

Physics for Game Programmers

GRANT PALMER

Physics for Game Programmers

Copyright © 2005 by Grant Palmer

All rights reserved. No part of this work may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or by any information storage or retrieval system, without the prior written permission of the copyright owner and the publisher.

ISBN (pbk): 1-59059-472-X

Printed and bound in the United States of America 9 8 7 6 5 4 3 2 1

Trademarked names may appear in this book. Rather than use a trademark symbol with every occurrence of a trademarked name, we use the names only in an editorial fashion and to the benefit of the trademark owner, with no intention of infringement of the trademark.

Lead Editor: Tony Davis

Technical Reviewers: Alan McLeod, Jack Park

Editorial Board: Steve Anglin, Dan Appleman, Ewan Buckingham, Gary Cornell, Tony Davis, Jason Gilmore, Jonathan Hassell, Chris Mills, Dominic Shakeshaft, Jim Sumser

Assistant Publisher: Grace Wong

Project Manager: Laura E. Brown

Copy Manager: Nicole LeClerc

Copy Editor: Ami Knox

Production Manager: Kari Brooks-Copony

Production Editor: Kelly Winquist

Compositor: Susan Glinert

Proofreader: Liz Welch

Indexer: John Collin

Artist: Kinetic Publishing Services, LLC

Cover Designer: Kurt Krames

Manufacturing Manager: Tom Debolski

Distributed to the book trade in the United States by Springer-Verlag New York, Inc., 233 Spring Street, 6th Floor, New York, NY 10013, and outside the United States by Springer-Verlag GmbH & Co. KG, Tiergartenstr. 17, 69112 Heidelberg, Germany.

In the United States: phone 1-800-SPRINGER, fax 201-348-4505, e-mail orders@springer-ny.com, or visit <http://www.springer-ny.com>. Outside the United States: fax +49 6221 345229, e-mail orders@springer.de, or visit <http://www.springer.de>.

For information on translations, please contact Apress directly at 2560 Ninth Street, Suite 219, Berkeley, CA 94710. Phone 510-549-5930, fax 510-549-5939, e-mail info@apress.com, or visit <http://www.apress.com>.

The information in this book is distributed on an “as is” basis, without warranty. Although every precaution has been taken in the preparation of this work, neither the author(s) nor Apress shall have any liability to any person or entity with respect to any loss or damage caused or alleged to be caused directly or indirectly by the information contained in this work.

The source code for this book is available to readers at www.apress.com in the Downloads section.

This book is dedicated to my wonderful wife, Lisa.

Contents at a Glance

About the Author	xvii
About the Technical Reviewers	xix
Acknowledgments	xxi
Introduction	xxiii
CHAPTER 1 Adding Realism to Your Games	1
CHAPTER 2 Some Basic Concepts	5
CHAPTER 3 Basic Newtonian Mechanics	21
CHAPTER 4 Basic Kinematics	49
CHAPTER 5 Projectiles	83
CHAPTER 6 Collisions	139
CHAPTER 7 Sports Simulations	167
CHAPTER 8 Cars and Motorcycles	211
CHAPTER 9 Boats and Things That Float	245
CHAPTER 10 Airplanes	275
CHAPTER 11 Rockets and Missiles	319
CHAPTER 12 The Physics of Solids	351
CHAPTER 13 Explosions	371
CHAPTER 14 Lasers	385
CHAPTER 15 Probabilistic and Monte Carlo Simulations	403
■ INDEX	423

Contents

About the Author	xvii
About the Technical Reviewers	xix
Acknowledgments	xxi
Introduction	xxiii

■ CHAPTER 1 Adding Realism to Your Games 1

Physics Will Keep Your Games from Looking Fake	1
Adding Physics-Based Realism Is Easier Than You Might Think	2
Adding Physics Won't Affect Game Performance	3
Knowing Some Physics Will Make You a Better Game Programmer	4
Let's Add Some Realism to Your Games	4

■ CHAPTER 2 Some Basic Concepts 5

Systems of Units	6
Scientific Notation	7
Summation Notation	8
Greek Letters	8
Coordinate Systems and Frames of Reference	9
Scalars and Vectors	10
Computing the Magnitude of a Vector	11
The Unit Vector	11
Vector Cross Product	12
Matrices	12
Matrix Multiplication	13
Rotation Matrices	13
Derivatives	15
Differential Equations	18
Summary	19

CHAPTER 3	Basic Newtonian Mechanics	21
	A Short Biography of Sir Isaac Newton	22
	Newton's First Law of Motion: Inertia	22
	Newton's Second Law of Motion: Force, Mass, and Acceleration	23
	Newton's Third Law of Motion: Equal and Opposite Forces	24
	Force Vector	24
	Types of Forces	25
	Gravitational Force	25
	Friction	31
	Centripetal Force	38
	Force Balances and Force Diagrams	39
	Work	41
	Energy	43
	Kinetic Energy	43
	Potential Energy	44
	Other Forms of Energy	44
	Conservation of Energy	45
	Power	45
	Summary	46
	Answers to Exercises	46
 CHAPTER 4	 Basic Kinematics	 49
	Translational Motion	49
	The Relationship Between Force, Acceleration, Velocity, and Location	50
	Solving the Translational Equations of Motion	51
	Beanbag Game	53
	Solving Ordinary Differential Equations	55
	Rotational Motion	69
	Torque	71
	Torque and Angular Acceleration	72
	Rigid Body Motion	73
	Center of Mass	73
	Rigid Body Motion Coordinate Axes	75
	Rolling Motion	75
	Bowling Ball Kinematics	77
	Summary	79
	Answers to Exercises	80

CHAPTER 5	Projectiles	83
	Basic Concepts	84
	The Gravity-Only Model	84
	Force and Acceleration Equations	85
	Location Equations	86
	Finding the Time for a Projectile to Reach the Trajectory Apex	88
	The SimpleProjectile Class	88
	The Golf Game	91
	Summary: Gravity-Only Projectile Trajectory Model	97
	Aerodynamic Drag	98
	Basic Concepts	98
	Drag Coefficient	99
	Altitude Effects on Density	103
	Laminar and Turbulent Flow	103
	Adding Drag Effects to the Equations of Motion	104
	Force and Acceleration Equations	105
	Velocity Equations	106
	Location Equations	107
	Terminal Velocity	108
	Programming Drag Effects into the Projectile Trajectory Model	108
	Golf Game Version 2	111
	Summary: Adding Drag to the Projectile Trajectory Model	113
	Wind Effects	114
	Programming Wind Effects into the Projectile Trajectory Model	116
	Golf Game Version 3	119
	Summary: Adding Wind Effects to the Projectile Trajectory Model	122
	Spin Effects	122
	Magnus Force	123
	Programming Spin Effects into the Projectile Trajectory Model	125
	Golf Game Version 4	129
	Summary: Adding Spin Effects to the Projectile Trajectory Model	133

Details on Specific Types of Projectiles	134
Bullets	134
Cannonballs.....	135
Arrows	136
Summary	137
Answers to Exercises	138
 CHAPTER 6 Collisions	 139
Linear Momentum and Impulse	140
Conservation of Linear Momentum	141
Elastic and Inelastic Collisions	142
Two-Body Linear Collisions	143
Collisions with Immovable Objects.....	146
Linear Collision Simulator	146
General Two-Dimensional Collisions	149
A Paddle Game	153
Three-Dimensional Collisions	157
Determining Whether a Collision Occurs	157
Angular Momentum and Impulse	159
Collisions with Friction	160
Frictional Impulse.....	161
Modeling Two-Dimensional Oblique Collisions.....	162
Modeling Three-Dimensional Oblique Collisions.....	164
Summary	165
Answers to Exercises	165
 CHAPTER 7 Sports Simulations	 167
Golf	167
Equipment Specifications	168
Modeling the Club-Ball Impact	170
Modeling the Golf Ball in Flight.....	176
A Golf Game.....	178
Putting	184
Soccer	189
Equipment Specifications	190
Modeling the Impact of Ball and Foot.....	191
Modeling the Soccer Ball in Flight	191
Free-Kick Game	195

Basketball	199
Equipment Specifications	199
Modeling the Jump Shot	202
A Free-Throw Game	203
Baseball	204
Equipment Specifications	204
Modeling the Pitch	206
Modeling the Hit	207
Simulating Other Sports	208
Football	208
Hockey	209
Tennis	209
Summary	209
References	209

■ CHAPTER 8 **Cars and Motorcycles** 211

Cars	212
A Brief History of the Automobile	212
Basic Force Diagram	212
Engine Torque and Power	214
Gears and Wheel Torque	217
Gear Shifting	219
Manual and Automatic Transmissions	220
Aerodynamic Drag	220
Rolling Friction	221
Computing Acceleration and Velocity	222
Braking	226
A Car Simulator	227
Wheel Traction	236
Driving Around Curves	237
Modeling Car Crashes	239
Motorcycles	240
Turning a Motorcycle	241
Adding Sophisticated Effects to the Car or Motorcycle Models	242
Summary	242
References	243

CHAPTER 9	Boats and Things That Float	245
	Some Nautical Terminology	245
	Boat Hull Types	246
	Basic Force Diagram	247
	Buoyancy	248
	Buoyancy and Density	250
	Thrust	250
	Drive System Types	250
	Propeller Basics	251
	Thrust	253
	Drag	254
	Skin Friction Drag	255
	Form Drag	256
	Wave Drag	256
	Other Hydrodynamic Drag Components	257
	Determining the Wetted Area	257
	Aerodynamic Drag	258
	Modeling the Acceleration and Velocity of a Boat	258
	Speedboat Simulator	261
	Powerboat Turns	267
	Jet Skis	268
	Jet Drives	268
	Thrust and Drag	269
	The Physics of Sailing	269
	The Physics of Surfing	270
	Buoyancy and Balance	271
	The Physics of a Wave	272
	Catching a Wave	272
	Turning	272
	Summary	273
	Answers to Exercises	273
	References	274
CHAPTER 10	Airplanes	275
	Historical Stuff	276
	Airplane Terminology	276
	Basic Force Diagram	278

Lift	278
Airfoils	278
How Lift Is Created	279
Evaluating Airfoil Lift	280
Stall	282
Flaps	283
Center of Pressure	284
Thrust	285
Propeller Engines	285
Jet Engines	291
Drag	292
Skin Friction and Form Drag	292
Induced Drag	293
Total Drag Equation Revisited	294
Lift over Drag Ratio	295
Full-Body Aerodynamics	295
Turning	296
Aircraft Orientation	297
Takeoff	299
Landing	301
A Basic Flight Simulator	301
Trim and Stability	310
Moments	310
Trim	311
Stability	313
Stability and Trim	314
Dynamic Stability	315
Summary	316
Answer to Exercise	317
References	317

CHAPTER 11 Rockets and Missiles 319

A Brief History of Rockets	319
Some Rocket Terminology	321
Rocket Engine Types	321
Liquid-Cryogenic Engines	321
Solid-Propellant Engines	322
Liquid-Hypergolic Engines	322
Hybrid Engines	322
Nuclear Engines	322
Exotic Engines	322

General Force Diagram	323
Thrust	323
The Rocket Equation	324
Specific Impulse	325
Altitude Effects	326
Computing Atmospheric Pressure, Density, and Temperature ...	327
Gravity	330
Drag	331
Lift	333
Stability	333
Wind	333
A Rocket Simulator	334
Orbits	342
Circular Orbits	343
Other Types of Orbits	343
Escape Velocity	343
Using the Earth's Rotation	344
Payload to Orbit	344
Multistage Rockets	345
Missiles	347
Missile Guidance	347
Missile Specifications	348
Summary	349
References	349

CHAPTER 12 The Physics of Solids

Ballistic Impacts	351
What Happens During a Ballistic Impact	352
Energy Considerations	352
Steel Armor	353
Body Armor	354
Animal Skin Penetration	356
Momentum	356
Body Wounds	357
Heat Conduction	358
Fourier's Law	359
The Heat Conduction Equation	360
Solving the Heat Conduction Equation	361
The Gas Tank Simulator	364

Summary	369
References	370

CHAPTER 13 Explosions 371

Some Explosion Terminology	372
Explosion Basics	372
Explosive Types	373
Gunpowder	373
Nitroglycerine	373
Dynamite	373
TNT	374
Ammonium Nitrate	374
C4	374
Blast Damage	375
TNT Explosion Model	376
Example: Computing the Blast Damage for a Soldier	
Standing by a Window	378
Blast Damage from Other Types of Explosives	378
Other Explosion Models	379
TNT Equivalence of Bombs	379
Fragmentation Devices	380
Nuclear Explosions	381
Summary	382
References	383

CHAPTER 14 Lasers 385

A Brief History of the Laser	385
An Introduction to Atoms	386
How Lasers Work	389
Types of Lasers	391
Gas Lasers	391
Dye Lasers	392
Solid-State Lasers	392
Semiconductor Lasers	392
Pulsed and Continuous Wave Lasers	393
Military Lasers	393
ABL	393
SBL	394
HELEX	395

Laser Damage	395
Laser Simulation	397
Creating Your Own Laser Systems	400
Laser Visual Effects	401
Summary	401
References	402
 ■ CHAPTER 15 Probabilistic and Monte Carlo Simulations	403
Random Number Generation	404
Probability Functions	405
Gaussian Distribution	408
Other Probability Functions	410
Monte Carlo Simulations	410
Using Monte Carlo Methods to Simulate Crowd Behavior	411
Using Monte Carlo Methods to Estimate Functions	418
Summary	421
References	421
 ■ INDEX	423

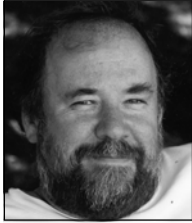
About the Author



GRANT PALMER works for the ELORET Corporation, an engineering consulting company under contract to the NASA Ames Research Center in Moffett Field, CA. Grant develops computer programs to simulate the fluid dynamics, thermodynamics, and gas chemistry of spacecraft reentering planetary atmospheres. Grant has authored or coauthored eight books on computer programming, including *Beginning C# Objects* and *Java Programmer's Reference*.

Grant lives in Bothell, WA, with his wife, Lisa, and sons, Jackson and Zachary. He has a dog, Bailey, and cat, Callie, who recently decided that she should start living in Grant's house.

About the Technical Reviewers



ALAN MCLEOD graduated from MIT with a doctorate in materials engineering, having previously gained bachelor and master's degrees in metallurgical engineering from the University of Toronto. He then worked for Alcan International as a materials scientist. After several years in industry, he decided to follow his true passion and is now teaching programming to first- and second-year engineering students as a professor and professional engineer at Queen's University and the Royal Military College in Kingston, Ontario. He also runs his own contract programming company, CA Technical Consulting.



JACK PARK gives pretty good google. To do that, he remains very active developing software in the open source arena. His projects have included NexistWiki, an experimental platform that combines topic maps, issue-based information systems, and storytelling, together with wiki behaviors and weblogs. He produced, with technical editorial help from Sam Hunting, and with authors drawn from all over the planet, the book *XML Topic Maps: Creating and Using Topic Maps for the Web* (Addison-Wesley, 2002). In a former life, he built windmills and solar heaters, and created the book *The Wind Power Book* (Cheshire-Van Nostrand, 1981). He is presently employed as a research scientist with SRI International.

Acknowledgments

As anyone who writes a book knows, a lot of people have to work very hard to bring a book to print. I would like to thank my lead editor, Tony Davis, for always being in my corner during the writing of this book and for helping to formulate the vision for what this book would become. I would also like to thank the project manager, Laura Brown, for keeping this book on track and on schedule and for making sure that things didn't fall through the cracks. The entire production staff at Apress, Ami Knox, Kelly Winkvist, and Glenn Munlawin, did a first-rate job throughout this project and always did their best to make the book the way that I wanted it to be.

I would like to thank the two technical reviewers for the book, Alan McLeod and Jack Park. I put them through quite a lot during the course of this book, and I think they both really earned their money on this project. Their insightful, constructive, and sometimes biting comments greatly improved the quality of the final product. Finally, as always, I would like to thank my wife, Lisa, and my sons, Jackson and Zachary, for being patient with me for "living" in my office the past six months while I was writing this book.

Introduction

Welcome to the wonderful world of physics. You may be thinking that “wonderful” and “physics” don’t belong in the same sentence. Once you start to learn a little physics, however, you will find that it is a really interesting and rewarding subject because you will begin to gain an understanding of how things work. You will learn, for example, why a golf ball hooks or slices. You will also learn that physics really isn’t as hard as you might have thought it was. Just a few basic concepts are pretty much all you need to start adding realistic physics into your game programs.

I’ve been a computer programmer and aerospace engineer working for NASA for the past 20 years. I really like my job, but one of the things I don’t like is when I have to research the physical model for one of the programs I’m writing. Inevitably the references I find are incomplete. Either they don’t fully explain things or they “forget” to include key elements of the model. Then I have to try to find another resource to fill in the missing pieces. This process can be very frustrating and time consuming.

What I have tried to do with this book is to spare you as a game programmer from this torturous process. This book is intended to give you all the information you need to install realistic physics into your game programs. This book will be *the* resource that you will turn to for all of your physics needs. For example, if you want to create a car race game, this book will give you not only the basic acceleration equations for a car, but also the drag coefficient for a sportscar and the equations that govern skidding and turning. You won’t have to endlessly search the Internet or dig up another book to fill in the missing pieces.

Who This Book Is For

As you probably guessed from the title, this book is focuses on the physics needed by game programmers in order to add realism to their games. You don’t need to have any background in physics to make use of this book. You don’t need to have an extensive background in math for that matter either. As long as you know basic high-school-level algebra and trigonometry, you will be able to understand the physical models that are presented. This book might have been titled “Basic Physics for Game Programmers” because it focuses on the big picture. You will learn the fundamental physics concepts needed to incorporate physics-based realism into your games with the least amount of pain and suffering on your part. This book does not get bogged down in hopelessly complicated mathematical formulas that would have only a small effect on your game programs.

What This Book Is Not

This book primarily concerns itself with physics and is not a game programming book per se. There will be nothing in this book on game theory or how to render images on the screen. Many other good books on those elements of game programming are available, including *Advanced Java Game Programming* by David Croft (Apress, 2004). This book also focuses on fundamental physics and generally won't go into really advanced topics. For example, equations are presented that will let you create a realistic flight simulator, but advanced subjects like modeling the dynamic stability of an airplane in flight are not covered.

How the Book Is Divided

This book is organized into two main sections. The first six chapters will cover basic concepts, subjects like Newtonian mechanics, kinematics, and collisions. These topics will be applicable to a wide range of game programming situations. The first six chapters will provide you with the tools for your physics toolbox. Chapters 7 through 15 take the basic concepts and apply them to specific physics models. You will learn how to model cars, planes, boats, and rockets. You will find chapters on developing sports simulations and on how to model explosions, lasers, and projectile penetrations. The later chapters will give you all the information you need to install physics-based realism into your games.

A Note on the Sample Programs

Just about every chapter contains one or more sample games that demonstrate how to code up the physics models presented in the chapter. Because this book focuses on physics, the graphics in the GUIs for the sample games are pretty basic—usually just two-dimensional figures and cartoons. While the graphics are primitive, the physics built into the sample games is real and will realistically depict whatever the game is intended to model.

Game programs can be written in many different programming languages. To keep things consistent throughout the book, the sample programs shown in this book are all written in Java, but the code that implements the physical models should be easily recognizable to anyone with a C, C++, or C# programming background. There are lots of comments throughout the programs, and the code has been made to be as readable as possible. For those of you who prefer to program in C or C#, you can download versions of all of the sample programs written in those languages from the Apress website at www.apress.com.

A Note on the Exercises

Many of the programs include exercises that test the reader's knowledge of the concepts that are covered in the chapter. Usually, the exercises go a little bit beyond the material that is presented in the chapter and are a good way to test your general understanding of the subject matter. The exercises were intended for students who are using this book as part of their course, but other readers are encouraged to try the exercises as well. Answers for the exercises are always provided at the end of the chapter in which they are presented.

Tidbits

Physics really is an interesting subject, and it is one that has been developing over thousands of years. The history of physics is full of many fascinating and quirky characters. Scattered throughout the book are Tidbit sections that provide historical trivia and other interesting information about the subjects being covered in the chapter. Did you ever wonder what they used to make golf balls out of in the old days? Well, there is a tidbit that will tell you.

Contact Me

If you have any questions or comments about the book, you can send me an e-mail at grantepalmer@msn.com. Tell me what you like about the book, or things that you think I could have done better. Also let me know if there are any subjects that you would like to see in future editions of the book.