JONAS GOMES LUIZ VELHO

Translated by silvio Levy

Image Processing for Computer Graphics

计算机图形学中的图像处理

Springer-Verlag

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With 180 Black & White Illustrations and 13 Color Plates

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Jonas Gomes Luiz Velho
Instituto de Matematica Pura e Aplicada
Estrada Dona Castorina, 110
Rio de Janiero, 22460-320
Brazil

Silvio Levy, translator
Mathematical Sciences Research Institute
Berkeley, CA 94720-5070
USA

Cover: Mosaic of *Fish Out of Water* by Mike Miller, created in PovRay. The mosaic is composed of different image processing techniques applied to the computer-generated image.

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Preface

A escrita é a forma mais duradoura de conservar nossos pensamentos. Através dela, nos é permitido transmitir, de geração em geração, a essência de nossas reflexões sobre a vida, a humanidade e, sobretudo, o amor.

Solange Visgueiro

This book originated when we noticed, several years ago, that the importance of image processing in the area of visualization and computer graphics was not reflected in either the existing curricula or the current textbooks.

On the one hand, traditional image processing books do not cover important topics for computer graphics such as warping, morphing, digital compositing, color quantization, and dithering. Often even basic facts about signals are not adequately discussed in the context of graphics applications. This kind of knowledge is now more important than ever for computer graphics students, given the interactions between audio, images, and models in most applications.

Computer graphics books, on the other hand, emphasize primarily modeling, rendering, and animation, and usually do not contain a proper exposition of signal processing techniques.

We have adopted a conceptual approach, with emphasis on the mathematical concepts and their applications. We introduce an abstraction paradigm that relates mathematical models with image processing techniques and implementation methods. This paradigm is used throughout the book, and helps the reader understand the mathematical theory and its practical use. At the same time, we keep the presentation as elementary as possible by sacrificing mathematical rigor, when necessary, for an intuitive description.

This book is intended to be useful either as a textbook or as a reference book. In draft form and after publication, the Portuguese edition has been used since 1992 at a course taught at Instituto de Matemática Pura e Aplicada (IMPA) in Rio de Janeiro, attended by undergraduate and master's students in mathematics and computer science. The first seven chapters correspond to the course's contents; the remaining chapters are used as topics for discussion and seminars with the students. The English version has been in use outside Brazil since the fall of 1996.

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We wish to thank our friend Silvio Levy, who accepted the invitation to translate the book and did an excellent job. Our interaction with him during the translation was very rewarding, and his comments greatly influenced several changes we have made for this English edition.

We are grateful to numerous colleagues who contributed their comments and criticism to this work: André Antunes, Bruno Costa, Lucia Darsa, Marcelo Dreux, Luiz Henrique de Figueiredo, and Valéria Iório, among others. We also thank Siome Goldenstein and Paulo Roma, who helped us revise the translation, and Martin Gilchrist of Springer-Verlag, who agreed to publish it.

Rio de Janeiro, December 1996

Jonas Gomes
Luiz Velho

Contents

1 Introduction

Images are the final product of most processes in computer graphics. This book is devoted to the study of images and of image manipulation systems by computer. It also covers important mathematical concepts in the analysis and understanding of images.

1.1 Computer Graphics

The International Standards Organization (ISO) defines computer graphics as the sum total of "methods and techniques for converting data for a graphics device by computer." This definition would probably not help a reader totally unfamiliar with the field to understand what it's all about. In fact, the best way to understand a field is to grasp what its main problems are. From this point of view, the ISO definition can be said, with goodwill, to define the main problem of computer graphics: *converting data into images.*

The process of converting data into images is known as *visualization.* It is schematically illustrated in Figure 1.1.

In order to understand computer graphics, then, we must study the methods for creating and structuring data in the computer as well as methods for turning these data into images. These two steps correspond

Figure 1.1.
Computer graphics: converting data into images.

to the two main areas of research in computer graphics: *modeling* and *visualization.*

In this book we will not study modeling or data visualization. Instead, we will focus on a more fundamental and very important problem: understanding the notion of an image and also the techniques of image manipulation by computer—in other words, *image processing.* At the same time, this is not a typical image processing book, because it covers primarily the aspects of image processing used most often in computer graphics.

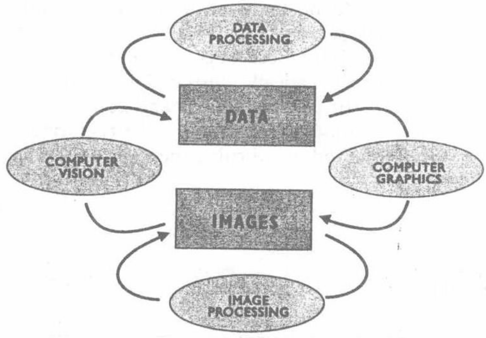
Since its inception, computer graphics has sought methods to allow the visualization of information stored in computer memory. Since there are practically no limitations on the nature or origins of such data, researchers and professionals use computer graphics today in the most diverse fields of human knowledge. Its use is important whenever it is necessary to have a visual representation of *objects, actions, relations,* or *concepts.* The importance of this visual representation is reflected in the huge number of computer graphics applications, ranging from scientific visualization to special effects in the entertainment industry.

Partly because computer graphics has so many applications, there are no sharp boundaries between it and related fields. However, we can take as a working criterion in differentiating among these fields the nature of the input and output of the process in question, as shown in Figure 1.2.

In *data processing,* the system takes in data and, after processing, returns data of more or less the same nature. For example, a bank account management system processes input transactions and yields output data such as a daily balance, interest earned, and so on.

In *computer graphics,* the input data are (typically) nonvisual, and the output is an *image* that can be seen through some graphics output device.

Figure 1.2. Computer graphics and kindred disciplines.



For instance, the account management system of the preceding paragraph might plot a graph of the daily balance over a period.

In *digital image processing*, the input is already an image, which gets processed to yield another image, the output. The latter can again be seen through a graphics output device. An example would be the processing of data sent by an orbiting satellite, with the purpose of coloring or enhancing the image.

The goal of *computer vision* is to, given an input image, obtain information about the physical, geometric, or topological properties of the objects that appear in it. This is used, for example, in robotics, to endow machines with a sense of sight.

In most applications, two or more of these areas act in concert. Thus, the data output by an image processing or computer vision system might be further subjected to computer graphics techniques, to give the user better qualitative information. For instance, height information can be extracted from satellite images and processed to yield a relief map, which can further be combined with enhanced and colorized image data to yield a realistic three-dimensional model of the area. It is exactly the joint use of techniques in these various areas that holds the greatest potential for applications.

Sometimes these cross-disciplinary links are so vigorous that they can spawn new disciplines. The joint use of geometric modeling and computer vision is the basis of the discipline known as *visual modeling*, which allows the creation of models starting from the images of a scene. Medical imaging, likewise, uses (almost transparently) techniques from image processing, computer graphics, and computer vision.

Another way to summarize these distinctions is by saying that computer vision is interested in *analyzing* images, while computer graphics is interested in *synthesizing* them. These two areas, plus image processing, are the triple foundation of all computational processes involving images. In computer graphics, the image is the end product; image processing plays a role in the early phase of image generation and in a later phase called postprocessing. In computer vision, the image is the input data, and in general the early, preprocessing phase involves image processing. Figure 1.3 illustrates this idea.

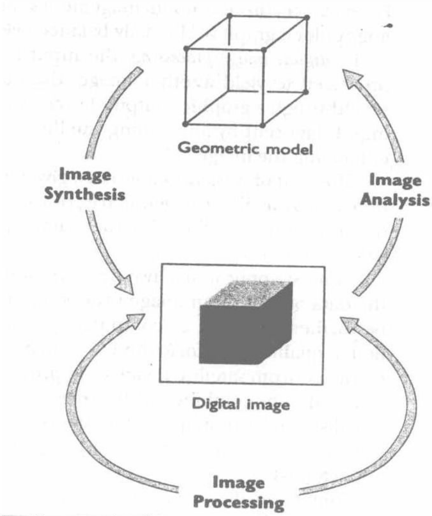
In all these areas, of course, the study of images as abstractions is of paramount importance. We therefore turn to the general ideas that underlie this study.

1.2 Abstraction Paradigms

In any area of applied mathematics, one needs to model the objects under study mathematically. To set things on the right conceptual footing, one must create a hierarchy of abstractions, and at each level of abstraction one must apply the most appropriate models.

In applied areas that involve computational methods, and in particular in computer graphics, one abstraction paradigm that is generally

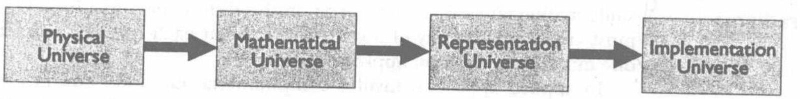
Figure 1.3. Image synthesis, processing and analysis.



applicable consists in establishing four universes (sets), shown schematically in Figure 1.4: the physical universe P, the mathematical universe M, the representation universe R, and the implementation universe I. The ***physical universe*** contains the real-world objects we intend to study; the ***mathematical universe*** contains an abstract description of the objects from the physical world; the ***representation universe*** is made up of the discrete representations associated with the objects from the mathematical universe; and, finally, in the ***implementation universe***, we map the entities from the representation universe to concrete data structures, in order to actually represent the objects on the computer. The implementation universe is designed to separate the discretization step (representation) from the particularities of the programming language used in the implementation.

We call this conceptual layering the ***four-universe paradigm***. In short, in order to study a given phenomenon or object on the computer, we must

Figure 1.4. Conceptual levels of abstraction.



associate to it a mathematical model and then find a discrete representation of the model that can be implemented in the computer.

Based on this paradigm, here are the main types of problems that we can expect to encounter in an area of study:

- defining the elements of the universe M;
- relating the universes P, M, R, and I with one another;
- defining representation relations from M to R;
- studying the properties of the possible representations from M to R;
- converting among the different representations;
- devising good data structures for implementation.

Clearly, once the elements of M are defined, other specific problems can be posed; for instance, one may create additional abstraction sublevels, in a process similar to top-down structured programming. Creating abstraction levels allows one better to encapsulate, pose, and solve the problems at each level, much as object-oriented programming does. We will use the paradigm above many times in this book; in each case we will discuss how it applies to a particular area and how the problems itemized above translate to that area.

1.3 About This Book

We now turn to the contents of each chapter of this book. Our goal throughout has been to present the subject from a theoretically consistent point of view, and we have adopted innovative formulations whenever we felt that this was necessary for clarity of exposition. We have likewise included a great many examples and illustrations, as an aid to understanding.

To the extent possible, we have avoided the discussion of implementation details. There is no "pseudocode" in this book. Throughout the work, the emphasis is on describing and analyzing underlying concepts rather than on presenting algorithms or discussing optimization questions. A good conceptual understanding is exceedingly important as a basis for further studies, and it is also a prerequisite for understanding existing algorithms and creating new ones.

The chapters of the book are as follows.

Chapter 2: Signal Theory Discusses signal theory and so introduces the reader to the various ideas and results of digital signal processing. It also prepares the reader for the study of color and images, two particular cases of signals used in computer graphics, and which are studied in detail in subsequent chapters.

Chapter 3: Fundamentals of Color Introduces color theory from the point of view of signal processing. Discusses the various mathematical models of color and develops the notion of color space representation, or discretization of the visible spectrum, as a means of allowing the representation of color on the computer.

Chapter 4: Color Systems	Discusses the different color systems used for the specification and computation of color, emphasizing the RGB and XYZ standards from the International Commission for Illumination (CIE). Also covers video component systems, which have acquired great importance in video and computer graphics applications.
Chapter 5: Digital Images	Introduces the main object of study of this book: the mathematical model for an image, and its digital representation. The problem of image discretization is extensively discussed, with emphasis on color quantization. The chapter also includes a brief discussion on image compression techniques.
Chapter 6: Operations on Images	Covers the important topic of operations on an image's domain and color space. Emphasizes image filtering, a topic of great importance in computer graphics. Discusses a variety of linear filters, both in the spatial and the frequency domain, and gives applications to reconstruction, compression and multiscale representation of images. There is some overlap between this chapter and Chapter 2, for the benefit of readers who have already studied signal processing and who may want to read this chapter independently.
Chapter 7: Sampling and Reconstruction	This chapter uses the theory and concepts developed in the previous chapters to discuss in more detail the important problem of image sampling and reconstruction.
Chapter 8: Dithering and Halftoning	Dithering is often treated together with quantization, in a very superficial way. We treat it separately, to stress the fact that dithering is a type of nonlinear filtering. The decision to devote a whole chapter to the subject was based on the importance of dithering in electronic publishing. The chapter contains a detailed study of dithering algorithms, including some stochastic screening techniques.
Chapter 9: Image Compositing	Studies several operations that allow one to combine into one image elements from several. This is a very important topic in applications of image processing to computer graphics, especially in the creation of special effects for video and movies.
Chapter 10: Warping and Morphing	Discusses in detail, from a conceptual point of view, image warping and morphing. These techniques are used to obtain smooth transitions between two images and involve a correspondence of geometric elements simultaneously with color interpolation.
Chapter 11: Imaging Systems	Discusses a number of problems related to image analysis and processing systems. As an example, it treats in some detail the case of an electronic publishing system with the ability to produce color separations for offset printing.

Chapter 12: Appendix on Radiometry and Photometry Covers in detail necessary background material on these classical areas of physics, which, while useful for understanding parts of Chapter 3, would break the conceptual flow of ideas if included in the main text.

Naturally, the study of images takes up most of the book. However, the contents are not identical with those of a traditional course in image processing: as already remarked, our interest is to exploit the aspects of image processing that have importance in computer graphics. For this reason we stress more color quantization than, say, the different methods of image encoding and compression. This also has led us to devote whole chapters to operations on images, dithering, warping and morphing, and image composition, topics of great importance in computer graphics applications, which are not covered in most books devoted to image processing.

1.4 Comments and References

Until recently, many computer graphics books included a historical synopsis of the field's evolution. This started in early days, when the field was new and relatively little-known, as a way to acquaint the public with the potential of computer graphics; later the tradition was maintained, in large measure because the explosive growth in the body of knowledge and applications demanded constant updating of the literature.

Today, although still a young discipline in comparison with other areas of science, computer graphics has developed to the point where the historical dimension plays a different role. A history of computer graphics must cover not only applications but also the evolution of mathematical and physical models, the algorithms, and even the hardware. Such a history, or even a bare chronology, would be far too long to be adequately dealt with in a single chapter. What is needed is a book entirely devoted to the history of computer graphics.

Nonetheless, here are some highlights of the literature, from a historical point of view.

The seminal work of Ivan Sutherland, in his Ph.D. thesis (Sutherland 1963), marked a watershed between early, rudimentary uses of the computer for graphics and the modern notion of interactive computer graphics. Sutherland's "Sketchpad" allowed the user to interactively manipulate plane geometric figures.

The first texts that refer to computer graphics as such were connected with computer-aided design (CAD) in high-technology industries, especially the automobile, aircraft and shipbuilding industries. See, for example, (Parslow 1969) and (Prince 1971).

Many introductory articles about computer graphics have appeared in popular scientific magazines. Among the oldest, and yet most interesting for its historical perspective, is the article (Sutherland 1970) in *Scientific American.* We mention also (Crow 1978), (Whitted 1982), and (van Dam 1984).

An excellent way to get an overall view of the evolution of the state of the art in computer graphics is to watch the videos put out every year since 1978 by SIGGRAPH, the Special Interest Group in Computer Graphics of the ACM (Association for Computing Machinery). These videos contain the animations selected for display at the annual SIGGRAPH meeting in the United States, itself a showcase of the most important current work in the field.

Among the many introductory computer graphics books available, we mention two classics: (Newman and Sproull 1979) and (Foley et al. 1990). Both stress the interactive aspects of the field and have appeared in a second, revised, edition. Other general texts are (Giloi 1978), (Magnenat-Thalmann and Thalmann 1987), and (Watt 1990).

Another general textbook, with good coverage of implementation aspects of algorithms, is (Rogers 1985). Along the same lines, (Harrington 1983, pp. 345–352) is geared toward the implementation of a graphics system in the spirit of the CORE system proposed by the ACM (Michener and Van Dam 1979) as a possible ISO standard.

There is a series of "Graphics Gems" books devoted to the implementation of graphics algorithms, covering many problems in image synthesis, processing and analysis: (Glassner 1990), (Arvo 1991), (Kirk 1992), (Heckbert 1994), and (Paeth 1995). They can be used (selectively) to complement the present book, which does not stress the implementation side.

Although it can be appropriately applied to all areas of applied mathematics that involve computational methods, the four-universe paradigm first appeared explicitly in the literature in (Requicha 1980), in the context of geometric modeling. More details on the use of this paradigm in various areas of computer graphics can be found in (Gomes and Velho 1995).

As the subject of computer graphics matured, textbooks started to appear on specific subfields, such as ray tracing (Glassner 1989) and lighting (Hall 1989). The book (Fiume 1989), devoted to raster graphics, is an effort to lay a solid conceptual foundation for this subject.

Scientific visualization, and its importance to scientific and technological development, are well documented in (McCormick 1987).

A historical, if anecdotal, perspective on computer graphics can be gleaned from (Machover 1978) and (Rivlin 1986).

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