

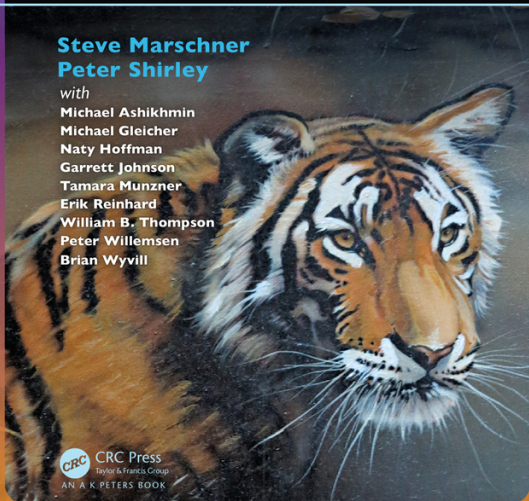
Fundamentals of Computer Graphics

FOURTH EDITION

Steve Marschner
Peter Shirley

with

Michael Ashikhmin
Michael Gleicher
Naty Hoffman
Garrett Johnson
Tamara Munzner
Erik Reinhard
William B. Thompson
Peter Willemsen
Brian Wyvill



CRC Press

Taylor & Francis Group

AN A K PETERS BOOK

Fundamentals *of* Computer Graphics

F O U R T H E D I T I O N

Fundamentals *of* Computer Graphics

F O U R T H E D I T I O N

Steve Marschner

Cornell University

Peter Shirley

Purity, LLC

with

Michael Ashikhmin
Michael Gleicher
Naty Hoffman
Garrett Johnson
Tamara Munzner
Erik Reinhard
William B. Thompson
Peter Willemsen
Brian Wyvill



CRC Press

Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business
AN A K PETERS BOOK

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2016 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works
Version Date: 20151012

International Standard Book Number-13: 978-1-4822-2941-7 (eBook - PDF)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>
and the CRC Press Web site at
<http://www.crcpress.com>

Contents

Preface	xi
1 Introduction	1
1.1 Graphics Areas	2
1.2 Major Applications	3
1.3 Graphics APIs	4
1.4 Graphics Pipeline	4
1.5 Numerical Issues	5
1.6 Efficiency	7
1.7 Designing and Coding Graphics Programs	8
2 Miscellaneous Math	13
2.1 Sets and Mappings	13
2.2 Solving Quadratic Equations	17
2.3 Trigonometry	18
2.4 Vectors	21
2.5 Curves and Surfaces	30
2.6 Linear Interpolation	44
2.7 Triangles	44
3 Raster Images	53
3.1 Raster Devices	54
3.2 Images, Pixels, and Geometry	59
3.3 RGB Color	64
3.4 Alpha Compositing	65
4 Ray Tracing	69
4.1 The Basic Ray-Tracing Algorithm	70
4.2 Perspective	71
4.3 Computing Viewing Rays	73
4.4 Ray-Object Intersection	76
4.5 Shading	81



4.6	A Ray-Tracing Program	84
4.7	Shadows	86
4.8	Ideal Specular Reflection	87
4.9	Historical Notes	87
5	Linear Algebra	89
5.1	Determinants	89
5.2	Matrices	91
5.3	Computing with Matrices and Determinants	96
5.4	Eigenvalues and Matrix Diagonalization	101
6	Transformation Matrices	109
6.1	2D Linear Transformations	109
6.2	3D Linear Transformations	123
6.3	Translation and Affine Transformations	128
6.4	Inverses of Transformation Matrices	132
6.5	Coordinate Transformations	133
7	Viewing	139
7.1	Viewing Transformations	140
7.2	Projective Transformations	146
7.3	Perspective Projection	149
7.4	Some Properties of the Perspective Transform	153
7.5	Field-of-View	154
8	The Graphics Pipeline	159
8.1	Rasterization	160
8.2	Operations Before and After Rasterization	171
8.3	Simple Antialiasing	177
8.4	Culling Primitives for Efficiency	179
9	Signal Processing	183
9.1	Digital Audio: Sampling in 1D	184
9.2	Convolution	187
9.3	Convolution Filters	201
9.4	Signal Processing for Images	208
9.5	Sampling Theory	217



10 Surface Shading	233
10.1 Diffuse Shading	233
10.2 Phong Shading	236
10.3 Artistic Shading	239
11 Texture Mapping	243
11.1 Looking Up Texture Values	244
11.2 Texture Coordinate Functions	246
11.3 Antialiasing Texture Lookups	260
11.4 Applications of Texture Mapping	267
11.5 Procedural 3D Textures	273
12 Data Structures for Graphics	281
12.1 Triangle Meshes	282
12.2 Scene Graphs	295
12.3 Spatial Data Structures	297
12.4 BSP Trees for Visibility	309
12.5 Tiling Multidimensional Arrays	317
13 More Ray Tracing	323
13.1 Transparency and Refraction	324
13.2 Instancing	327
13.3 Constructive Solid Geometry	328
13.4 Distribution Ray Tracing	329
14 Sampling	337
14.1 Integration	337
14.2 Continuous Probability	342
14.3 Monte Carlo Integration	346
14.4 Choosing Random Points	349
15 Curves	359
15.1 Curves	359
15.2 Curve Properties	365
15.3 Polynomial Pieces	368
15.4 Putting Pieces Together	375
15.5 Cubics	378
15.6 Approximating Curves	385
15.7 Summary	402

16 Computer Animation	405
16.1 Principles of Animation	406
16.2 Keyframing	410
16.3 Deformations	418
16.4 Character Animation	419
16.5 Physics-Based Animation	426
16.6 Procedural Techniques	428
16.7 Groups of Objects	431
17 Using Graphics Hardware	437
17.1 Hardware Overview	437
17.2 What Is Graphics Hardware	437
17.3 Heterogeneous Multiprocessing	439
17.4 Graphics Hardware Programming: Buffers, State, and Shaders	441
17.5 State Machine	443
17.6 Basic OpenGL Application Layout	444
17.7 Geometry	445
17.8 A First Look at Shaders	447
17.9 Vertex Buffer Objects	450
17.10 Vertex Array Objects	452
17.11 Transformation Matrices	455
17.12 Shading with Per-Vertex Attributes	457
17.13 Shading in the Fragment Processor	461
17.14 Meshes and Instancing	467
17.15 Texture Objects	469
17.16 Object-Oriented Design for Graphics Hardware Programming	475
17.17 Continued Learning	476
18 Light	479
18.1 Radiometry	479
18.2 Transport Equation	488
18.3 Photometry	489
19 Color	493
19.1 Colorimetry	495
19.2 Color Spaces	504
19.3 Chromatic Adaptation	510
19.4 Color Appearance	514



20 Visual Perception 515

20.1 Vision Science	516
20.2 Visual Sensitivity	517
20.3 Spatial Vision	534
20.4 Objects, Locations, and Events	547
20.5 Picture Perception	556

21 Tone Reproduction 559

21.1 Classification	562
21.2 Dynamic Range	563
21.3 Color	565
21.4 Image Formation	567
21.5 Frequency-Based Operators	567
21.6 Gradient-Domain Operators	569
21.7 Spatial Operators	570
21.8 Division	572
21.9 Sigmoids	573
21.10 Other Approaches	578
21.11 Night Tonemapping	581
21.12 Discussion	582

22 Implicit Modeling 585

22.1 Implicit Functions, Skeletal Primitives, and Summation	
Blending	586
22.2 Rendering	594
22.3 Space Partitioning	595
22.4 More on Blending	601
22.5 Constructive Solid Geometry	602
22.6 Warping	604
22.7 Precise Contact Modeling	606
22.8 The BlobTree	608
22.9 Interactive Implicit Modeling Systems	610

23 Global Illumination 613

23.1 Particle Tracing for Lambertian Scenes	614
23.2 Path Tracing	617
23.3 Accurate Direct Lighting	619

