Real-Time Rendering
Fourth Edition

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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

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Printed on acid-free paper

International Standard Book Number-13: 978-1-1386-2700-0 (Hardback)

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Library of Congress Cataloging-in-Publication Data

Names: Möller, Tomas, 1971- author.
Title: Real-time rendering / Tomas Akenine-Möller, Eric Haines, Naty Hoffman, Angelo Pesce, Michał Iwanicki, Sébastien Hillaire
Description: Fourth edition. | Boca Raton : Taylor & Francis, CRC Press, 2018.
Identifiers: LCCN 2018009546 | ISBN 9781138627000 (hardback : alk. paper)
Subjects: LCSH: Computer graphics. | Real-time data processing. | Rendering (Computer graphics)
Classification: LCC T385 .M635 2018 | DDC 006.6/773--dc23
LC record available at https://lccn.loc.gov/2018009546

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

Dedicated to Eva, Felix, and Elina
T. A-M.

Dedicated to Cathy, Ryan, and Evan
E. H.

Dedicated to Dorit, Karen, and Daniel
N. H.

Dedicated to Fei, Clelia, and Alberto
A. P.

Dedicated to Aneta and Weronika
M. I.

Dedicated to Stéphanie and Svea
S. H.

Contents

Preface

"Things have not changed *that* much in the past eight years," was our thought entering into this fourth edition. "How hard could it be to update the book?" A year and a half later, and with three more experts recruited, our task is done. We could probably spend another year editing and elaborating, at which time there would be easily a hundred more articles and presentations to fold in. As a data point, we made a Google Doc of references that is more than 170 pages long, with about 20 references and related notes on each page. Some references we cite could and do each take up a full section in some other book. A few of our chapters, such as that on shadows, have entire books dedicated to their subjects. While creating more work for us, this wealth of information is good news for practitioners. We will often point to these primary sources, as they offer much more detail than appropriate here.

This book is about algorithms that create synthetic images fast enough that the viewer can interact with a virtual environment. We have focused on three-dimensional rendering and, to a limited extent, on the mechanics of user interaction. Modeling, animation, and many other areas are important to the process of making a real-time application, but these topics are beyond the scope of this book.

We expect you to have some basic understanding of computer graphics before reading this book, as well as knowledge of computer science and programming. We also focus on algorithms, not APIs. Many texts are available on these other subjects. If some section does lose you, skim on through or look at the references. We believe that the most valuable service we can provide you is a realization of what you yet do not know about—a basic kernel of an idea, a sense of what others have discovered about it, and ways to learn more, if you wish.

We make a point of referencing relevant material as possible, as well as providing a summary of further reading and resources at the end of most chapters. In prior editions we cited nearly everything we felt had relevant information. Here we are more a guidebook than an encyclopedia, as the field has far outgrown exhaustive (and exhausting) lists of all possible variations of a given technique. We believe you are better served by describing only a few representative schemes of many, by replacing original sources with newer, broader overviews, and by relying on you, the reader, to pursue more information from the references cited.

Most of these sources are but a mouse click away; see realtimerendering.com for the list of links to references in the bibliography. Even if you have only a passing interest in a topic, consider taking a little time to look at the related references, if for nothing else than to see some of the fantastic images presented. Our website also contains links to resources, tutorials, demonstration programs, code samples, software libraries, book corrections, and more.

Our true goal and guiding light while writing this book was simple. We wanted to write a book that we wished we had owned when we had started out, a book that both was unified yet also included details and references not found in introductory texts. We hope that you will find this book, our view of the world, of use in your travels.

Acknowledgments for the Fourth Edition

We are not experts in everything, by any stretch of the imagination, nor perfect writers. Many, many people's responses and reviews improved this edition immeasurably, saving us from our own ignorance or inattention. As but one example, when we asked around for advice on what to cover in the area of virtual reality, Johannes Van Waveren (who did not know any of us) instantly responded with a wonderfully detailed outline of topics, which formed the basis for that chapter. These kind acts by computer graphics professionals were some of the great pleasures in writing this book. One person is of particular note: Patrick Cozzi did a yeoman's job, reviewing every chapter in the book. We are grateful to the many people who helped us along the way with this edition. We could write a sentence or three about everyone who helped us along the way, but this would push us further past our book-breaking page limit.

To all the rest, in our hearts we give our appreciation and thanks to you: Sebastian Aaltonen, Johan Andersson, Magnus Andersson, Ulf Assarsson, Dan Baker, Chad Barb, Rasmus Barringer, Michal Bastien, Louis Bavoil, Michael Beale, Adrian Bentley, Ashwin Bhat, Antoine Bouthors, Wade Brainerd, Waylon Brinck, Ryan Brucks, Eric Bruneton, Valentin de Bruyn, Ben Burbank, Brent Burley, Ignacio Castaño, Cem Cebenoyan, Mark Cerny, Matthaeus Chajdas, Danny Chan, Rob Cook, Jean-Luc Corenthin, Adrian Courrèges, Cyril Crassin, Zhihao Cui, Kuba Cupisz, Robert Cupisz, Michal Drobot, Wolfgang Engel, Eugene d'Eon, Matej Drame, Michal Drobot, Alex Evans, Cass Everitt, Kayvon Fatahalian, Adam Finkelstein, Kurt Fleischer, Tim Foley, Tom Forsyth, Guillaume François, Daniel Girardeau-Montaut, Olga Gocmen, Marcin Gollent, Ben Golus, Carlos Gonzalez-Ochoa, Judah Graham, Simon Green, Dirk Gregorius, Larry Gritz, Andrew Hamilton, Earl Hammon, Jr., Jon Harada, Jon Hasselgren, Aaron Hertzmann, Stephen Hill, Rama Hoetzlein, Nicolas Holzschuch, Liwen Hu, John "Spike" Hughes, Ben Humberston, Warren Hunt, Andrew Hurley, John Hutchinson, Milan Ikits, Jon Jansen, Jorge Jimenez, Anton Kaplanyan, Gökhan Karadayi, Brian Karis, Nicolas Kasyan, Alexander Keller, Brano Kemen, Emmett Kilgariff, Byumjin Kim, Chris King, Joe Michael Kniss, Manuel Kraemer, Anders Wang Kristensen, Christopher Kulla, Edan Kwan, Chris Landreth, David Larsson, Andrew Lauritzen, Aaron Lefohn, Eric Lengyel, David Li, Ulrik Lindahl, Edward Liu, Ignacio Llamas, Dulce Isis Segarra López, David Luebke, Patrick Lundell, Miles Macklin, Dzmitry Malyshau, Sam Martin, Morgan McGuire, Brian McIntyre, James McLaren, Mariano Merchante, Arne Meyer, Sergiy Migdalskiy, Kenny Mitchell, Gregory Mitrano, Adam Moravanszky, Jacob Munkberg, Kensaku Nakata, Srinivasa G. Narasimhan, David Neubelt, Fabrice Neyret, Jane Ng, Kasper Høy Nielsen, Matthias

Nießner, Jim Nilsson, Reza Nourai, Chris Oat, Ola Olsson, Rafael Orozco, Bryan Pardilla, Steve Parker, Ankit Patel, Jasmin Patry, Jan Pechenik, Emil Persson, Marc Petit, Matt Pettineo, Agnieszka Piechnik, Jerome Platteaux, Aras Pranckevičius, Elinor Quittner, Silvia Rasheva, Nathaniel Reed, Philip Rideout, Jon Rocatis, Robert Runesson, Marco Salvi, Nicolas Savva, Andrew Schneider, Michael Schneider, Markus Schuetz, Jeremy Selan, Tarek Sherif, Peter Shirley, Peter Sikachev, Peter-Pike Sloan, Ashley Vaughan Smith, Rys Sommefeldt, Edvard Sørgård, Tiago Sousa, Tomasz Stachowiak, Nick Stam, Lee Stemkoski, Jonathan Stone, Kier Storey, Jacob Ström, Filip Strugar, Pierre Terdiman, Aaron Thibault, Nicolas Thibieroz, Robert Toth, Thatcher Ulrich, Mauricio Vives, Alex Vlachos, Evan Wallace, Ian Webster, Nick Whiting, Brandon Whitley, Mattias Widmark, Graham Wihlidal, Michael Wimmer, Daniel Wright, Bart Wroński, Chris Wyman, Ke Xu, Cem Yuksel, and Egor Yusov. We thank you for your time and effort, selflessly offered and gratefully received.

Finally, we want to thank the people at Taylor & Francis for all their efforts, in particular Rick Adams, for getting us going and guiding us along the way, Jessica Vega and Michele Dimont, for their efficient editorial work, and Charlotte Byrnes, for her superb copyediting.

Tomas Akenine-Möller
Eric Haines
Naty Hoffman
Angelo Pesce
Michał Iwanicki
Sébastien Hillaire
February 2018

Acknowledgments for the Third Edition

Special thanks go out to a number of people who went out of their way to provide us with help. First, our graphics architecture case studies would not have been anywhere as good without the extensive and generous cooperation we received from the companies making the hardware. Many thanks to Edvard Sørgard, Borgar Ljosland, Dave Shreiner, and Jørn Nystad at ARM for providing details about their Mali 200 architecture. Thanks also to Michael Dougherty at Microsoft, who provided extremely valuable help with the Xbox 360 section. Masaaki Oka at Sony Computer Entertainment provided his own technical review of the PLAYSTATION® 3 system case study, while also serving as the liaison with the Cell Broadband Engine™ and RSX® developers for their reviews.

In answering a seemingly endless stream of questions, fact-checking numerous passages, and providing many screenshots, Natalya Tatarchuk of ATI/AMD went well beyond the call of duty in helping us out. In addition to responding to our usual requests for information and clarification, Wolfgang Engel was extremely helpful in providing us with articles from the upcoming *ShaderX*^{6} book and copies of the difficult-toobtain $ShaderX^2$ books [427, 428], now available online for free. Ignacio Castaño at NVIDIA provided us with valuable support and contacts, going so far as to rework a refractory demo so we could get just the right screenshot.

The chapter reviewers provided an invaluable service to us. They suggested numerous improvements and provided additional insights, helping us immeasurably. In alphabetical order they are: Michael Ashikhmin, Dan Baker, Willem de Boer, Ben Diamand, Ben Discoe, Amir Ebrahimi, Christer Ericson, Michael Gleicher, Manny Ko, Wallace Lages, Thomas Larsson, Grégory Massal, Ville Miettinen, Mike Ramsey, Scott Schaefer, Vincent Scheib, Peter Shirley, K.R. Subramanian, Mauricio Vives, and Hector Yee.

We also had a number of reviewers help us on specific sections. Our thanks go out to Matt Bronder, Christine DeNezza, Frank Fox, Jon Hasselgren, Pete Isensee, Andrew Lauritzen, Morgan McGuire, Jacob Munkberg, Manuel M. Oliveira, Aurelio Reis, Peter-Pike Sloan, Jim Tilander, and Scott Whitman.

We particularly thank Rex Crowle, Kareem Ettouney, and Francis Pang from Media Molecule for their considerable help in providing fantastic imagery and layout concepts for the cover design.

Many people helped us out in other ways, such as answering questions and providing screenshots. Many gave significant amounts of time and effort, for which we thank you. Listed alphabetically: Paulo Abreu, Timo Aila, Johan Andersson, Andreas Bærentzen, Louis Bavoil, Jim Blinn, Jaime Borasi, Per Christensen, Patrick Conran, Rob Cook, Erwin Coumans, Leo Cubbin, Richard Daniels, Mark DeLoura, Tony DeRose, Andreas Dietrich, Michael Dougherty, Bryan Dudash, Alex Evans, Cass Everitt, Randy Fernando, Jim Ferwerda, Chris Ford, Tom Forsyth, Sam Glassenberg, Robin Green, Ned Greene, Larry Gritz, Joakim Grundwall, Mark Harris, Ted Himlan, Jack Hoxley, John "Spike" Hughes, Ladislav Kavan, Alicia Kim, Gary King, Chris Lambert, Jeff Lander, Daniel Leaver, Eric Lengyel, Jennifer Liu, Brandon Lloyd, Charles Loop, David Luebke, Jonathan Maïm, Jason Mitchell, Martin Mittring, Nathan Monteleone, Gabe Newell, Hubert Nguyen, Petri Nordlund, Mike Pan, Ivan Pedersen, Matt Pharr, Fabio Policarpo, Aras Pranckevičius, Siobhan Reddy, Dirk Reiners, Christof Rezk-Salama, Eric Risser, Marcus Roth, Holly Rushmeier, Elan Ruskin, Marco Salvi, Daniel Scherzer, Kyle Shubel, Philipp Slusallek, Torbjörn Söderman, Tim Sweeney, Ben Trumbore, Michal Valient, Mark Valledor, Carsten Wenzel, Steve Westin, Chris Wyman, Cem Yuksel, Billy Zelsnack, Fan Zhang, and Renaldas Zioma.

We also thank many others who responded to our queries on public forums such as GD Algorithms. Readers who took the time to send us corrections have also been a great help. It is this supportive attitude that is one of the pleasures of working in this field.

As we have come to expect, the cheerful competence of the people at A K Peters made the publishing part of the process much easier. For this wonderful support, we thank you all.

On a personal note, Tomas would like to thank his son Felix and daughter Elina for making him understand (again) just how fun it can be to play computer games (on the Wii), instead of just looking at the graphics, and needless to say, his beautiful wife Eva…

Eric would also like to thank his sons Ryan and Evan for their tireless efforts in finding cool game demos and screenshots, and his wife Cathy for helping him survive it all.

Naty would like to thank his daughter Karen and son Daniel for their forbearance when writing took precedence over piggyback rides, and his wife Dorit for her constant encouragement and support.

Tomas Akenine-Möller
Eric Haines
Naty Hoffman
March 2008

Acknowledgments for the Second Edition

One of the most agreeable aspects of writing this second edition has been working with people and receiving their help. Despite their own pressing deadlines and concerns, many people gave us significant amounts of their time to improve this book. We would particularly like to thank the major reviewers. They are, listed alphabetically: Michael Abrash, Ian Ashdown, Ulf Assarsson, Chris Brennan, Sébastien Dominé, David Eberly, Cass Everitt, Tommy Fortes, Evan Hart, Greg James, Jan Kautz, Alexander Keller, Mark Kilgard, Adam Lake, Paul Lalonde, Thomas Larsson, Dean Macri, Carl Marshall, Jason L. Mitchell, Kasper Høy Nielsen, Jon Paul Schelter, Jacob Ström, Nick Triantos, Joe Warren, Michael Wimmer, and Peter Wonka. Of these, we wish to single out Cass Everitt at NVIDIA and Jason L. Mitchell at ATI Technologies for spending large amounts of time and effort in getting us the resources we needed. Our thanks also go out to Wolfgang Engel for freely sharing the contents of his upcoming book, *ShaderX* [426], so that we could make this edition as current as possible.

From discussing their work with us, to providing images or other resources, to writing reviews of sections of the book, many others helped in creating this edition. They all have our gratitude. These people include: Jason Ang, Haim Barad, Jules Bloomenthal, Jonathan Blow, Chas. Boyd, John Brooks, Cem Cebenoyan, Per Christensen, Hamilton Chu, Michael Cohen, Daniel Cohen-Or, Matt Craighead, Paul Debevec, Joe Demers, Walt Donovan, Howard Dortch, Mark Duchaineau, Phil Dutré, Dave Eberle, Gerald Farin, Simon Fenney, Randy Fernando, Jim Ferwerda, Nickson Fong, Tom Forsyth, Piero Foscari, Laura Fryer, Markus Giegl, Peter Glaskowsky, Andrew Glassner, Amy Gooch, Bruce Gooch, Simon Green, Ned Greene, Larry Gritz, Joakim Grundwall, Juan Guardado, Pat Hanrahan, Mark Harris, Michael Herf, Carsten Hess, Rich Hilmer, Kenneth Hoff III, Naty Hoffman, Nick Holliman, Hugues Hoppe, Heather Horne, Tom Hubina, Richard Huddy, Adam James, Kaveh Kardan, Paul Keller, David

Kirk, Alex Klimovitski, Jason Knipe, Jeff Lander, Marc Levoy, J.P. Lewis, Ming Lin, Adrian Lopez, Michael McCool, Doug McNabb, Stan Melax, Ville Miettinen, Kenny Mitchell, Steve Morein, Henry Moreton, Jerris Mungai, Jim Napier, George Ngo, Hubert Nguyen, Tito Pagán, Jörg Peters, Tom Porter, Emil Praun, Kekoa Proudfoot, Bernd Raabe, Ravi Ramamoorthi, Ashutosh Rege, Szymon Rusinkiewicz, Chris Seitz, Carlo Séquin, Jonathan Shade, Brian Smits, John Spitzer, Wolfgang Straßer, Wolfgang Stürzlinger, Philip Taylor, Pierre Terdiman, Nicolas Thibieroz, Jack Tumblin, Fredrik Ulfves, Thatcher Ulrich, Steve Upstill, Alex Vlachos, Ingo Wald, Ben Watson, Steve Westin, Dan Wexler, Matthias Wloka, Peter Woytiuk, David Wu, Garrett Young, Borut Zalik, Harold Zatz, Hansong Zhang, and Denis Zorin. We also wish to thank the journal *ACM Transactions on Graphics* for providing a mirror website for this book.

Alice and Klaus Peters, our production manager Ariel Jaffee, our editor Heather Holcombe, our copyeditor Michelle M. Richards, and the rest of the staff at A K Peters have done a wonderful job making this book the best possible. Our thanks to all of you.

Finally, and most importantly, our deepest thanks go to our families for giving us the huge amounts of quiet time we have needed to complete this edition. Honestly, we never thought it would take this long!

Tomas Akenine-Möller
Eric Haines
May 2002

Acknowledgments for the First Edition

Many people helped in making this book. Some of the greatest contributions were made by those who reviewed parts of it. The reviewers willingly gave the benefit of their expertise, helping to significantly improve both content and style. We wish to thank (in alphabetical order) Thomas Barregren, Michael Cohen, Walt Donovan, Angus Dorbie, Michael Garland, Stefan Gottschalk, Ned Greene, Ming C. Lin, Jason L. Mitchell, Liang Peng, Keith Rule, Ken Shoemake, John Stone, Phil Taylor, Ben Trumbore, Jorrit Tyberghein, and Nick Wilt. We cannot thank you enough.

Many other people contributed their time and labor to this project. Some let us use images, others provided models, still others pointed out important resources or connected us with people who could help. In addition to the people listed above, we wish to acknowledge the help of Tony Barkans, Daniel Baum, Nelson Beebe, Curtis Beeson, Tor Berg, David Blythe, Chas. Boyd, Don Brittain, Ian Bullard, Javier Castellar, Satyan Coorg, Jason Della Rocca, Paul Diefenbach, Alyssa Donovan, Dave Eberly, Kells Elmquist, Stuart Feldman, Fred Fisher, Tom Forsyth, Marty Franz, Thomas Funkhouser, Andrew Glassner, Bruce Gooch, Larry Gritz, Robert Grzeszczuk, Paul Haeberli, Evan Hart, Paul Heckbert, Chris Hecker, Joachim Helenklaken, Hugues Hoppe, John Jack, Mark Kilgard, David Kirk, James Klosowski, Subodh Kumar, André LaMothe, Jeff Lander, Jens Larsson, Jed Lengyel, Fredrik Liliegren, David Luebke, Thomas Lundqvist, Tom McReynolds, Stan Melax, Don Mitchell, André Möller, Steve Molnar, Scott R. Nelson, Hubert Nguyen, Doug Rogers, Holly Rushmeier, Gernot Schaufler, Jonas Skeppstedt, Stephen Spencer, Per Stenström, Jacob Ström, Filippo Tampieri, Gary Tarolli, Ken Turkowski, Turner Whitted, Agata and Andrzej Wojaczek, Andrew Woo, Steve Worley, Brian Yen, Hans-Philip Zachau, Gabriel Zachmann, and Al Zimmerman. We also wish to thank the journal *ACM Transactions on Graphics* for providing a stable website for this book.

Alice and Klaus Peters and the staff at AK Peters, particularly Carolyn Artin and Sarah Gillis, have been instrumental in making this book a reality. To all of you, thanks.

Finally, our deepest thanks go to our families and friends for providing support throughout this incredible, sometimes grueling, often exhilarating process.

Tomas Möller
Eric Haines
March 1999

Chapter 1

Introduction

Real-time rendering is concerned with rapidly making images on the computer. It is the most highly interactive area of computer graphics. An image appears on the screen, the viewer acts or reacts, and this feedback affects what is generated next. This cycle of reaction and rendering happens at a rapid enough rate that the viewer does not see individual images, but rather becomes immersed in a dynamic process.

The rate at which images are displayed is measured in frames per second (FPS) or Hertz (Hz). At one frame per second, there is little sense of interactivity; the user is painfully aware of the arrival of each new image. At around 6 FPS, a sense of interactivity starts to grow. Video games aim for 30, 60, 72, or higher FPS; at these speeds the user focuses on action and reaction.

Movie projectors show frames at 24 FPS but use a shutter system to display each frame two to four times to avoid flicker. This *refresh rate* is separate from the display rate and is expressed in Hertz (Hz). A shutter that illuminates the frame three times has a 72 Hz refresh rate. LCD monitors also separate refresh rate from display rate.

Watching images appear on a screen at 24 FPS might be acceptable, but a higher rate is important for minimizing response time. As little as 15 milliseconds of temporal delay can slow and interfere with interaction [1849]. As an example, head-mounted displays for virtual reality often require 90 FPS to minimize latency.

There is more to real-time rendering than interactivity. If speed was the only criterion, any application that rapidly responded to user commands and drew anything on the screen would qualify. Rendering in real time normally means producing three-dimensional images.

Interactivity and some sense of connection to three-dimensional space are sufficient conditions for real-time rendering, but a third element has become a part of its definition: graphics acceleration hardware. Many consider the introduction of the 3Dfx Voodoo 1 card in 1996 the real beginning of consumer-level three-dimensional graphics [408]. With the rapid advances in this market, every computer, tablet, and mobile phone now comes with a graphics processor built in. Some excellent examples of the results of real-time rendering made possible by hardware acceleration are shown in Figures 1.1 and 1.2.

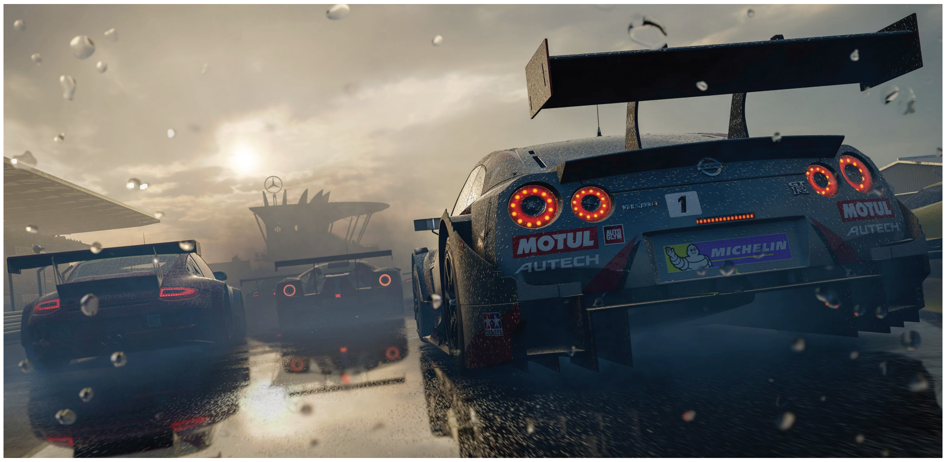

Figure 1.1. A shot from *Forza Motorsport 7. (Image courtesy of Turn 10 Studios, Microsoft.)*

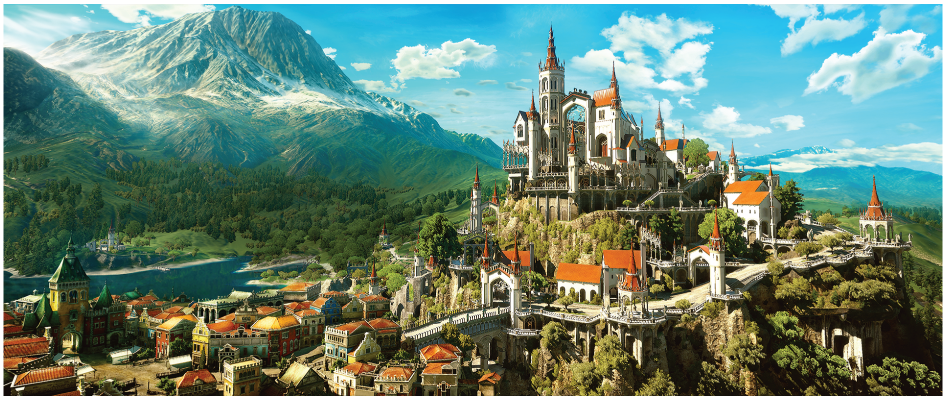

Figure 1.2. The city of Beauclair rendered in *The Witcher 3. (CD PROJEKT®, The Witcher® are registered trademarks of CD PROJEKT Capital Group. The Witcher game © CD PROJEKT S.A. Developed by CD PROJEKT S.A. All rights reserved. The Witcher game is based on the prose of Andrzej Sapkowski. All other copyrights and trademarks are the property of their respective owners.)*

Advances in graphics hardware have fueled an explosion of research in the field of interactive computer graphics. We will focus on providing methods to increase speed and improve image quality, while also describing the features and limitations of acceleration algorithms and graphics APIs. We will not be able to cover every topic in depth, so our goal is to present key concepts and terminology, explain the most robust and practical algorithms in the field, and provide pointers to the best places to go for more information. We hope our attempts to provide you with tools for understanding this field prove to be worth the time and effort you spend with our book.

1.1 Contents Overview

What follows is a brief overview of the chapters ahead.

Chapter 2, The Graphics Rendering Pipeline. The heart of real-time rendering is the set of steps that takes a scene description and converts it into something we can see.

Chapter 3, The Graphics Processing Unit. The modern GPU implements the stages of the rendering pipeline using a combination of fixed-function and programmable units.

Chapter 4, Transforms. Transforms are the basic tools for manipulating the position, orientation, size, and shape of objects and the location and view of the camera.

Chapter 5, Shading Basics. Discussion begins on the definition of materials and lights and their use in achieving the desired surface appearance, whether realistic or stylized. Other appearance-related topics are introduced, such as providing higher image quality through the use of antialiasing, transparency, and gamma correction.

Chapter 6, Texturing. One of the most powerful tools for real-time rendering is the ability to rapidly access and display images on surfaces. This process is called texturing, and there are a wide variety of methods for applying it.

Chapter 7, Shadows. Adding shadows to a scene increases both realism and comprehension. The more popular algorithms for computing shadows rapidly are presented.

Chapter 8, Light and Color. Before we perform physically based rendering, we first need to understand how to quantify light and color. And after our physical rendering process is done, we need to transform the resulting quantities into values for the display, accounting for the properties of the screen and viewing environment. Both topics are covered in this chapter.

Chapter 9, Physically Based Shading. We build an understanding of physically based shading models from the ground up. The chapter starts with the underlying physical phenomena, covers models for a variety of rendered materials, and ends with methods for blending materials together and filtering them to avoid aliasing and preserve surface appearance.

Chapter 10, Local Illumination. Algorithms for portraying more elaborate light sources are explored. Surface shading takes into account that light is emitted by physical objects, which have characteristic shapes.

Chapter 11, Global Illumination. Algorithms that simulate multiple interactions between the light and the scene further increase the realism of an image. We discuss ambient and directional occlusion and methods for rendering global illumination effects on diffuse and specular surfaces, as well as some promising unified approaches.

Chapter 12, Image-Space Effects. Graphics hardware is adept at performing image processing at rapid speeds. Image filtering and reprojection techniques are discussed first, then we survey several popular post-processing effects: lens flares, motion blur, and depth of field.

Chapter 13, Beyond Polygons. Triangles are not always the fastest or most realistic way to describe objects. Alternate representations based on using images, point clouds, voxels, and other sets of samples each have their advantages.

Chapter 14, Volumetric and Translucency Rendering. The focus here is the theory and practice of volumetric material representations and their interactions with light sources. The simulated phenomena range from large-scale atmospheric effects down to light scattering within thin hair fibers.

Chapter 15, Non-Photorealistic Rendering. Attempting to make a scene look realistic is only one way of rendering it. Other styles, such as cartoon shading and watercolor effects, are surveyed. Line and text generation techniques are also discussed.

Chapter 16, Polygonal Techniques. Geometric data comes from a wide range of sources, and sometimes requires modification to be rendered rapidly and well. The many facets of polygonal data representation and compression are presented.

Chapter 17, Curves and Curved Surfaces. More complex surface representations offer advantages such as being able to trade off between quality and rendering speed, more compact representation, and smooth surface generation.

Chapter 18, Pipeline Optimization. Once an application is running and uses efficient algorithms, it can be made even faster using various optimization techniques. Finding the bottleneck and deciding what to do about it is the theme here. Multiprocessing is also discussed.

Chapter 19, Acceleration Algorithms. After you make it go, make it go fast. Various forms of culling and level of detail rendering are covered.

Chapter 20, Efficient Shading. A large number of lights in a scene can slow performance considerably. Fully shading surface fragments before they are known to be visible is another source of wasted cycles. We explore a wide range of approaches to tackle these and other forms of inefficiency while shading.

Chapter 21, Virtual and Augmented Reality. These fields have particular challenges and techniques for efficiently producing realistic images at rapid and consistent rates.

Chapter 22, Intersection Test Methods. Intersection testing is important for rendering, user interaction, and collision detection. In-depth coverage is provided here for a wide range of the most efficient algorithms for common geometric intersection tests.

Chapter 23, Graphics Hardware. The focus here is on components such as color depth, framebuffers, and basic architecture types. A case study of representative GPUs is provided.

Chapter 24, The Future. Take a guess (we do).

Due to space constraints, we have made a chapter about Collision Detection free for download at realtimerendering.com, along with appendices on linear algebra and trigonometry.

1.2 Notation and Definitions

First, we shall explain the mathematical notation used in this book. For a more thorough explanation of many of the terms used in this section, and throughout this book, get our linear algebra appendix at realtimerendering.com.

1.2.1 Mathematical Notation

Table 1.1 summarizes most of the mathematical notation we will use. Some of the concepts will be described at some length here.

Note that there are some exceptions to the rules in the table, primarily shading equations using notation that is extremely well established in the literature, e.g., L for radiance, E for irradiance, and σ_s for scattering coefficient.

The angles and the scalars are taken from $\mathbb{R}$, i.e., they are real numbers. Vectors and points are denoted by bold lowercase letters, and the components are accessed as

$$\mathbf{v} = \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix},$$

that is, in column vector format, which is commonly used in the computer graphics world. At some places in the text we use (v_x, v_y, v_z) instead of the formally more correct $(v_x \;\; v_y \;\; v_z)^T$, since the former is easier to read.

Type	**Notation**	**Examples**
angle	lowercase Greek	$\alpha_i, \phi, \rho, \eta, \gamma_{242}, \theta$
scalar	lowercase italic	a, b, t, u_k, v, w_{ij}
vector or point	lowercase bold	$\mathbf{a}$,$\mathbf{u}$, $\mathbf{v}_s$ $\mathbf{h}(\rho)$, $\mathbf{h}_z$
matrix	capital bold	$\mathbf{T}(\mathbf{t})$, $\mathbf{X}$, $\mathbf{R}_x(\rho)$
plane	π: a vector and a scalar	$\pi : \mathbf{n} \cdot \mathbf{x} + d = 0$, $\pi_1 : \mathbf{n}_1 \cdot \mathbf{x} + d_1 = 0$
triangle	$\triangle$ 3 points	$\triangle\mathbf{v}_0\mathbf{v}_1\mathbf{v}_2$, $\triangle\mathbf{cba}$
line segment	two points	$\mathbf{uv}$, $\mathbf{a}_i\mathbf{b}_j$
geometric entity	capital italic	A_{OBB}, T, B_{AABB}

Table 1.1. Summary of the notation used in this book.

Using homogeneous notation, a coordinate is represented by four values $\mathbf{v} = (v_x \;\; v_y \;\; v_z \;\; v_w)^T$, where a vector is $\mathbf{v} = (v_x \;\; v_y \;\; v_z \;\; 0)^T$ and a point is $\mathbf{v} = (v_x \;\; v_y \;\; v_z \;\; 1)^T$. Sometimes we use only three-element vectors and points, but we try to avoid any ambiguity as to which type is being used. For matrix manipulations, it is extremely advantageous to have the same notation for vectors as for points. For more information, see Chapter 4 on transforms. In some algorithms, it will be convenient to use numeric indices instead of x, y, and z, for example $\mathbf{v} = (v_0 \;\; v_1 \;\; v_2)^T$. All these rules for vectors and points also hold for two-element vectors; in that case, we simply skip the last component of a three-element vector.

The matrix deserves a bit more explanation. The common sizes that will be used are 2×2, 3×3, and 4×4. We will review the manner of accessing a 3×3 matrix $\mathbf{M}$, and it is simple to extend this process to the other sizes. The (scalar) elements of $\mathbf{M}$ are denoted m_{ij}, $0 \leq (i, j) \leq 2$, where i denotes the row and j the column, as in Equation 1.1:

$$\mathbf{M} = \begin{pmatrix} m_{00} & m_{01} & m_{02} \\ m_{10} & m_{11} & m_{12} \\ m_{20} & m_{21} & m_{22} \end{pmatrix}. \tag{1.1}$$

The following notation, shown in Equation 1.2 for a 3×3 matrix, is used to isolate vectors from the matrix $\mathbf{M}$: $\mathbf{m}_{,j}$ represents the jth column vector and $\mathbf{m}_{i,}$ represents the ith row vector (in column vector form). As with vectors and points, indexing the column vectors can also be done with x, y, z, and sometimes w, if that is more convenient:

$$\mathbf{M} = \begin{pmatrix} \mathbf{m}_{,0} & \mathbf{m}_{,1} & \mathbf{m}_{,2} \end{pmatrix} = \begin{pmatrix} \mathbf{m}_x & \mathbf{m}_y & \mathbf{m}_z \end{pmatrix} = \begin{pmatrix} \mathbf{m}_{0,}^T \\ \mathbf{m}_{1,}^T \\ \mathbf{m}_{2,}^T \end{pmatrix}. \tag{1.2}$$

A plane is denoted $\pi : \mathbf{n} \cdot \mathbf{x} + d = 0$ and contains its mathematical formula, the plane normal $\mathbf{n}$ and the scalar d. The normal is a vector describing what direction the plane faces. More generally (e.g., for curved surfaces), a normal describes this direction for a particular point on the surface. For a plane the same normal happens to apply to all its points. π is the common mathematical notation for a plane. The plane π is said to divide the space into a *positive half-space*, where $\mathbf{n} \cdot \mathbf{x} + d > 0$, and a *negative half-space*, where $\mathbf{n} \cdot \mathbf{x} + d < 0$. All other points are said to lie in the plane.

A triangle can be defined by three points $\mathbf{v}_0$, $\mathbf{v}_1$, and $\mathbf{v}_2$ and is denoted by $\triangle \mathbf{v}_0 \mathbf{v}_1 \mathbf{v}_2$.

Table 1.2 presents some additional mathematical operators and their notation. The dot, cross, determinant, and length operators are explained in our downloadable linear algebra appendix at realtimerendering.com. The transpose operator turns a column vector into a row vector and vice versa. Thus a column vector can be written in compressed form in a block of text as $\mathbf{v} = (v_x \;\; v_y \;\; v_z)^T$. Operator 4, introduced in *Graphics Gems IV* [735], is a unary operator on a two-dimensional vector. Letting

	Operator	**Description**
1:	$\cdot$	dot product
2:	$\times$	cross product
3:	$\mathbf{v}^T$	transpose of the vector $\mathbf{v}$
4:	$^{\perp}$	the unary, perp dot product operator
5:	$\lvert \cdot \rvert$	determinant of a matrix
6:	$\lvert \cdot \rvert$	absolute value of a scalar
7:	$\lVert \cdot \rVert$	length (or norm) of argument
8:	x^{+}	clamping x to 0
9:	$x^{\mp}$	clamping x between 0 and 1
10:	$n!$	factorial
11:	$\binom{n}{k}$	binomial coefficients

Table 1.2. Notation for some mathematical operators.

this operator work on a vector $\mathbf{v} = (v_x \;\; v_y)^T$ gives a vector that is perpendicular to $\mathbf{v}$, i.e., $\mathbf{v}^{\perp} = (-v_y \;\; v_x)^T$. We use $|a|$ to denote the absolute value of the scalar a, while $|\mathbf{A}|$ means the determinant of the matrix $\mathbf{A}$. Sometimes, we also use $|\mathbf{A}| = |\mathbf{a} \;\; \mathbf{b} \;\; \mathbf{c}| = \det(\mathbf{a}, \mathbf{b}, \mathbf{c})$, where $\mathbf{a}$, $\mathbf{b}$, and $\mathbf{c}$ are column vectors of the matrix $\mathbf{A}$.

Operators 8 and 9 are clamping operators, commonly used in shading calculations. Operator 8 clamps negative values to 0:

$$x^{+} = \begin{cases} x, & \text{if } x > 0, \\ 0, & \text{otherwise,} \end{cases} \tag{1.3}$$

and operator 9 clamps values between 0 and 1:

$$x^{\mp} = \begin{cases} 1, & \text{if } x \geq 1, \\ x, & \text{if } 0 < x < 1, \\ 0, & \text{otherwise.} \end{cases} \tag{1.4}$$

The tenth operator, factorial, is defined as shown below, and note that $0! = 1$:

$$n! = n(n-1)(n-2)\cdots 3 \cdot 2 \cdot 1. \tag{1.5}$$

The eleventh operator, the binomial factor, is defined as shown in Equation 1.6:

$$\binom{n}{k} = \frac{n!}{k!(n-k)!}. \tag{1.6}$$

	Function	Description
1:	$\texttt{atan2}(\texttt{y},\texttt{x})$	two-value arctangent
2:	$\log(n)$	natural logarithm of n

Table 1.3. Notation for some specialized mathematical functions.

Further on, we call the common planes $x = 0$, $y = 0$, and $z = 0$ the *coordinate planes* or *axis-aligned planes*. The axes $\mathbf{e}_x = (1 \quad 0 \quad 0)^T$, $\mathbf{e}_y = (0 \quad 1 \quad 0)^T$, and $\mathbf{e}_z = (0 \quad 0 \quad 1)^T$ are called *main axes* or *main directions* and individually called the x-axis, y-axis, and z-axis. This set of axes is often called the *standard basis*. Unless otherwise noted, we will use orthonormal bases (consisting of mutually perpendicular unit vectors).

The notation for a range that includes both a and b, and all numbers in between, is $[a, b]$. If we want all number between a and b, but not a and b themselves, then we write (a, b). Combinations of these can also be made, e.g., $[a, b)$ means all numbers between a and b including a but not b.

The C-math function `atan2(y,x)` is often used in this text, and so deserves some attention. It is an extension of the mathematical function $\arctan(x)$. The main differences between them are that $-\frac{\pi}{2} < \arctan(x) < \frac{\pi}{2}$, that $0 \leq \texttt{atan2}(\texttt{y},\texttt{x}) < 2\pi$, and that an extra argument has been added to the latter function. A common use for arctan is to compute $\arctan(y/x)$, but when $x = 0$, division by zero results. The extra argument for `atan2(y,x)` avoids this.

In this volume the notation $\log(n)$ always means the natural logarithm, $\log_e(n)$, not the base-10 logarithm, $\log_{10}(n)$.

We use a right-hand coordinate system since this is the standard system for three-dimensional geometry in the field of computer graphics.

Colors are represented by a three-element vector, such as (*red, green, blue*), where each element has the range $[0, 1]$.

1.2.2 Geometrical Definitions

The basic rendering primitives (also called *drawing primitives*) used by almost all graphics hardware are points, lines, and triangles.[1]

Throughout this book, we will refer to a collection of geometric entities as either a *model* or an *object*. A *scene* is a collection of models comprising everything that is included in the environment to be rendered. A scene can also include material descriptions, lighting, and viewing specifications.

Examples of objects are a car, a building, and even a line. In practice, an object often consists of a set of drawing primitives, but this may not always be the case; an object may have a higher kind of geometrical representation, such as Bézier curves or

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[1] The only exceptions we know of are Pixel-Planes [502], which could draw spheres, and the NVIDIA NV1 chip, which could draw ellipsoids.

surfaces, or subdivision surfaces. Also, objects can consist of other objects, e.g., a car object includes four door objects, four wheel objects, and so on.

1.2.3 Shading

Following well-established computer graphics usage, in this book terms derived from "shading," "shader," and related words are used to refer to two distinct but related concepts: computer-generated visual appearance (e.g., "shading model," "shading equation," "toon shading") or a programmable component of a rendering system (e.g., "vertex shader," "shading language"). In both cases, the intended meaning should be clear from the context.

Further Reading and Resources

The most important resource we can refer you to is the website for this book: realtimerendering.com. It contains links to the latest information and websites relevant to each chapter. The field of real-time rendering is changing with real-time speed. In the book we have attempted to focus on concepts that are fundamental and techniques that are unlikely to go out of style. On the website we have the opportunity to present information that is relevant to today's software developer, and we have the ability to keep it up-to-date.

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