 1.0 s and *t* 5.0 s?

**91** A rock is dropped from a 100-m-high cliff. How long does it take to fall (a) the first 50 m and (b) the second 50 m?

**92** Two subway stops are separated by 1100 m. If a subway train accelerates at 1.2 m/s2 from rest through the first half of the dis tance and decelerates at 1.2 m/s2 through the second half, what are (a) its travel time and (b) its maximum speed? (c) Graph *x*, *v*, and *a* versus *t* for the trip.

**93** A stone is thrown vertically upward. On its way up it passes point *A* with speed *v*, and point *B*, 3.00 m higher than *A*, with speed

you find any pattern in the answers?)

1

Calculate (a) the speed *v* and (b) the maximum height reached 2 *v*.

Reaction time (ms)

by the stone above point *B*.

**94** A rock is dropped (from rest) from the top of a 60-m-tall building. How far above the ground is the rock 1.2 s before it reaches the ground?

050

1

00

1

50

2

00

**95** An iceboat has a constant velocity toward the east when

2

**SSM**

5

0

**Figure 2-45** Problem 83.

**84** A rocket-driven sled running on a straight, level track is used to investigate the effects of large accelerations on humans. One such sled can attain a speed of 1600 km/h in 1.8 s, starting from rest. Find (a) the acceleration (assumed constant) in terms of *g* and (b) the distance traveled. 

**85** A mining cart is pulled up a hill at 20 km/h and then pulled back down the hill at 35 km/h through its original level. (The time required for the cart’s reversal at the top of its climb is negligible.) What is the average speed of the cart for its round trip, from its original level back to its original level?

a sudden gust of wind causes the iceboat to have a constant accel eration toward the east for a period of 3.0 s. A plot of *x* versus *t* is

shown in Fig. 2-47, where *t* 0 is taken to be the instant the wind starts to blow and the positive *x* axis is toward the east. (a) What is the acceleration of the iceboat during the 3.0 s interval? (b) What is the velocity of the iceboat at the end of the 3.0 s interval? (c) If the acceleration remains constant for an additional 3.0 s, how far does the iceboat travel during this second 3.0 s interval?

30

25

20

)

m

**86** A motorcyclist who is moving along an *x* axis directed to

(

*x*

ward the east has an acceleration given by *a*  (6.1 1.2*t*) m/s2 for 0 *t* 6.0 s. At *t* 0, the velocity and position of the cyclist

are 2.7 m/s and 7.3 m. (a) What is the maximum speed achieved by the cyclist? (b) What total distance does the cyclist travel be tween *t*  0 and 6.0 s?

**87** When the legal speed limit for the New York Thruway

15

10

5

00 0.5 1 1.5 2 2.5 3 *t* (s)

**Figure 2-47** Problem 95.

**SSM**

was increased from 55 mi/h to 65 mi/h, how much time was saved by a motorist who drove the 700 km between the Buffalo entrance and the New York City exit at the legal speed limit? **88** A car moving with constant acceleration covered the distance between two points 60.0 m apart in 6.00 s. Its speed as it passed the second point was 15.0 m/s. (a) What was the speed at the first point? (b) What was the magnitude of the acceleration? (c) At what prior distance from the first point was the car at rest? (d) Graph *x* versus *t* and *v* versus *t* for the car, from rest (*t*  0).

**89** A certain juggler usually tosses balls vertically to 

**SSM**

a height *H*. To what height must they be tossed if they are to spend twice as much time in the air?

**96** A lead ball is dropped in a lake from a diving board 5.20 m above the water. It hits the water with a certain velocity and then sinks to the bottom with this same constant velocity. It reaches the bottom 4.80 s after it is dropped. (a) How deep is the lake? What are the (b) magnitude and (c) direction (up or down) of the aver age velocity of the ball for the entire fall? Suppose that all the wa ter is drained from the lake.The ball is now thrown from the diving board so that it again reaches the bottom in 4.80 s. What are the (d) magnitude and (e) direction of the initial velocity of the ball?

**97** The single cable supporting an unoccupied construction ele vator breaks when the elevator is at rest at the top of a 120-m-high building. (a) With what speed does the elevator strike the ground? (b) How long is it falling? (c) What is its speed when it passes the

**90** A particle starts from the ori gin at *t* 0 and moves along the

positive *x* axis. A graph of the veloc

)

s

/

ity of the particle as a function of the m

(

time is shown in Fig. 2-46; the *v*-axis *v*

scale is set by *vs* 4.0 m/s. (a) What

is the coordinate of the particle at *t* 5.0 s? (b) What is the velocity of

*vs*

0 1 2

3456 *t* (s)

halfway point on the way down? (d) How long has it been falling when it passes the halfway point?

**98** Two diamonds begin a free fall from rest from the same height, 1.0 s apart. How long after the first diamond begins to fall will the two diamonds be 10 m apart?

**99** A ball is thrown vertically downward from the top of a 36.6- m-tall building. The ball passes the top of a window that is 12.2 m above the ground 2.00 s after being thrown. What is the speed of

the particle at *t*  5.0 s? (c) What is

**Figure 2-46** Problem 90.

the ball as it passes the top of the window?

PROBLEMS

39

**100** A parachutist bails out and freely falls 50 m. Then the para chute opens, and thereafter she decelerates at 2.0 m/s2. She reaches the ground with a speed of 3.0 m/s. (a) How long is the parachutist in the air? (b) At what height does the fall begin?

**101** A ball is thrown *down* vertically with an initial *speed* of *v*0 from a height of *h*. (a) What is its speed just before it strikes the ground? (b) How long does the ball take to reach the ground? What would be the answers to (c) part a and (d) part b if the ball were thrown *upward* from the same height and with the same ini tial speed? Before solving any equations, decide whether the an swers to (c) and (d) should be greater than, less than, or the same as in (a) and (b).

**102** The sport with the fastest moving ball is jai alai, where measured speeds have reached 303 km/h. If a professional jai alai player faces a ball at that speed and involuntarily blinks, he blacks out the scene for 100 ms. How far does the ball move dur ing the blackout?

**103** If a baseball pitcher throws a fastball at a horizontal speed of 160 km/h, how long does the ball take to reach home plate 18.4 m away?

**104** A proton moves along the *x* axis according to the equation

top speed. What must this distance be if he is to achieve a time of 10.0 s for the race?

**112** The speed of a bullet is measured to be 640 m/s as the bullet emerges from a barrel of length 1.20 m.Assuming constant accelera tion, find the time that the bullet spends in the barrel after it is fired.

**113** The Zero Gravity Research Facility at the NASA Glenn Research Center includes a 145 m drop tower.This is an evacuated ver tical tower through which, among other possibilities, a 1-m-diameter sphere containing an experimental package can be dropped. (a) How long is the sphere in free fall? (b) What is its speed just as it reaches a catching device at the bottom of the tower? (c) When caught, the sphere experiences an average deceleration of 25*g* as its speed is reduced to zero.Through what distance does it travel during the deceleration?

**114** A car can be braked to a stop from the autobahn-like speed of 200 km/h in 170 m. Assuming the acceleration is constant, find its magnitude in (a) SI units and (b) in terms of *g*. (c) How much time *Tb* is required for the braking? Your *reaction time Tr* is the time you require to perceive an emergency, move your foot to the brake, and begin the braking. If *Tr*  400 ms, then (d) what is *Tb* in terms of *Tr*, and (e) is most of the full time required to stop spent in reacting 

*x*  50*t*  10*t*2

, where *x* is in meters and *t* is in seconds. Calculate (a)

or braking? Dark sunglasses delay the visual signals sent from the

the average velocity of the proton during the first 3.0 s of its motion, (b) the instantaneous velocity of the proton at *t*  3.0 s, and (c) the instantaneous acceleration of the proton at *t*  3.0 s. (d) Graph *x* versus *t* and indicate how the answer to (a) can be obtained from the plot. (e) Indicate the answer to (b) on the graph. (f) Plot *v* versus *t* and indicate on it the answer to (c).

**105** A motorcycle is moving at 30 m/s when the rider applies the brakes, giving the motorcycle a constant deceleration. During the 3.0 s interval immediately after braking begins, the speed decreases to 15 m/s. What distance does the motorcycle travel from the instant braking begins until the motorcycle stops?

**106** A shuffleboard disk is accelerated at a constant rate from rest to a speed of 6.0 m/s over a 1.8 m distance by a player using a cue.At this point the disk loses contact with the cue and slows at a constant rate of 2.5 m/s2 until it stops. (a) How much time elapses from when the disk begins to accelerate until it stops? (b) What total distance does the disk travel?

**107** The head of a rattlesnake can accelerate at 50 m/s2 in striking a victim. If a car could do as well, how long would it take to reach a speed of 100 km/h from rest?

**108** A jumbo jet must reach a speed of 360 km/h on the runway for takeoff. What is the lowest constant acceleration needed for takeoff from a 1.80 km runway?

**109** An automobile driver increases the speed at a constant rate from 25 km/h to 55 km/h in 0.50 min. A bicycle rider speeds up at a constant rate from rest to 30 km/h in 0.50 min. What are the magni tudes of (a) the driver’s acceleration and (b) the rider’s acceleration?

**110** On average, an eye blink lasts about 100 ms. How far does a MiG-25 “Foxbat” fighter travel during a pilot’s blink if the plane’s average velocity is 3400 km/h?

**111** A certain sprinter has a top speed of 11.0 m/s. If the sprinter starts from rest and accelerates at a constant rate, he is able to reach his top speed in a distance of 12.0 m. He is then able to main tain this top speed for the remainder of a 100 m race. (a) What is his time for the 100 m race? (b) In order to improve his time, the sprinter tries to decrease the distance required for him to reach his

eyes to the visual cortex in the brain, increasing *Tr*. (f) In the extreme case in which *Tr* is increased by 100 ms, how much farther does the car travel during your reaction time?

**115** In 1889, at Jubbulpore, India, a tug-of-war was finally won af ter 2 h 41 min, with the winning team displacing the center of the rope 3.7 m. In centimeters per minute, what was the magnitude of the average velocity of that center point during the contest?

**116** Most important in an investigation of an airplane crash by the U.S. National Transportation Safety Board is the data stored on the airplane’s flight-data recorder, commonly called the “black box” in spite of its orange coloring and reflective tape. The recorder is engi neered to withstand a crash with an average deceleration of magni tude 3400*g* during a time interval of 6.50 ms. In such a crash, if the recorder and airplane have zero speed at the end of that time inter val, what is their speed at the beginning of the interval?

**117** From January 26, 1977, to September 18, 1983, George Meegan of Great Britain walked from Ushuaia, at the southern tip of South America, to Prudhoe Bay in Alaska, covering 30 600 km. In meters per second, what was the magnitude of his average velocity during that time period?

**118** The wings on a stonefly do not flap, and thus the insect cannot fly. However, when the insect is on a water surface, it can sail across the surface by lifting its wings into a breeze. Suppose that you time stoneflies as they move at constant speed along a straight path of a certain length. On average, the trips each take 7.1 s with the wings set as sails and 25.0 s with the wings tucked in. (a) What is the ratio of the sailing speed *vs* to the nonsailing speed *vns*? (b) In terms of *vs*, what is the difference in the times the insects take to travel the first 2.0 m along the path with and without sailing?

**119** The position of a particle as it moves along a *y* axis is given by *y*  (2.0 cm) sin (p*t*/4),

with *t* in seconds and *y* in centimeters. (a) What is the average veloc ity of the particle between *t*  0 and *t*  2.0 s? (b) What is the instan taneous velocity of the particle at *t*  0, 1.0, and 2.0 s? (c) What is the average acceleration of the particle between *t*  0 and *t*  2.0 s? (d) What is the instantaneous acceleration of the particle at *t*  0, 1.0, and 2.0 s?

**CHAPTER 3** Vectors

**3-1 VECTORS AND THEIR COMPONENTS** Learning Objectives

*After reading this module, you should be able to . . .*

**3.01** Add vectors by drawing them in head-to-tail arrange ments, applying the commutative and associative laws. **3.02** Subtract a vector from a second one.

**3.03** Calculate the components of a vector on a given coordi nate system, showing them in a drawing.

Key Ideas

● Scalars, such as temperature, have magnitude only. They

**3.04** Given the components of a vector, draw the vector and determine its magnitude and orientation.

**3.05** Convert angle measures between degrees and radians. ● The (scalar) components and of any two-dimensional

*a*:

are specified by a number with a unit (10°C) and obey the

*ax ay*

rules of arithmetic and ordinary algebra. Vectors, such as dis placement, have both magnitude and direction (5 m, north) and obey the rules of vector algebra.

vector along the coordinate axes are found by dropping *a*:

perpendicular lines from the ends of onto the coordinate axes. The components are given by

*ax*  *a* cos u and *ay*  *a* sin u,

*a*:

*b*:

● Two vectors and may be added geometrically by draw ing them to a common scale and placing them head to tail. The vector connecting the tail of the first to the head of the *a*: *b*: *b*: *b*: *a*: *b*:

*s*:

second is the vector sum . To subtract from , reverse the direction of to get ; then add to . Vector addition is commutative and obeys the associative law.

where u is the angle between the positive direction of the *x a*:

axis and the direction of . The algebraic sign of a component indicates its direction along the associated axis. Given its components, we can find the magnitude and orientation of *a*:

the vector with

**What Is Physics?**

*a*  2*a*2*x*  *a*2*y*

and tan ~~.~~ *ay ax*

Physics deals with a great many quantities that have both size and direction, and it needs a special mathematical language—the language of vectors—to describe those quantities. This language is also used in engineering, the other sciences, and even in common speech. If you have ever given directions such as “Go five blocks down this street and then hang a left,” you have used the language of vectors. In fact, navigation of any sort is based on vectors, but physics and engineering also need vectors in special ways to explain phenomena involving rotation and mag netic forces, which we get to in later chapters. In this chapter, we focus on the basic language of vectors.

**Vectors and Scalars**

A particle moving along a straight line can move in only two directions. We can take its motion to be positive in one of these directions and negative in the other. For a particle moving in three dimensions, however, a plus sign or minus sign is no longer enough to indicate a direction. Instead, we must use a *vector.*

40

3-1 VECTORS AND THEIR COMPONENTS 41

A **vector** has magnitude as well as direction, and vectors follow certain (vector) rules of combination, which we examine in this chapter. A **vector quantity** is a quantity that has both a magnitude and a direction and thus can be represented with a vector. Some physical quantities that are vector quantities are displacement, velocity, and acceleration. You will see many more throughout this book, so learning the rules of vector combination now will help you greatly in later chapters.

Not all physical quantities involve a direction.Temperature, pressure, energy, mass, and time, for example, do not “point” in the spatial sense. We call such

*B'*

*B"*

*A*

*B*

*A'*

*A"*

(*a*)

quantities **scalars,** and we deal with them by the rules of ordinary algebra. A sin gle value, with a sign (as in a temperature of 40°F), specifies a scalar.

The simplest vector quantity is displacement, or change of position. A vec

tor that represents a displacement is called, reasonably, a **displacement vector.** (Similarly, we have velocity vectors and acceleration vectors.) If a particle changes

*B*

its position by moving from *A* to *B* in Fig. 3-1*a*, we say that it undergoes a displace ment from *A* to *B*, which we represent with an arrow pointing from *A* to *B*.The ar row specifies the vector graphically. To distinguish vector symbols from other

*A*

kinds of arrows in this book, we use the outline of a triangle as the arrowhead.

(*b*)

In Fig. 3-1*a*, the arrows from *A* to *B*, from *A* to *B* , and from *A* to *B* have the same magnitude and direction. Thus, they specify identical displacement vec tors and represent the same *change of position* for the particle. A vector can be shifted without changing its value *if* its length and direction are not changed.

The displacement vector tells us nothing about the actual path that the parti cle takes. In Fig. 3-1*b*, for example, all three paths connecting points *A* and *B* cor respond to the same displacement vector, that of Fig. 3-1*a*. Displacement vectors represent only the overall effect of the motion, not the motion itself.

**Adding Vectors Geometrically**

Suppose that, as in the vector diagram of Fig. 3-2*a*, a particle moves from *A* to *B* and then later from *B* to *C*. We can represent its overall displacement (no matter what its actual path) with two successive displacement vectors, *AB* and *BC*. The *net* displacement of these two displacements is a single displacement from *A* to *C*. We call *AC* the **vector sum** (or **resultant**) of the vectors *AB* and *BC*. This sum is not the usual algebraic sum.

In Fig. 3-2*b*, we redraw the vectors of Fig. 3-2*a* and relabel them in the way that we shall use from now on, namely, with an arrow over an italic symbol, as *a*:

in .If we want to indicate only the magnitude of the vector (a quantity that lacks a sign or direction), we shall use the italic symbol, as in *a*, *b*, and *s*. (You can use just a handwritten symbol.) A symbol with an overhead arrow always implies both properties of a vector, magnitude and direction.

We can represent the relation among the three vectors in Fig. 3-2*b* with the *vector equation*

*s*:  *a*:  *b*:,

**Figure 3-1** (*a*) All three arrows have the same magnitude and direction and thus represent the same displacement. (*b*) All three paths connecting the two points cor respond to the same displacement vector.

*B*

Actual

path

*AC*

Net displacement

is the vector sum

(*a*)

To add *a*and *b*,

(3-1)

*b*

*~~a~~*

*b*:

*a*: *s*:

draw them head to tail.

which says that the vector is the vector sum of vectors and .The symbol in Eq. 3-1 and the words “sum” and “add” have different meanings for vectors than

*~~s~~*

they do in the usual algebra because they involve both magnitude *and* direction. (*b*)

This is the

*b*:

*a*:

Figure 3-2 suggests a procedure for adding two-dimensional vectors and *b*: *a*:

resulting vector,

geometrically. (1) On paper, sketch vector to some convenient scale and at the proper angle. (2) Sketch vector to the same scale, with its tail at the head of vec *b*: *a*:*s*: *a*:

tor , again at the proper angle. (3) The vector sum is the vector that extends from the tail of to the head of .

***Properties.*** Vector addition, defined in this way, has two important proper ties. First, the order of addition does not matter. Adding to gives the same *b*:

*a*:

from tail of *a*

to head of *b*.

**Figure 3-2** (*a*) *AC* is the vector sum of the vectors *AB* and *BC.* (*b*) The same vectors relabeled.

42 CHAPTER 3 VECTORS

*b*

Vector sum *~~a~~*

*~~a~~* + *b*

*a*: *b*:

result as adding to (Fig. 3-3); that is, *a*:  *b*: *b*: *a*:

(commutative law). (3-2)

*b* + *~~a~~* Start Finish

Second, when there are more than two vectors, we can group them in any order *c*: *b*: *c*:*b*:

*a*:

*a*: *c*: *b*:

*~~a~~*

*b*

You get the same vector result for either order of adding vectors.

as we add them. Thus, if we want to add vectors *,* , and , we can add and first and then add their vector sum to . We can also add and first and then *a*:

add *that* sum to . We get the same result either way, as shown in Fig. 3-4. That is, (*a* (associative law). (3-3) :  *b*:) *c*:  *a*:  (*b*: *c*:)

*a*:

You get the same vector result for

*b*:

**Figure 3-3** The two vectors and can be added in either order; see Eq. 3-2.

*~~a a~~*

*c*

+

*b*

*c*

*a* + (*b* + *c* )

*b*

*~~a~~* + *b*

any order of adding the vectors. *~~a~~* + *b*

(*a* + *b*)

*a* + *b* + *c*

*a*:

+

*b*

*c*: *b*:

*~~c c~~*  + *c*

**Figure 3-4** The three vectors , , and can be grouped in any way as they are added; see Eq. 3-3.

*b*:

*b*:

–*b*

*b*

The vector is a vector with the same magnitude as but the opposite direction (see Fig. 3-5).Adding the two vectors in Fig. 3-5 would yield *b*: ( *b*:) 0.

*d*:  *a*:  *b*:*b*:  *b*:

**Figure 3-5** The vectors and have the *b*:

*b*:

same magnitude and opposite directions.

Thus, adding has the effect of subtracting . We use this property to define the difference between two vectors: let . Then

*d*:  *a*:  *b*:  *a*:  ( *b*:) *d*:

(vector subtraction); (3-4) *a*:  *b*:

*~~a~~*

(*a*)

that is, we find the difference vector by adding the vector to the vector . Figure 3-6 shows how this is done geometrically.

As in the usual algebra, we can move a term that includes a vector symbol from

one side of a vector equation to the other, but we must change its sign. For example, *a*:

if we are given Eq. 3-4 and need to solve for , we can rearrange the equation as

*d*: *b*: *a*: or *a*:  *d*: *b*:.

Remember that, although we have used displacement vectors here, the rules

for addition and subtraction hold for vectors of all kinds, whether they represent –*b*

velocities, accelerations, or any other vector quantity. However, we can add only vectors of the same kind. For example, we can add two displacements, or two

*b*

velocities, but adding a displacement and a velocity makes no sense. In the arith metic of scalars, that would be like trying to add 21 s and 12 m.

Note head-to-tail

–*b* **Checkpoint 1**

arrangement for

addition

*c*:  *a*:  *b*: *b*: *a*:

The magnitudes of displacements and are 3 m and 4 m, respectively, and .

*a*:

*b*:

*d* = *~~a~~* – *b*

(*b*)

Considering various orientations of and , what are (a) the maximum possible magnitude for and (b) the minimum possible magnitude? *c*:

*~~a~~*

**Components of Vectors**

add vector to vector . *a*:  *b*: *a*: *b*:  *b*: *b*: *a*:

**Figure 3-6** (*a*) Vectors , , and . (*b*) To subtract vector from vector ,

Adding vectors geometrically can be tedious. A neater and easier technique involves algebra but requires that the vectors be placed on a rectangular coordi nate system.The *x* and *y* axes are usually drawn in the plane of the page, as shown

3-1 VECTORS AND THEIR COMPONENTS

43

in Fig. 3-7*a.*The *z* axis comes directly out of the page at the origin; we ignore it for now and deal only with two-dimensional vectors.

A **component** of a vector is the projection of the vector on an axis. In

*y*

*a*:

Fig. 3-7*a*, for example, *ax* is the component of vector on (or along) the *x* axis and

This is the *y* component of the vector.

*y*

*ay* is the component along the *y* axis. To find the projection of a vector along an axis, we draw perpendicular lines from the two ends of the vector to the axis, as *ay*

shown.The projection of a vector on an *x* axis is its *x component*, and similarly the projection on the *y* axis is the *y component.* The process of finding the components of a vector is called **resolving the vector.**

| *~~a~~*  θ | |
| --- | --- |
|  |  |

*ay ~~a~~* θ

A component of a vector has the same direction (along an axis) as the vector. *a*:

*x O ax*

*x ax O*

In Fig. 3-7, *ax* and *ay* are both positive because extends in the positive direction of both axes. (Note the small arrowheads on the components, to indicate their di *b*: *a*:

rection.) If we were to reverse vector , then both components would be negative and their arrowheads would point toward negative *x* and *y.* Resolving vector in Fig. 3-8 yields a positive component *bx* and a negative component *by*.

(*a*) (*b*)

This is the *x* component of the vector.

In general, a vector has three components, although for the case of Fig. 3-7*a* the component along the *z* axis is zero.As Figs. 3-7*a* and *b* show, if you shift a vec tor without changing its direction, its components do not change.

The components

*~~a~~*

and the vector

θ

form a right triangle.

*ay*

*ax*

*a*:

(*c*)

***Finding the Components.*** We can find the components of in Fig. 3-7*a* geo

metrically from the right triangle there:

*ax*  *a* cos u and *ay*  *a* sin u, (3-5)

*a*:

where u is the angle that the vector makes with the positive direction of the *a*: *a*:

*x* axis, and *a* is the magnitude of . Figure 3-7*c* shows that and its *x* and *y* com ponents form a right triangle. It also shows how we can reconstruct a vector from its components: we arrange those components *head to tail.* Then we complete a right triangle with the vector forming the hypotenuse, from the tail of one com ponent to the head of the other component.

Once a vector has been resolved into its components along a set of axes, the *a*:

components themselves can be used in place of the vector. For example, in Fig. 3-7*a* is given (completely determined) by *a* and u. It can also be given by its components *ax* and *ay*. Both pairs of values contain the same information. If we know a vector in *component notation* (*ax* and *ay*) and want it in *magnitude-angle*

**Figure 3-7** (*a*) The components *ax* and *ay* of *a*:

vector . (*b*) The components are unchanged if the vector is shifted, as long as the magnitude and orientation are maintained. (*c*) The com ponents form the legs of a right triangle whose hypotenuse is the magnitude of the vector.

This is the *x* component

of the vector.

*y* (m)

*b x* = 7 m

θ *x* (m) *O*

m

5

–

=

*notation* (*a* and u), we can use the equations *a*  2*a*2*x*  *ay*2

*y*

*b*

*ay*

*b*

This is the *y* component

and tan (3-6)

*ax*

to transform it.

of the vector.

*b*:

In the more general three-dimensional case, we need a magnitude and two angles (say, *a*, u, and f) or three components (*ax*, *ay*, and *az*) to specify a vector.

**Checkpoint 2**

**Figure 3-8** The component of on the *x* axis is positive, and that on the *y* axis is negative.

In the figure, which of the indicated methods for combining the *x* and *y* components of vector are proper to determine that vector? *a*:

*~~a~~*

*y*

*x ax ay*

(*a*)

*~~a~~*

*y*

*x ax ay*

(*b*)

*y*

*x ax*

*ay*

*~~a~~*

(*c*)

*~~a~~*

*~~a~~x*

(*d*)

*y*

*x*

*ay*

*y*

*x ax*

*ay*

*~~a~~*

(*e*)

*~~a~~*

*y*

*x ax ay*

( *f* )

44 CHAPTER 3 VECTORS

Sample Problem 3.01 Adding vectors in a drawing, orienteering

In an orienteering class, you have the goal of moving as far (straight-line distance) from base camp as possible by making three straight-line moves. You may use the follow *b*: *a*:

*~~a~~*

*~~a~~*

–*~~c~~*

*b b* –*b*

ing displacements in any order: (a) , 2.0 km due east (directly toward the east); (b) , 2.0 km 30° north of east (at an angle of 30° toward the north from due east); *~~c~~*

*b*: *c*:

(c) , 1.0 km due west. Alternatively, you may substitute *c*:  *c*: *b*:

either for or for . What is the greatest distance

30°

–*~~c~~*

Scale of km

*d* = *b+a* – *c*

This is the vector result for adding those three vectors in any order.

you can be from base camp at the end of the third displace

0 1

2

ment? (We are not concerned about the direction.) *c*: *b*: *a*:

*Reasoning:* Using a convenient scale, we draw vectors , *c*:  *b*:

, , , and as in Fig. 3-9*a.* We then mentally slide the vectors over the page, connecting three of them at a time *d*:

in head-to-tail arrangements to find their vector sum . The tail of the first vector represents base camp. The head of the third vector represents the point at which you stop. *d*:

The vector sum extends from the tail of the first vector to the head of the third vector. Its magnitude *d* is your dis tance from base camp. Our goal here is to maximize that base-camp distance.

We find that distance *d* is greatest for a head-to-tail arrangement of vectors , , and . They can be in any *c*: *b*:

*a*:

(*a*) (*b*)

**Figure 3-9** (*a*) Displacement vectors; three are to be used. (*b*) Your distance from base camp is greatest if you undergo displacements , , and , in any order. *c*: *b*: *a*:

order, because their vector sum is the same for any order. (Recall from Eq. 3-2 that vectors commute.) The order shown in Fig. 3-9*b* is for the vector sum

*d*: *b*: *a*:  ( *c*:).

Using the scale given in Fig. 3-9*a*, we measure the length *d* of this vector sum, finding

*d*  4.8 m. (Answer)

Sample Problem 3.02 Finding components, airplane flight

A small airplane leaves an airport on an overcast day and is later sighted 215 km away, in a direction making an angle of 22° east of due north. This means that the direction is not due north (directly toward the north) but is rotated 22° to ward the east from due north. How far east and north is the airplane from the airport when sighted?

*y*

200

*P*

*d*

)

KEY IDEA

We are given the magnitude (215 km) and the angle (22° east of due north) of a vector and need to find the components of the vector.

*Calculations:* We draw an *xy* coordinate system with the positive direction of *x* due east and that of *y* due north (Fig. 3-10). For convenience, the origin is placed at the airport. (We don’t have to do this. We could shift and misalign the coordinate system but, given a choice, why make the prob *d*:

lem more difficult?) The airplane’s displacement points from the origin to where the airplane is sighted. *d*:

To find the components of , we use Eq. 3-5 with u

m

k

(

e

c

n

a

22°

100

m

k

5

68° ( 90° 22°):

*dx*  *d* cos u (215 km)(cos 68°)

t

s

iD

1

2

θ

00 100 Distance (km)

81 km (Answer)

*dy*  *d* sin u (215 km)(sin 68°)

*x*

199 km 2.0 102 km. (Answer)

**Figure 3-10** A plane takes off from an airport at the origin and is later sighted at *P.*

Thus, the airplane is 81 km east and 2.0 102 km north of the airport.

Additional examples, video, and practice available at *WileyPLUS*

45

3-1 VECTORS AND THEIR COMPONENTS

Problem-Solving Tactics Angles, trig functions, and inverse trig functions

*Tactic 1: Angles—Degrees and Radians* Angles that are measured relative to the positive direction of the *x* axis are positive if they are measured in the counterclockwise direc tion and negative if measured clockwise. For example, 210° and 150° are the same angle.

Angles may be measured in degrees or radians (rad).To

Quadrants

IV I II III IV

+1

sin

–90° 90° 270°

0

relate the two measures, recall that a full circle is 360° and

–1

2p rad.To convert, say, 40° to radians, write

40 2 rad

360  0.70 rad.

(*a*)

*Tactic 2: Trig Functions* You need to know the definitions

of the common trigonometric functions—sine, cosine, and

tangent—because they are part of the language of science

and engineering. They are given in Fig. 3-11 in a form that

+1

does not depend on how the triangle is labeled.

180° 360° cos

You should also be able to sketch how the trig functions vary with angle, as in Fig. 3-12, in order to be able to judge whether a calculator result is reasonable. Even knowing the signs of the functions in the various quadrants can be of help.

*Tactic 3: Inverse Trig Functions* When the inverse trig functions sin 1, cos 1, and tan 1 are taken on a calculator, you must consider the reasonableness of the answer you

–90° 90° 180° 270° 360° 0

–1

(*b*)

get, because there is usually another possible answer that

tan

+2

the calculator does not give. The range of operation for a

calculator in taking each inverse trig function is indicated

+1

in Fig. 3-12. As an example, sin 1 0.5 has associated angles

of 30° (which is displayed by the calculator, since 30° falls

within its range of operation) and 150°. To see both values, draw a horizontal line through 0.5 in Fig. 3-12*a* and note where it cuts the sine curve. How do you distinguish a cor rect answer? It is the one that seems more reasonable for the given situation.

*Tactic 4: Measuring Vector Angles* The equations for cos u and sin u in Eq. 3-5 and for tan u in Eq. 3-6 are valid only if the angle is measured from the positive direction of

sin θ leg opposite θ

hypotenuse =

–90° 90° 270°

0 180° 360°

–1

–2

(*c*)

**Figure 3-12** Three useful curves to remember. A calculator’s range of operation for taking *inverse* trig functions is indicated by the darker portions of the colored curves.

the *x* axis. If it is measured relative to some other direc

cos θ hypotenuse = leg adjacent to θ

leg opposite θ

tan θ = leg adjacent to θ

Hypotenuse

θ

Leg adjacent to θ

Leg

opposite θ

tion, then the trig functions in Eq. 3-5 may have to be in terchanged and the ratio in Eq. 3-6 may have to be inverted. A safer method is to convert the angle to one measured from the positive direction of the *x* axis. In *WileyPLUS*, the system expects you to report an angle of

**Figure 3-11** A triangle used to define the trigonometric functions. See also Appendix E.

direction like this (and positive if counterclockwise and negative if clockwise).

Additional examples, video, and practice available at *WileyPLUS*

46 CHAPTER 3 VECTORS

**3-2 UNIT VECTORS, ADDING VECTORS BY COMPONENTS** Learning Objectives

*After reading this module, you should be able to . . .*

**3.06** Convert a vector between magnitude-angle and unit vector notations.

**3.07** Add and subtract vectors in magnitude-angle notation and in unit-vector notation.

Key Ideas

**3.08** Identify that, for a given vector, rotating the coordinate system about the origin can change the vector’s compo nents but not the vector itself.

kˆ jˆ iˆ in which , , and are the vector components of and

● Unit vectors , , and have magnitudes of unity and are directed in the positive directions of the *x*, *y*, and *z* axes, respectively, in a right-handed coordinate system. We can *a*:

write a vector in terms of unit vectors as

*a*: *a az*kˆ *y*j *a* ˆ *x*iˆ *ax*, *ay*, and *az* are its scalar components.

● To add vectors in component form, we use the rules *rx*  *ax*  *bx ry*  *ay*  *by rz*  *az*  *bz*.

*ax*iˆ  *ay*jˆ  *az*kˆ *a* , :

*r*: *b*: *a*:

Here and are the vectors to be added, and is the vector

sum. Note that we add components axis by axis.

**Unit Vectors**

The unit vectors point along axes.

*y*

ˆj

*x*

ˆk ˆi

*z*

A **unit vector** is a vector that has a magnitude of exactly 1 and points in a particu lar direction. It lacks both dimension and unit. Its sole purpose is to point—that is, to specify a direction. The unit vectors in the positive directions of the *x*, *y*, and k ˆ ˆ jˆ iˆ

*z* axes are labeled , , and , where the hat is used instead of an overhead arrow as for other vectors (Fig. 3-13).The arrangement of axes in Fig. 3-13 is said to be a **right-handed coordinate system.** The system remains right-handed if it is rotated rigidly.We use such coordinate systems exclusively in this book.

Unit vectors are very useful for expressing other vectors; for example, we can *b*: *a*:

express and of Figs. 3-7 and 3-8 as

**Figure 3.13** Unit vectors iˆ, , and define the

kˆ jˆ

directions of a right-handed coordinate

*a*:  *ax*iˆ  *ay*jˆ *b*: *bx*iˆ  *by* jˆ

(3-7)

system.

and . (3-8) jˆ iˆ

These two equations are illustrated in Fig. 3-14.The quantities *ax* and *ay* are vec *a*:

tors, called the **vector components** of .The quantities *ax* and *ay* are scalars, called the **scalar components** of (or, as before, simply its *a* **components**). :

This is the *y* vector component.

*y*

*y*

ˆ

*~~a~~ b x*ˆi

*ay* j

θ *O x*

θ

*b*

**Figure 3-14** (*a*) The vector components of vector . *b*:*a*:

*x O ax*i

ˆ

This is the *x* vector

ˆ

*by* j

of vector . (*b*) The vector components

(*a*)

component.

(*b*)

**Adding Vectors by Components**

We can add vectors geometrically on a sketch or directly on a vector-capable calculator.A third way is to combine their components axis by axis.

47

To start, consider the statement

3-2 UNIT VECTORS, ADDING VECTORS BY COMPONENTS

*r*:  *a*:  *b*:

, (3-9) (*a*:  *b*:

*r* ) :

which says that the vector is the same as the vector . Thus, each (*a*:  *b*:

*r* ) :

component of must be the same as the corresponding component of : *rx*  *ax*  *bx* (3-10)

*ry*  *ay*  *by* (3-11)

*rz*  *az*  *bz*. (3-12)

In other words, two vectors must be equal if their corresponding components are *b*: *a*:

equal. Equations 3-9 to 3-12 tell us that to add vectors and , we must (1) re solve the vectors into their scalar components; (2) combine these scalar compo *r*:

nents, axis by axis, to get the components of the sum ; and (3) combine *r*: *r*: *r*:

the components of to get itself. We have a choice in step 3. We can express in unit-vector notation or in magnitude-angle notation.

This procedure for adding vectors by components also applies to vector *a*: *d*: *a*:  ( *b*:)*d*: *a*:  *b*:

subtractions. Recall that a subtraction such as can be rewritten as an *b*:

addition .To subtract, we add and by components, to get *dx*  *ax*  *bx*, *dy*  *ay*  *by*, and *dz*  *az*  *bz*,

where . (3-13) *d*: *dx*iˆ  *dy*jˆ  *dz*kˆ

**Checkpoint 3**

(a) In the figure here, what are the signs of the *x* : *d*1

:

components of and ? (b) What are the signs of :*d*2

: *d*1

the *y* components of and ? (c) What are the *d*2 signs of the *x* and *y* components of *d*2? :

:

*d*1

**Vectors and the Laws of Physics**

*y*

*x*

*d* 2

*d* 1

*y*

So far, in every figure that includes a coordinate system, the *x* and *y* axes are par *a*:

allel to the edges of the book page. Thus, when a vector is included, its compo nents *ax* and *ay* are also parallel to the edges (as in Fig. 3-15*a*).The only reason for

*ay*

θ

*~~a~~*

that orientation of the axes is that it looks “proper”; there is no deeper reason.

*O*

We could, instead, rotate the axes (but not the vector ) through an angle *a* f as in : Fig. 3-15*b*, in which case the components would have new values, call them *a* *x* and

*x ax* (*a*)

*a* *y*. Since there are an infinite number of choices of f, there are an infinite num *a*:

ber of different pairs of components for .

Which then is the “right” pair of components? The answer is that they are all equally valid because each pair (with its axes) just gives us a different way of de *a*:

scribing the same vector ; all produce the same magnitude and direction for the vector. In Fig. 3-15 we have

Rotating the axes

changes the components but not the vector.

*y*

*y'*

(3-14)

and

*a*  2*a*2*x*  *a*2*y*  2*a* 2

*x*  *a* 2

*y*

*~~a~~*

u u f. (3-15)

*a'xx'*

The point is that we have great freedom in choosing a coordinate system, be cause the relations among vectors do not depend on the location of the origin or on the orientation of the axes.This is also true of the relations of physics; they are all independent of the choice of coordinate system.Add to that the simplicity and

*a'y*φ *'*

θ

*O*

(*b*)

*a*:

*x*

richness of the language of vectors and you can see why the laws of physics are almost always presented in that language: one equation, like Eq. 3-9, can repre sent three (or even more) relations, like Eqs. 3-10, 3-11, and 3-12.

**Figure 3-15** (*a*) The vector and its components. (*b*) The same vector, with the axes of the coordinate system rotated through an angle f.

48 CHAPTER 3 VECTORS

Sample Problem 3.03 Searching through a hedge maze

A hedge maze is a maze formed by tall rows of hedge. After entering, you search for the center point and then for the exit. Figure 3-16*a* shows the entrance to such a maze and the first two choices we make at the junctions we encounter in moving from point *i* to point *c*. We un dergo three displacements as indicated in the overhead view of Fig. 3-16*b*:

*d*1  6.00 m 1  40°

*d*2  8.00 m 2  30°

*d*3  5.00 m 3  0°,

where the last segment is parallel to the superimposed *x* axis. When we reach point *c*, what are the magnitude and *d*:

angle of our net displacement net from point *i*? KEY IDEAS

*d*:

(1) To find the net displacement net, we need to sum the three individual displacement vectors:

*Calculations:*To evaluate Eqs. 3-16 and 3-17, we find the *x* and *y* components of each displacement. As an example, the com ponents for the first displacement are shown in Fig. 3-16*c*. We draw similar diagrams for the other two displacements and then we apply the *x* part of Eq. 3-5 to each displacement, using angles relative to the positive direction of the *x* axis:

*d*l*x*  (6.00 m) cos 40° 4.60 m

*d*2*x*  (8.00 m) cos ( 60°) 4.00 m

*d*3*x*  (5.00 m) cos 0° 5.00 m.

Equation 3-16 then gives us

*d*net, *x*  4.60 m 4.00 m 5.00 m

13.60 m.

Similarly, to evaluate Eq. 3-17, we apply the *y* part of Eq. 3-5 to each displacement:

*d*l*y*  (6.00 m) sin 40° = 3.86 m

*d*2*y*  (8.00 m) sin ( 60°) = 6.93 m

*d*:

*d*:

*d*:

*d*:

net  1  2  3.

(2) To do this, we first evaluate this sum for the *x* compo nents alone,

*d*net,*x*  *d*l*x*  *d*2*x*  *d*3*x*, (3-16)

and then the *y* components alone,

*d*net,*y*  *d*1*y*  *d*2*y*  *d*3*y*. (3-17)

(3) Finally, we construct net *d* from its *x* and *y* components. :

*y* 

*a*

**

*d*3*y*  (5.00 m) sin 0° 0 m.

Equation 3-17 then gives us

*d*net, *y*  3.86 m 6.93 m 0 m

3.07 m.

*d*:

Next we use these components of net to construct the vec tor as shown in Fig. 3-16*d*: the components are in a head-to tail arrangement and form the legs of a right triangle, and

*y*

Three

vectorsFirst

*a *

*d*1 *d*2

u2

*i* u1



*x*

*b c d*3

vector *d*1

*d*1*x*

*d*1*y*

*x*

*i* (*b*)

*b c*

**

(*a*)

*i*

*y*

*x*

Net

vector

(*c*)

*d*net,*x*

*d*net

*d*net,*y*

*c*

(*d*)

**Figure 3-16** (*a*) Three displacements through a hedge maze. (*b*) The displacement vectors. (*c*) The first displacement vector and its components. (*d*) The net displacement vector and its components.

49

3-2 UNIT VECTORS, ADDING VECTORS BY COMPONENTS

the vector forms the hypotenuse.We find the magnitude and

*d*: tangent on a calculator. The answer it displays is mathe matically correct but it may not be the correct answer for angle of net with Eq. 3-6. The magnitude is

*d*net  (3-18) 2*d*2net,*x*  *d*2net,*y*

13.9 m. (Answer) 2(13.60 m)2  ( 3.07 m)2

To find the angle (measured from the positive direction of *x*), we take an inverse tangent:

*d*net,*x*

*d*net,*y*

tan 1 (3-19)

–3.07 m

13.60 m

tan 1  12.7°. (Answer)

The angle is negative because it is measured clockwise from positive *x*. We must always be alert when we take an inverse

the physical situation. In those cases, we have to add 180° to the displayed answer, to reverse the vector. To check, we always need to draw the vector and its components as we did in Fig. 3-16*d*. In our physical situation, the figure shows us that 12.7° is a reasonable answer, whereas 12.7° 180° 167° is clearly not.

We can see all this on the graph of tangent versus angle in Fig. 3-12*c*. In our maze problem, the argument of the in verse tangent is 3.07/13.60, or 0.226. On the graph draw a horizontal line through that value on the vertical axis. The line cuts through the darker plotted branch at 12.7° and also through the lighter branch at 167°. The first cut is what a calculator displays.

Sample Problem 3.04 Adding vectors, unit-vector components

Figure 3-17*a* shows the following three vectors: *a*:  (4.2 m)iˆ  (1.5 m)jˆ,

*b*: ( 1.6 m)iˆ  (2.9 m)jˆ,

KEY IDEA

We can add the three vectors by components, axis by axis, and then combine the components to write the vector *r*:

and

*c*:  ( 3.7 m)jˆ.

sum .

*r*: *c*: *b* , :,*a*:,

What is their vector sum which is also shown? *r*: *y*

*Calculations:* For the *x* axis, we add the *x* components of and to get the *x* component of the vector sum :

*rx*  *ax*  *bx*  *cx*

*b*

3

To add these vectors,

find their net *x* component

2

and their net *y* component. 1

4.2 m 1.6 m 0 2.6 m.

Similarly, for the *y* axis,

*ry*  *ay*  *by*  *cy*

*x*

–3 2 –2 –1 3 4

1

–1

*~~a~~*

–2

1.5 m 2.9 m 3.7 m 2.3 m.

*r*:

We then combine these components of to write the vector in unit-vector notation:

*r*:  (2.6 m)iˆ  (2.3 m)jˆ,

–3

*y*

*~~c~~*

(*a*)

1

*~~r~~*

ˆ

2.6i

Then arrange the net components head to tail.

*x*

(Answer)

where (2.6 m)iˆ is the vector component of along the *x* axis

*r*:

and (2.3 m)jˆ is that along the *y* axis. Figure 3-17*b* shows

*r*:

one way to arrange these vector components to form . (Can you sketch the other way?)

We can also answer the question by giving the magnitude

–3 2 –2 –1 3 4

*r*:

–1

–2

–3

(*b*)

–2.3ˆj

*~~r~~*

This is the result of the addition.

and an angle for .From Eq.3-6,the magnitude is

*r*  2(2.6 m)2  ( 2.3 m)2  3.5 m

and the angle (measured from the *x* direction) is tan 1  2.3 m

2.6 m  41 ,

(Answer) (Answer)

**Figure 3-17** Vector is the vector sum of the other three vectors. *r*:

where the minus sign means clockwise.

Additional examples, video, and practice available at *WileyPLUS*

50 CHAPTER 3 VECTORS

**3-3 MULTIPLYING VECTORS** Learning Objectives

*After reading this module, you should be able to . . .*

**3.09** Multiply vectors by scalars.

**3.10** Identify that multiplying a vector by a scalar gives a vec tor, taking the dot (or scalar) product of two vectors gives a scalar, and taking the cross (or vector) product gives a new vector that is perpendicular to the original two.

**3.11** Find the dot product of two vectors in magnitude-angle notation and in unit-vector notation.

**3.12** Find the angle between two vectors by taking their dot prod uct in both magnitude-angle notation and unit-vector notation.

Key Ideas

*v*:

● The product of a scalar *s* and a vector is a new vector whose magnitude is and whose direction is the same as

*sv*

*v*: *v*:

that of if *s* is positive, and opposite that of if *s* is negative. *v*: *v*:

To divide by *s*, multiply by 1/*s*.

**3.13** Given two vectors, use a dot product to find how much of one vector lies along the other vector.

**3.14** Find the cross product of two vectors in magnitude angle and unit-vector notations.

**3.15** Use the right-hand rule to find the direction of the vector that results from a cross product.

**3.16** In nested products, where one product is buried inside another, follow the normal algebraic procedure by starting with the innermost product and working outward.

*c*: *b*: *a*:*b*:

*a*:

● The vector (or cross) product of two vectors and is written and is a *vector* whose magnitude *c* is given by

*c*  *ab* sin ,

*a*:

in which is the smaller of the angles between the directions *b*:

● The scalar (or dot) product of two vectors and is writ *a*:

*c*: *b*:

*a*:

of and . The direction of is perpendicular to the plane

*b*:

ten and is the *scalar* quantity given by

*b*:

*a*:

*b*: *a*:

defined by and and is given by a right-hand rule, as shown

*ab* cos ,

*a*:

*b*:

*a*: *b*:

*a*:

in Fig. 3-19. Note that ( ). In unit-vector *b*:

notation,

in which is the angle between the directions of and . A scalar product is the product of the magnitude of one vec

*a*:

tor and the scalar component of the second vector along the

(*bx*iˆ  *by*jˆ  *bz*kˆ (*a* ), *x*iˆ  *ay*jˆ  *az*kˆ *b* ) :

direction of the first vector. In unit-vector notation,

which we may expand with the distributive law.

(*bx*iˆ  *by*jˆ  *bz*kˆ (*a* ), *x*iˆ  *ay*jˆ  *az*kˆ *b* ) : *a*:

● In nested products, where one product is buried inside an other, follow the normal algebraic procedure by starting with

which may be expanded according to the distributive law. Note that *a*. : *b*:

the innermost product and working outward.

*a*:

*b*:

**Multiplying Vectors\***

There are three ways in which vectors can be multiplied, but none is exactly like

the usual algebraic multiplication. As you read this material, keep in mind that a

vector-capable calculator will help you multiply vectors only if you understand

the basic rules of that multiplication.

**Multiplying a Vector by a Scalar**

*a*:

If we multiply a vector by a scalar *s*, we get a new vector. Its magnitude is

*a*:

the product of the magnitude of and the absolute value of *s*. Its direction is the

*a*: *a*:

direction of if *s* is positive but the opposite direction if *s* is negative. To divide

*a*:

by *s*, we multiply by 1/*s.*

**Multiplying a Vector by a Vector**

There are two ways to multiply a vector by a vector: one way produces a scalar

(called the *scalar product*), and the other produces a new vector (called the *vector*

*product*). (Students commonly confuse the two ways.)

\*This material will not be employed until later (Chapter 7 for scalar products and Chapter 11 for vec

tor products), and so your instructor may wish to postpone it.

51

3-3 MULTIPLYING VECTORS

**The Scalar Product**

*a*:  *b*: *b*: *a*:

The **scalar product** of the vectors and in Fig. 3-18*a* is written as and defined to be

*a*:  *b*:

*ab* cos f, (3-20)

*b*: *a*: *b*: *a*:*b*  : *a*:

where *a* is the magnitude of , *b* is the magnitude of , and is the angle between and (or, more properly, between the directions of and ).There are actually two such angles: and 360° . Either can be used in Eq. 3-20, because their

cosines are the same.

Note that there are only scalars on the right side of Eq. 3-20 (including the *b*: *a*: *b*: *a*:

value of cos ). Thus on the left side represents a *scalar* quantity. Because of the notation, is also known as the **dot product** and is spoken as “a dot b.” A dot product can be regarded as the product of two quantities: (1) the mag nitude of one of the vectors and (2) the scalar component of the second vector *b*: *b*: *a*:*b*: *a*:

along the direction of the first vector. For example, in Fig. 3-18*b*, has a scalar component *a* cos along the direction of ; note that a perpendicular dropped from the head of onto determines that component. Similarly, has a scalar component *b* cos along the direction of . *a*:

If the angle between two vectors is 0°, the component of one vector along the

other is maximum, and so also is the dot product of the vectors. If, instead, is 90°,

the component of one vector along the other is zero, and so is the dot product. Equation 3-20 can be rewritten as follows to emphasize the components:

*b*:

*a*:

(*a* cos f)(*b*) (*a*)(*b* cos f). (3-21)

The commutative law applies to a scalar product, so we can write *a*: *b*: *b*: *a*:

.

When two vectors are in unit-vector notation, we write their dot product as

kˆ jˆ i kˆ ˆ jˆ i *b* ˆ :

*a*:

(*ax*  *ay*  *az* ) (*bx*  *by*  *bz* ), (3-22)

which we can expand according to the distributive law: Each vector component of the first vector is to be dotted with each vector component of the second vec tor. By doing so, we can show that

*axbx*  *ayby*  *azbz b* . (3-23) : *a*:

*~~a~~*

φ

*b*

(*a*)

Component of *b*

along direction of

*~~a~~* is *b* cos φ

Multiplying these gives

*b*: *a*:

**Figure 3-18** (*a*) Two vectors and , with an angle f between them. (*b*) Each vector has a component along the direction of the other vector.

the dot product.

Or multiplying these gives the dot product.

*~~a~~*

φ

*b*

Component of *~~a~~*

along direction of

*b* is *a* cos φ

(*b*)

52 CHAPTER 3 VECTORS

**Checkpoint 4**

*D*: *C*: *D*  : *C*: *D*: *C*:

Vectors and have magnitudes of 3 units and 4 units, respectively.What is the

angle between the directions of and if equals (a) zero, (b) 12 units, and

(c) 12 units?

**The Vector Product**

*a*:

*a*: *b*:

*c*: *b*:

The **vector product** of and , written , produces a third vector whose magnitude is

*c*  *ab* sin f, (3-24)

where f is the *smaller* of the two angles between and . (You must use the *b*:

*a*:

smaller of the two angles between the vectors because sin f and sin(360° f)

*a*:

*b*:

differ in algebraic sign.) Because of the notation, is also known as the **cross product,** and in speech it is “a cross b.”

*b*: *a*: *b*: *a*: *b*: *a*:

If and are parallel or antiparallel, 0. The magnitude of , which can be written as , is maximum when and are perpendicular to each other. *b*: *a*:  *a*:  *b*:

The direction of is perpendicular to the plane that contains and . *b*:

*a*: *c*:

*b*: *a*:*b*: *a*: *c*:

Figure 3-19*a* shows how to determine the direction of with what is known as a **right-hand rule.** Place the vectors and tail to tail without altering their orientations, and imagine a line that is perpendicular to their plane where they meet. Pretend to place your *right* hand around that line in such a way that *b*: *a*:

your fingers would sweep into through the smaller angle between them.Your *c*:

outstretched thumb points in the direction of .

The order of the vector multiplication is important. In Fig. 3-19*b*, we are *b*: *c* :  *b*:  *a*:

determining the direction of , so the fingers are placed to sweep *a*:

into through the smaller angle. The thumb ends up in the opposite direction *c* :  *c*:

from previously, and so it must be that ; that is,

*b*:  *a*:  (*a*:  *b*:)

. (3-25)

In other words, the commutative law does not apply to a vector product. In unit-vector notation, we write

kˆ jˆ i kˆ ˆ jˆ i *b* ˆ : *a*:

(*ax*  *ay*  *az* ) (*bx*  *by*  *bz* ), (3-26)

which can be expanded according to the distributive law; that is, each component of the first vector is to be crossed with each component of the second vector. The cross products of unit vectors are given in Appendix E (see “Products of Vectors”). For example, in the expansion of Eq. 3-26, we have

iˆ iˆ iˆ iˆ

*ax*  *bx*  *axbx*( ) 0,

iˆ iˆ

because the two unit vectors and are parallel and thus have a zero cross prod uct. Similarly, we have

kˆ jˆ iˆ jˆ iˆ

*ax*  *by*  *axby*( ) *axby* .

ˆ iˆ jˆ iˆ

In the last step we used Eq. 3-24 to evaluate the magnitude of as unity. (These vectors and each have a magnitude of unity, and the angle between j being in the positive direction of the *z* axis (thus in the direction of ). kˆ jˆ iˆ

them is 90°.) Also, we used the right-hand rule to get the direction of as

3-3 MULTIPLYING VECTORS 53

Continuing to expand Eq. 3-26, you can show that

kˆ jˆ i *b* ˆ :

*a*:

(*aybz*  *byaz*) (*azbx*  *bzax*) (*axby*  *bxay*) . (3-27)

A determinant (Appendix E) or a vector-capable calculator can also be used.

To check whether any *xyz* coordinate system is a right-handed coordinate

jˆ iˆ kˆ jˆ iˆ

system, use the right-hand rule for the cross product with that system. If

your fingers sweep (positive direction of *x*) into (positive direction of *y*) with

the outstretched thumb pointing in the positive direction of *z* (not the negative

direction), then the system is right-handed.

**Checkpoint 5**

*D*: *C*: *D*  : *C*: *D*: *C*:

Vectors and have magnitudes of 3 units and 4 units, respectively.What is the an

gle between the directions of and if the magnitude of the vector product

is (a) zero and (b) 12 units?

A

*~~c~~*

*~~a~~*

*b b b*

(*a*)

*b*

*~~a~~*

(*b*)

*~~a a~~* ***~~c~~***

*b*: *a*: *c*:  *a*:  *b*: *b*: *a*:

**Figure 3-19** Illustration of the right-hand rule for vector products. (*a*) Sweep vector into vector with the fingers of your right hand. Your outstretched thumb shows the direction of vector . (*b*) Showing that is the reverse of . *a*:  *b*:

54 CHAPTER 3 VECTORS

Sample Problem 3.05 Angle between two vectors using dot products kˆ i ˆ *b*:

*a* ˆi ˆj :

What is the angle between 3.0 4.0 and 2.0 3.0 ? (*Caution:* Although many of the following steps can be bypassed with a vector-capable calculator, you

We can separately evaluate the left side of Eq. 3-28 by writing the vectors in unit-vector notation and using the distributive law:

will learn more about scalar products if, at least here, you *a*:

use these steps.)

KEY IDEA

kˆ iˆ jˆ i *b* ˆ :

(3.0 4.0 ) ( 2.0 3.0 ) kˆ iˆ iˆ iˆ

(3.0 ) ( 2.0 ) (3.0 ) (3.0 ) kˆ jˆ iˆ jˆ

( 4.0 ) ( 2.0 ) ( 4.0 ) (3.0 ).

The angle between the directions of two vectors is included in the definition of their scalar product (Eq. 3-20):

We next apply Eq. 3-20 to each term in this last expression. iˆ iˆ

The angle between the unit vectors in the first term ( and ) is 0°, and in the other terms it is 90°.We then have

*b*:

*a*:

*ab* cos f. (3-28)

*a*:

*a*:

*b*:

(6.0)(1) (9.0)(0) (8.0)(0) (12)(0) 6.0.

*Calculations:* In Eq. 3-28, *a* is the magnitude of , or

*a*  23.02  ( 4.0)2  5.00,

*b*:

and *b* is the magnitude of , or

(3-29)

Substituting this result and the results of Eqs. 3-29 and 3-30 into Eq. 3-28 yields

6.0 (5.00)(3.61) cos f,

so (Answer) cos 1  6.0

*b*  2( 2.0) (3-30) 2  3.02  3.61.

Sample Problem 3.06 Cross product, right-hand rule *a*:

In Fig. 3-20, vector lies in the *xy* plane, has a magnitude of 18 units, and points in a direction 250° from the positive di *b*:

rection of the *x* axis. Also, vector has a magnitude of 12 units and points in the positive direction of the *z* axis.What *b*: *a*: *c*:

is the vector product ?

KEY IDEA

*z*

*~~a~~ b* 250°

(5.00)(3.61)  109 110 .

Sweep *a*into *b*.

*c* **=** *a b*

This is the resulting

vector, perpendicular to

When we have two vectors in magnitude-angle notation, we find the magnitude of their cross product with Eq. 3-24 and the direction of their cross product with the right-hand rule

160°

*x y c*:

both *a*and *b*.

of Fig. 3-19.

*Calculations:* For the magnitude we write

*c*  *ab* sin f (18)(12)(sin 90°) 216. (Answer)

To determine the direction in Fig. 3-20, imagine placing the fingers of your right hand around a line perpendicular to the

**Figure 3-20** Vector (in the *xy* plane) is the vector (or cross) product of vectors and . *b*: *a*:

*c*: *c*:

gives the direction of .Thus, as shown in the figure, lies in the *xy* plane. Because its direction is perpendicular to the *a*:

direction of (a cross product always gives a perpendicular vector), it is at an angle of

250° 90° 160° (Answer)

*a*:

*c*: *b*:

plane of and (the line on which is shown) such that your fingers sweep into . Your outstretched thumb then *b*:

*a*:

from the positive direction of the *x* axis.

Sample Problem 3.07 Cross product, unit-vector notation

jˆ i :*a* ˆ

*a*: *c*: kˆ i *b* ˆ :

*b*:

*Calculations:* Here we write

If 3 4 and 2 3 , what is ? KEY IDEA

When two vectors are in unit-vector notation, we can find their cross product by using the distributive law.

kˆ iˆ jˆ iˆ *c*:

(3 4 ) ( 2 3 )

iˆ j kˆ ˆ iˆ iˆ iˆ

3 ( 2 ) 3 3 ( 4 ) ( 2 )  ( 4 ) 3 . kˆ jˆ