Computer Graphics

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Theory and Practice

Jonas Gomes
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Mario Costa Sousa


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To Solange and Daniel
—J.G.

To Noni and Alice
—L.V.

To Patricia and Marianna
—M.C.S.

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Foreword

Depiction is about creating a signal that tickles our visual systems in a way that is just good enough for us to extract meaning from it. Such a signal itself need not be visual, for there is now strong evidence that nonvisual signals such as suggestion, storytelling, recall, imagination, and visualization in the original sense of the word all can deeply engage our visual systems. Artists have understood this for millennia. They have developed ingenious techniques for visual depiction using various media, combining insights into both phenomenology and the power of suggestion.

Computer graphics is about giving visual depiction a systematic computational underpinning. Here, we immediately run into some difficult questions. What do we mean by *systematic*? What are the dependencies? What is fundamental and unchanging and what is ephemeral? How do we separate one from the other?

While such questions plague most fields, they are particularly acute in computer graphics. As a field it is barely a half-century old and combines the development of many original techniques with extensive adoption of ideas from other fields. It has undergone an extremely high rate of adaptation and growth, so that some techniques are older than the field itself, while others have only been around for a year or two. This can give rise to inconsistencies in representations, processes, and workflow. The field has also been steered in some ways by its most successful applications, including animated films, special effects, visual simulation, electronic games, and design and manufacture. As a result, it is not always clear how relevant certain aspects of computer graphics are to new applications. That said, what a remarkable success computer graphics has been as a mathematical science, an engineering discipline, and digital medium!

How then should one introduce the concepts of computer graphics? As a medium, we have seen a wide array of books on the use of certain graphics systems, and on the practice and aesthetics of graphical depiction. As a technology, there are numerous books providing instruction on the use of specific application programming interfaces (APIs) and programming development environments to build graphical applications. What has remained problematic is how to define and explain the fundamental concepts of computer graphics, knowing full well that ultimately these concepts must be relevant both to further research in the field as well as to practical applications. To this end, some authors have

advocated programming-based approaches that rely on specific languages or APIs. Others have removed the reliance on specific implementation environments and instead advocate algorithmic approaches. But then, what concepts are key to the development of algorithms, and how are those concepts to be stated outside of the algorithms themselves?

This book by Jonas Gomes, Luiz Velho, and Mario Costa Sousa has clear priorities: first, explain the concepts of computer graphics precisely, but not pedantically, using basic mathematics; second, explore the mathematical implications of these concepts by constructing models of graphical processes that are seen as fundamental; third, after those models are understood, exploring their algorithmic formulation. It thus means that in reading this book you will try to understand before you build, and the exercises in each chapter reinforce that discipline. After going through this book myself, I particularly enjoyed the early treatment of topics such as projective mappings and color spaces, as they informed many topics later on.

Ultimately, this book helps to expose what we do best in computer graphics. It isn't merely in our ability to create beautiful images, or in our ability to make things work very quickly. We of course help to do both of those things. It is instead in our ability to create an ever-growing set of *visual models*, to simulate or prove properties about those models so as to explore their capabilities, and to map those models onto usable technology so that we may all better express ourselves visually.

—Eugene Fiume, University of Toronto

About the Cover

"The Liquid Dark Side of the Moon"

Simplicity itself, a jet black $12'' \times 12''$ square with a line drawing of a luminous white prism at its center. A thin beam of white light penetrates the left side of the prism at an angle and exits on the right, split into a fanned spectrum of glowing color.

My name is Dan Abbott and I work as part of a compact but busy design collective StormStudios, based in London, England. You may or may not be familiar with our work, but chances are you've stumbled across the image I describe above as the 1973 cover graphic to Pink Floyd's gazillion-selling "The Dark Side of the Moon" album. Of course the same graphic elements were already well rooted in the collective conscious well before 1973, thanks to the work of our old friend Isaac Newton, and reproduced in a thousand and one school science textbooks.

That the prism landed on the cover of Pink Floyd's seventh album was due to the efforts of my esteemed colleague and tormentor Storm Thorgerson, who at that time co-helmed influential sleeve design company Hipgnosis with Aubrey 'Po' Powell. Hitherto, Storm and Po's designs for Pink Floyd had been exclusively photographic in nature, but the band requested something graphic by way of a change. Hipgnosis rustled up seven exciting new designs and much to their surprise the band voted unanimously for the one with the prism. Storm claims he tried to talk them out of it, but their minds were all made up. Thus ends the fable of "How the Prism Got Its Album" and magically leapt from textbook to record racks worldwide.

Two decades later in 1993 history started to repeat itself—traditional practice in the rock 'n' roll universe. The Dark Side of the Moon was re-released in shiny, all new digitally remastered, twentieth anniversary CD form. So Storm decided to "remaster" the cover too, replacing the 1973 drawing with a photo of real light being refracted through a real-life glass prism. What could be more honest than that? Funnily enough, few fans seemed to notice the switcheroo, which I think might tell you something about the power of the basic setup of the image.

Ten years later still and it was suggested that the design be tweaked once again for the thirtieth anniversary re-release on SACD (which we were reliably informed was the

absolutely definitive audio format of the future). Thirtieth anniversaries are very significant for all triangular life forms, so how could we refuse? So we built a four-foot square stained glass window to the exact proportions of the original design, and photographed it. "Hmm, maybe this idea's got legs after all" we thought. In the following years we created several further homages to the original design: a prism made of words for a book cover, a prism painted a-la Claude Monet, a Lichtenstein-esque pop art number, and rather curiously, a prism created entirely with fruit for a calendar (this probably came about after someone joked about calendars being made from "dates").

To execute the above-mentioned "Fruity Side of the Moon," we built a large wooden tray with each line of the design being a walled-off section, keeping all the dates, raisins, cranberries, apricots, oranges, and baby lemons in their right and proper positions. It was then photographed from above. I can't remember if we ate the contents afterwards, but shoots are hungry work so it's very likely. Later, one of us (might've been Pete, might've been Storm) inspected the empty tray and had the bright idea that colored paint or ink poured into the various sections might make yet another cool photo. The tray was quickly modified with any leaky corners made watertight, and the relevant hue of paint was poured into each section. The effect was smooth, glossy, and rather pleasing to the eye.

Then, the unplanned started to occur. The separate areas of paint began slowly but surely to bleed into each other. But rather than becoming a hideous mess the experiment began to take on a whole new dimension, and we experienced something of a eureka moment. We started helping the migrating paint go its own sweet way. A swish here, a couple of drips there, and soon the previously rather rigid composition began to unravel into a wild psychedelic jungle. Areas of leaking paint expanded into impressive swirling whorls and delicate curlicues of color, stark and vibrant against their black backdrop. Fine and feathery veins of pigment unfurled like close-ups of a peacock's plumage or like NASA photos of the gigantic swirls in Jupiter's atmosphere. Blobs and bubbles emerged organically bringing to mind Pink Floyd's early liquid light shows. Detail was crisp and went on and on, a feast for the eyes and seriously entertaining for us. All the time, our intrepid photographer Rupert was poised a few feet above, dangling with his camera from a gantry, snapping frame after frame. Our magic tray had done most of our work for us, and we christened the process "controlled random." All that remained was for us to select a couple of shots for use—a nigh-on-impossible task given the multitude of beautiful frames we'd captured.

And so we come to the most recent stop on our prismatic journey. A few months ago we received an email from Mario Costa Sousa. He had spied "Liquid DSoM" (as we came to call it) on our website and politely enquired as to whether he and his fellow authors might use it as the cover for their new computer graphics textbook. Our first response was a friendly "yes" followed by fairly patronizing words to the effect of, "But Mario dear, do you realize that we created this for real, that it's not computer generated in any way?" Mario, clearly a man with his head screwed on the right way round, calmly explained that it was just what was needed.

First off, the basic image of the prism diffracting a beam of light is central to light and color theory and a truly crucial element in computer graphics. Second, the controlled ran-

domness of the paint as it flows in specific, distinct directions reflects algorithmic modeling techniques often used in computer graphics, particularly in procedural image synthesis. Third, they enjoyed the idea of featuring a hand-created real life image on the front of a computer graphics textbook, implying that a technical reader might gain valuable insights into the theory and practice of computer graphics by observing real-world phenomena. And fourth, I suspect the authors may also be Pink Floyd fans, but we'll leave that for another day.

How appropriate then, that our design, an image that some might say was cribbed from a school textbook, should wind up through a variety of fairly exotic twists and turns, back on the cover of a textbook. Nothing random about that, eh?

— Dan Abbott, StormStudios
London, December 2011

Preface

This book has been used for various years in an introductory graduate-level course at the Institute of Pure and Applied Mathematics (IMPA), Rio de Janeiro, as part of the joint graduate program with the Catholic University of Rio de Janeiro, PUC-Rio, in computer graphics. This material has also been used in recent years at a senior undergraduate/first-year graduate level course in computer graphics in the Department of Computer Science at the University of Calgary. Many students of mathematics, engineering, and computer science have attended these courses at both IMPA, PUC-Rio, and the University of Calgary. The results have strengthened our conviction of the importance of emphasizing mathematical models in teaching computer graphics. This is especially true for students interested in pursuing more advanced studies: the important problems at the knowledge frontier in computer graphics involve nonelementary aspects of mathematical modeling.

This textbook has its fundamental roots in a publication by Jonas Gomes and Luiz Velho, *Computação Gráfica*, Volume 1, IMPA, 1998 (in Portuguese). Various chapters have been rewritten, other chapters have been carefully reviewed, new chapters have been added, and exercises have been included in order to cover the core material usually offered in an introductory course in computer graphics at the upper undergraduate or first-year graduate level. The book uses a problem-based learning approach in the sense that its fundamental goal is to provide a broad conceptual view of the main problems in computer graphics and to provide a framework for their solution. The content and exposition were elaborated in order to avoid the need for complementary texts at the fundamental computer graphics level. Prerequisites for this book include calculus, linear algebra, and basic topology and data structures.

As this is an introductory textbook, no previous knowledge of computer graphics is required, although the conceptual approach of the book requires that the reader be familiar with some concepts in continuous and discrete mathematics. This conceptual approach also allows this book to be adopted in more advanced courses with the appropriate complements. To facilitate its use, we included a list of additional topics at the end of each chapter.

It is important to highlight that the mathematical models of computer graphics only blossomed as a result of the various graphics and images produced on a computer screen,

making the implementation of those models an inherent problem of the area. For this, we provide as supplemental material a complete e-book dedicated to this subject: *Design and Implementation of 3D Graphics Systems*. In our coursework programs we used this book and related notes to emphasize the implementation aspects.

Acknowledgments

Various colleagues collaborated on the initial volume from 1998 that gave origin to this book. Paulo Roma Cavalcanti gave us a great incentive for materializing this project. Paulo not only taught the course and created a set of initial notes, but also provided the very early preliminary reviews. Luiz Henrique de Figueiredo did a detailed and thorough review of some of the chapters and produced some of the illustrations that appear in the text, all properly credited. Many thanks to Margareth Prevot (IMPA, VisGraf Lab) who collaborated in the production of various images used in the text. We also thank everyone who allowed us to use figures from their works, all properly acknowledged in this book.

Various other colleagues read the preliminary versions of various chapters, saved us from some pitfalls, and gave us valuable suggestions. Among them, we can highlight Antonio Elias Fabris, Romildo José da Silva, Cícero Cavalcanti, Moacyr A. Silva, Fernando W. da Silva, Marcos V. Rayol Sobreiro, Silvio Levy, and Emilio Vital Brazil. We thank all sincerely. We also thank Jamie McInnis, Sarah Chow, and Patricia Rebolo Medici for their reviews and suggestions and for carefully editing and proofreading the book.

We sincerely thank Alice Peters for her dedication to this book project. We are honored to have the foreword in this book by Eugene Fiume and thank him for his inspiring words.

We are very grateful to Storm Thorgerson and Dan Abbott from StormStudios for giving us permission to use their original art photography "The Liquid Dark Side of the Moon" as our book cover. Many thanks to everyone else from StormStudios who helped to produce this art piece: Peter Curzon, Rupert Truman, Lee Baker, Laura Truman, Jerry Sweet, Charlotte Barnes, and Nick Baker. We would like to thank Dan Abbott very much for also describing "How the Prism Got Its Cover" as part of this book. Many thanks to Kara Ebrahim for working in the final cover layout design and production and to Dan Abbott for his valuable design suggestions.

The project of writing this book has been facilitated by the fruitful teaching and research environments of the computer graphics laboratory at IMPA (Visgraf Lab), and both the Department of Computer Science and the Interactive Reservoir Modeling and Visualization Group (*Illustra*Res/iRMV)/Computer Graphics Research Lab at the University of Calgary. Our sincere thanks go to all their members for their constant support. Finally, we sincerely appreciate the support from NSERC/Alberta Innovates Technology Futures (AITF)/Foundation CMG Industrial Research Chair program in Scalable Reservoir Visualization.

— Jonas Gomes, Luiz Velho, and Mario Costa Sousa
Rio de Janeiro and Calgary, December 2011