Graphics & Visualization

Principles and Algorithms

T. Theoharis • G. Papaioannou • N. Platis • N. M. Patrikalakis

Graphics & Visualization

Principles & Algorithms

T. Theoharis
G. Papaioannou
N. Platis
N. M. Patrikalakis

With contributions by
P. Dutré
A. Nasri, F. A. Salem, and G. Turkiyyah

A K Peters, Ltd.
Wellesley, Massachusetts

Editorial, Sales, and Customer Service Office

A K Peters, Ltd.
888 Worcester Street, Suite 230
Wellesley, MA 02482
www.akpeters.com

Library of Congress Cataloging-in-Publication Data

Graphics & visualization : principles & algorithms / T. Theoharis ... [et al.].
p. cm.
Includes bibliographical references and index.
ISBN 13: 978-1-56881-274-8 (alk. paper)
ISBN 10: 1-56881-274-X (alk. paper)
1. Computer graphics. 2. Computer vision. 3. Visual programming
I. Theoharis, T. (Theoharis), 1964-

T385.G69346 2007
006.6–dc22

2007021707

The cover is based on M. Denko's rendering *Waiting for Spring*, which we have renamed *The Impossible*. Front cover: final rendering. Back cover: three aspects of the rendering process (wireframe rendering superimposed on lit 3D surface, lit 3D surface, final rendering).

Printed in India
12 11 10 09 08 10 9 8 7 6 5 4 3 2 1

Graphics & Visualization

Preface

Graphics & Visualization: Principles and Algorithms is aimed at undergraduate and graduate students taking computer graphics and visualization courses. Students in computer-aided design courses with emphasis on visualization will also benefit from this text, since mathematical modeling techniques with parametric curves and surfaces as well as with subdivision surfaces are covered in depth. It is finally also aimed at practitioners who seek to acquire knowledge of the fundamental techniques behind the tools they use or develop. The book concentrates on established principles and algorithms as well as novel methods that are likely to leave a lasting mark on the subject.

The rapid expansion of the computer graphics and visualization fields has led to increased specialization among researchers. The vast nature of the relevant literature demands the cooperation of multiple authors. This book originated with a team of four authors. Two chapters were also contributed by well-known specialists: Chapter 16 (Global Illumination Algorithms) was written by P. Dutré. Chapter 8 (Subdivision for Graphics and Visualization) was coordinated by A. Nasri (who wrote most sections), with contributions by F. A. Salem (section on Analysis of Subdivision Surfaces) and G. Turkiyyah (section on Subdivision Finite Elements).

A novelty of this book is the integrated coverage of computer graphics and visualization, encompassing important current topics such as scene graphs, subdivision surfaces, multi-resolution models, shadow generation, ambient occlusion, particle tracing, spatial subdivision, scalar and vector data visualization, skeletal animation, and high dynamic range images. The material has been developed, refined, and used extensively in computer graphics and visualization courses over a number of years.

Some prerequisite knowledge is necessary for a reader to take full advantage of the presented material. Background on algorithms and basic linear algebra

Some prerequisite knowledge is necessary for a reader to take full advantage of the presented material. Background on algorithms and basic linear algebra principles are assumed throughout. Some, mainly advanced, sections also require understanding of calculus and signal processing concepts. The appendices summarize some of this prerequisite material.

Each chapter is followed by a list of exercises. These can be used as course assignments by instructors or as comprehension tests by students. A steady stream of small, low- and medium-level of difficulty exercises significantly helps understanding. Chapter 3 (2D and 3D Coordinate Systems and Transformations) also includes a long list of worked examples on both 2D and 3D coordinate transformations. As the material of this chapter must be thoroughly understood, these examples can form the basis for tutorial lessons or can be used by students as self-study topics.

The material can be split between a basic and an advanced graphics course, so that a student who does not attend the advanced course has an integrated view of most concepts. Advanced sections are indicated by an asterisk ⊛. The visualization course can either follow on from the basic graphics course, as suggested below, or it can be a standalone course, in which case the advanced computer-graphics content should be replaced by a more basic syllabus.

Course 1: Computer Graphics–Basic. This is a first undergraduate course in computer graphics.

- Chapter 1 (Introduction).
- Chapter 2 (Rasterization Algorithms).
- Chapter 3 (2D and 3D Coordinate Systems and Transformations). Section 3.9 (Quaternions) should be excluded.
- Chapter 4 (Projections and Viewing Transformations). Skip Section 4.5 (Extended Viewing Transformation).
- Chapter 5 (Culling and Hidden Surface Elimination Algorithms). Skip Section 5.4 (Occlusion Culling). Restrict Section 5.5 (Hidden Surface Elimination) to the Z-buffer algorithm.
- Chapter 6 (Model Representation and Simplification).
- Chapter 7 (Parametric Curves and Surfaces). Bézier curves and tensor product Bézier surfaces.

- Chapter 9 (Scene Management).
- Chapter 11 (Color in Graphics and Visualization).
- Chapter 12 (Illumination Models and Algorithms). Skip the advanced topics: Section 12.3 (The Lambert Illumination Model), Section 12.7 (The Cook–Torrance Illumination Model), Section 12.8 (The Oren–Nayar Illumination Model), and Section 12.9 (The Strauss Illumination Model), as well as Section 12.10 (Anisotropic Reflectance) and Section 12.11 (Ambient Occlusion).
- Chapter 13 (Shadows). Skip Section 13.4 (Shadow Maps).
- Chapter 14 (Texturing). Skip Section 14.4 (Texture Magnification and Minification), Section 14.5 (Procedural Textures), Section 14.6 (Texture Transformations), Section 14.7 (Relief Representation), Section 14.8 (Texture Atlases), and Section 14.9 (Texture Hierarchies).
- Chapter 17 (Basic Animation Techniques). Introduce the main animation concepts only and skip the section on interpolation of rotation (page 622), as well as Section 17.3 (Rigid-Body Animation), Section 17.4 (Skeletal Animation), Section 17.5 (Physically-Based Deformable Models), and Section 17.6 (Particle Systems).

Course 2: Computer Graphics–Advanced. This choice of topics is aimed at either a second undergraduate course in computer graphics or a graduate course; a basic computer-graphics course is a prerequisite.

- Chapter 3 (2D and 3D Coordinate Systems and Transformations). Review this chapter and introduce the advanced topic, Section 3.9 (Quaternions).
- Chapter 4 (Projections and Viewing Transformations). Review this chapter and introduce Section 4.5 (Extended Viewing Transformation).
- Chapter 5 (Culling and Hidden Surface Elimination Algorithms). Review this chapter and introduce Section 5.4 (Occlusion Culling). Also, present the following material from Section 5.5 (Hidden Surface Elimination): BSP algorithm, depth sort algorithm, ray-casting algorithm, and efficiency issues.
- Chapter 7 (Parametric Curves and Surfaces). Review Bézier curves and tensor product Bézier surfaces and introduce B-spline curves, rational B-spline curves, interpolation curves, and tensor product B-spline surfaces.

- Chapter 8 (Subdivision for Graphics and Visualization).
- Chapter 12 (Illumination Models and Algorithms). Review this chapter and introduce the advanced topics, Section 12.3 (The Lambert Illumination Model), Section 12.7 (The Cook–Torrance Illumination Model), Section 12.8 (The Oren–Nayar Illumination Model), and Section 12.9 (The Strauss Illumination Model), as well as Section 12.10 (Anisotropic Reflectance) and Section 12.11 (Ambient Occlusion).
- Chapter 13 (Shadows). Review this chapter and introduce Section 13.4 (Shadow Maps).
- Chapter 14 (Texturing). Review this chapter and introduce Section 14.4 (Texture Magnification and Minification), Section 14.5 (Procedural Textures), Section 14.6 (Texture Transformations), Section 14.7 (Relief Representation), Section 14.8 (Texture Atlases), and Section 14.9 (Texture Hierarchies).
- Chapter 15 (Ray Tracing).
- Chapter 16 (Global Illumination Algorithms).
- Chapter 17 (Basic Animation Techniques). Review this chapter and introduce the section on interpolation of rotation (page 620), as well as Section 17.3 (Rigid-Body Animation), Section 17.4 (Skeletal Animation), Section 17.5 (Physically-Based Deformable Models), and Section 17.6 (Particle Systems).

Course 3: Visualization. The topics below are intended for a visualization course that has the basic graphics course as a prerequisite. Otherwise, some of the sections suggested below should be replaced by sections from the basic graphics course.

- Chapter 6 (Model Representation and Simplification). Review this chapter.
- Chapter 3 (2D and 3D Coordinate Systems and Transformations). Review this chapter.
- Chapter 11 (Color in Graphics and Visualization). Review this chapter.
- Chapter 8 (Subdivision for Graphics and Visualization).
- Chapter 15 (Ray Tracing).

- Chapter 17 (Basic Animation Techniques). Review this chapter and introduce Section 17.3 (Rigid-Body Animation) and Section 17.6 (Particle Systems).
- Chapter 10 (Visualization Principles).
- Chapter 18 (Scientific Visualization Algorithms).

About the Cover

The cover is based on M. Denko's rendering *Waiting for Spring*, which we have renamed *The Impossible*. Front cover: final rendering. Back cover: three aspects of the rendering process (wireframe rendering superimposed on lit 3D surface, lit 3D surface, final rendering).

Acknowledgments

The years that we devoted to the composition of this book created a large number of due acknowledgments. We would like to thank G. Passalis, P. Katsaloulis, and V. Soultani for creating a large number of figures and M. Sagriotis for reviewing the physics part of light-object interaction. A. Nasri wishes to acknowledge support from URB grant #111135-788129 from the American University of Beirut, and LNCSR grant #111135-022139 from the Lebanese National Council for Scientific Research. Special thanks go to our colleagues throughout the world who provided images that would have been virtually impossible to recreate in a reasonable amount of time: P. Hall, A. Helgeland, L. Kobbelt, L. Perivoliotis, G. Ward, D. Zorin, G. Drettakis, and M. Stamminger.

Contents

1

Introduction

There are no painting police—just have fun.
—Valerie Kent

1.1 Brief History

Out of our five senses, we spend most resources to please our vision. The house we live in, the car we drive, even the clothes we wear, are often chosen for their visual qualities. This is no coincidence since vision, being the sense with the highest information bandwidth, has given us more advance warning of approaching dangers, or exploitable opportunities, than any other.

This section gives an overview of milestones in the history of computer graphics and visualization that are also presented in Figures 1.1 and 1.2 as a time-line. Many of the concepts that first appear here will be introduced in later sections of this chapter.

1.1.1 Infancy

Visual presentation has been used to convey information for centuries, as images are effectively comprehensible by human beings; a picture is worth a thousand words. Our story begins when the digital computer was first used to convey visual information. The term *computer graphics* was born around 1960 to describe the work of people who were attempting the creation of vector images using a digital computer. Ivan Sutherland's landmark work [Suth63], the Sketchpad system developed at MIT in 1963, was an attempt to create an effective bidirectional man-machine interface. It set the basis for a number of important concepts that defined the field, such as:

- hierarchical display lists;
- the distinction between object space and image space;
- interactive graphics using a light pen.

At the time, *vector displays* were used, which displayed arbitrary vectors from a *display list*, a sequence of elementary drawing commands. The length of the display list was limited by the refresh rate requirements of the display technology (see Section 1.6.1).

As curiosity in synthetic images gathered pace, the first two *computer art* exhibitions were held in 1965 in Stuttgart and New York.

The year 1967 saw the birth of an important modeling concept that was to revolutionize computer-aided geometric design (CAGD). The *Coons patch* [Coon67], developed by Steven Coons of MIT, allowed the construction of complex surfaces out of elementary patches that could be connected together by providing continuity constraints at their borders. The Coons Patch was the precursor to the Bézier and B-spline patches that are in wide CAGD use today.

The first computer graphics related companies were also formed around that time. Notably, Evans & Sutherland was started in 1968 and has since pioneered numerous contributions to graphics and visualization.

As interest in the new field was growing in the research community, a key conference ACM SIGGRAPH was established in 1969.

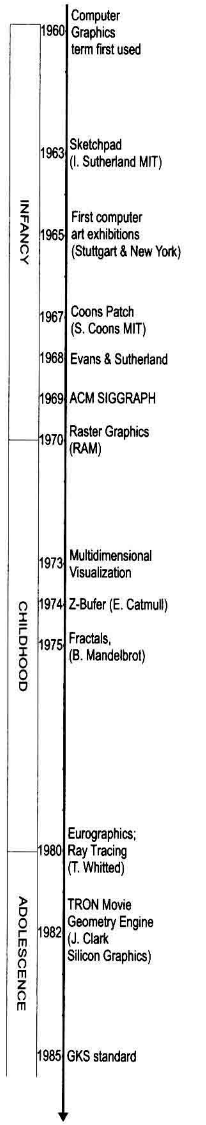

Figure 1.1. Historical milestones in computer graphics and visualization (Part 1).

1.1.2 Childhood

The introduction of transistor-based random access memory (RAM) around 1970 allowed the construction of the first *frame buffers* (see Section 1.5.2). *Raster displays* and, hence, *raster graphics* were born. The frame buffer decoupled the creation of an image from the refresh of the display device and thus enabled the production of arbitrarily complicated synthetic scenes, including filled surfaces, which were not previously possible on vector displays. This sparked the interest in the development of *photo-realistic algorithms* that could simulate the real visual appearance of objects, a research area that has been active ever since.

The year 1973 saw an initial contribution to the visualization of multidimensional data sets, which are hard to perceive as our brain is not used to dealing with more than three dimensions. Chernoff [Cher73] mapped data dimensions onto characteristics of human faces, such as the length of the nose or the curvature of the mouth, based on the innate ability of human beings to efficiently "read" human faces.