

---

---

**COLOR THEORY AND MODELING  
FOR COMPUTER GRAPHICS,  
VISUALIZATION, AND MULTIMEDIA  
APPLICATIONS**

---

**THE KLUWER INTERNATIONAL SERIES  
IN ENGINEERING AND COMPUTER SCIENCE**

---

**COLOR THEORY AND MODELING  
FOR COMPUTER GRAPHICS,  
VISUALIZATION, AND MULTIMEDIA  
APPLICATIONS**

*by*

**Haim Levkowitz**

*University of Massachusetts Lowell  
Lowell, Massachusetts, USA*



**KLUWER ACADEMIC PUBLISHERS**  
**Boston / Dordrecht / London**

---

**Distributors for North America:**

Kluwer Academic Publishers  
101 Philip Drive  
Assinippi Park  
Norwell, Massachusetts 02061 USA

**Distributors for all other countries:**

Kluwer Academic Publishers Group  
Distribution Centre  
Post Office Box 322  
3300 AH Dordrecht, THE NETHERLANDS

---

**Library of Congress Cataloging-in-Publication Data**

A C.I.P. Catalogue record for this book is available  
from the Library of Congress.

---

*The publisher offers discounts on this book when ordered in bulk quantities. For more information contact: Sales Department, Kluwer Academic Publishers, 101 Philip Drive, Assinippi Park, Norwell, MA 02061*

**Copyright © 1997 by Kluwer Academic Publishers**

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, mechanical, photocopying, recording, or otherwise, without the prior written permission of the publisher, Kluwer Academic Publishers, 101 Philip Drive, Assinippi Park, Norwell, Massachusetts 02061

*Printed on acid-free paper.*

Printed in the United States of America

---

# CONTENTS

<b>LIST OF FIGURES</b>	ix
<b>LIST OF TABLES</b>	xiii
<b>Preface</b>	xv
<b>Part I COLOR THEORY</b>	1
<b>1 HUMAN VISION</b>	3
1.1 The Human Interface	3
1.2 Color As a Tri-Stimulus Medium	6
1.3 A Tour of the Human Visual System	9
1.4 Basic Visual Mechanisms	12
1.5 Introduction to Human Color Vision	17
1.6 Color deficiencies	22
1.7 Color-Luminance Interactions	27
1.8 Summary and Notes	29
<b>2 COLOR ORGANIZATION AND COLOR MODELS</b>	31
2.1 Introduction to Color Modeling	31
2.2 Overview of Color Specification Systems	33
2.3 Process-dependent Systems (Instrumental)	33
2.4 Process-order Systems (Pseudo-perceptual)	35
2.5 Coordinate Systems Based on Human Visual Models	36
2.6 Perceptually Uniform Systems	40
2.7 Uniform Color Spaces (UCS)	41
2.8 Summary and Notes	44

<b>3</b>	<b>COLOR IN COMPUTER GRAPHICS</b>	45
3.1	Introduction	46
3.2	The Color Monitor, the Colorcube, and the RGB Model	47
3.3	The Lightness, Hue, and Saturation (LHS) Family of Models	49
3.4	GLHS: A Generalized Lightness, Hue, and Saturation Model	55
3.5	Illustrations of GLHS	69
3.6	Summary and Notes	73
<b>4</b>	<b>MULHS—A MOST UNIFORM LHS MODEL: APPROXIMATING UNIFORM COLOR SPACES WITH THE GLHS FAMILY OF MODELS</b>	75
4.1	Introduction: A Minimization Problem	76
4.2	GLHS Approximation of the CIELUV Uniform Color Space	77
4.3	GLHS Approximation of The Munsell Book of Color	78
4.4	Summary and Notes	80
<b>5</b>	<b>COLOR VISION FOR COMPLEX VISUAL TASKS</b>	89
5.1	Color and Visual Search	89
5.2	Visual-Verbal Interactions: The Stroop Effect (1935)	93
5.3	Color Discrimination vs. Color Naming	94
5.4	Color Contrast and Color Constancy	94
5.5	Context Dependence	98
5.6	Temporal Chromatic Effects	98
5.7	Summary and Notes	98
<b>Part II APPLICATIONS IN GRAPHICS, VISUALIZATION, AND MULTIMEDIA APPLICATIONS</b>		99
<b>6</b>	<b>COLOR DEVICES</b>	101
6.1	Introduction to Color Calibration	101
6.2	Gamut matching	106
6.3	Summary and Notes	107

<b>7</b>	<b>COLOR SCALES FOR IMAGE DATA: DESIGN AND EVALUATION</b>	109
7.1	Introduction	109
7.2	Desired Properties for Color Scales	110
7.3	Commonly Used Scales	111
7.4	The Problem of Optimal Color Scales	112
7.5	Solution Approach and Implementation	120
7.6	Results of <i>OPTIMAL-SCALES</i>	122
7.7	Linearization of Color Scales	126
7.8	Evaluation of Optimal Color Scales	126
7.9	Results of the Evaluation	129
7.10	Summary and Notes	132
<b>8</b>	<b>PERCEPTUAL STEPS ALONG COLOR SCALES</b>	135
8.1	Introduction	135
8.2	Adjusting Perceptual Steps of Color Scales	137
8.3	Linearization of Color Scales	137
8.4	Summary and Notes	142
<b>9</b>	<b>INTEGRATED VISUALIZATION OF MULTIPARAMETER DISTRIBUTIONS</b>	145
9.1	Introduction and Background	145
9.2	Visually-based Integration Techniques: The Iconographic Approach	149
9.3	Color Integrated Displays Using the GLHS Family of Color Models	150
9.4	Summary and Notes	152
<b>10</b>	<b>COLOR ICONS: MERGING COLOR AND TEXTURE PERCEPTION FOR INTEGRATED VISUALIZATION OF MULTIPLE PARAMETERS</b>	153
10.1	Merging Color, Shape, and Texture Perception for Integra- tion: The Original Color Icon	154
10.2	Illustrations and Examples	157
10.3	Second Generation: New Design and Implementation	164

10.4 Color Icon Surfaces	169
10.5 Parallel Implementation	169
10.6 Applications and Examples	177
10.7 Summary and Notes	187
<b>11 COLOR ON THE WORLD-WIDE WEB</b>	<b>189</b>
11.1 Color capabilities on the Web	190
11.2 What's ahead?	191
<b>REFERENCES</b>	<b>195</b>
<b>ADDITIONAL BIBILIOGRAPHY</b>	<b>205</b>
<b>INDEX</b>	<b>213</b>



---

# LIST OF FIGURES

## Chapter 1

1.1	Schematic of the eye.	9
1.2	Luminance response function.	13
1.3	Contrast sensitivity function.	14
1.4	Interlaced vs. non-interlaced flicker.	16
1.5	Individual cone mechanisms are color blind.	18
1.6	A bichromatic yellow.	19
1.7	A monochromatic yellow.	20
1.8	Photoreceptor output recombination into opponent channels.	23
1.9	Abnormal M-type cones.	24
1.10	Abnormal L-type cones.	25
1.11	Achromatic and chromatic grating detection.	28
1.12	Size and Perceived Color.	30

## Chapter 2

2.1	Continuous variations in hue, saturation, lightness.	32
2.2	Pseudo-perceptual order systems.	37
2.3	Pseudo-perceptual order systems.	38
2.4	Pseudo-perceptual order systems.	39

## Chapter 3

3.1	The RGB Colorcube.	48
3.2	Tints, shades, and tones.	50
3.3	Points of the same hue as c.	59
3.4	A general cross section through the GLHS Model.	63
3.5	Another general cross section through the GLHS Model.	64
3.6	A third general cross section through the GLHS Model.	65
3.7	The RGB-TO-GLHS transformation algorithm.	66

3.8	The GLHS-TO-RGB transformation algorithm.	68
3.9	MCMTRANS: Multiple Color Model Specification and Transformation System.	70
3.10	The plane perpendicular to the main diagonal.	72

## Chapter 4

4.1	Constant GLHS hue and saturation curves for maximizer space.	81
4.2	Constant GLHS hue and saturation curves for hexcone.	82
4.3	GLHS hue plane for maximizer space.	83
4.4	GLHS hue plane for hexcone.	84
4.5	Constant Munsell hue and chroma curves in $(u^*, v^*)$ -coordinates.	85
4.6	Munsell hue plane in $(L^*, C_{uv}^*)$ -coordinates.	86

## Chapter 5

5.1	Preattentive search.	90
5.2	Preattentive color features distract. (See Web site for color version.)	91
5.3	Preattentive color features help. (See Web site for color version.)	92
5.4	Visual-verbal interaction, after [Sch90a]. (See Web site for a color version.)	93
5.5	Perceived color depends on the color of background.	95
5.6	Induction of complementary hues.	96
5.7	Color Constancy isn't Perfect (after [WBR87]).	97

## Chapter 6

## Chapter 7

7.1	Non-linearized grayscale.	113
7.2	Linearized grayscale.	114
7.3	The rainbow scale.	115
7.4	The heated-object scale.	116
7.5	The magenta scale.	117
7.6	Algorithm <i>OPTIMAL-SCALES</i> .	123
7.7	OCS: The optimal color scale.	125
7.8	LOCS: The linearized optimal color scale.	127

7.9 An example of an abnormal image used in the study.	130
7.10 ROC curves.	131

**Chapter 8**

8.1 Illustration of the linearization process.	139
8.2 Scale comparison.	143

**Chapter 9**

9.1 MCMIDS—Multiple Color Model Image Display System.	151
---	-----

**Chapter 10**

10.1 The color icon with six linear features.	155
10.2 A picture of an enlarged color icon.	156
10.3 Increasing the number of parameters.	157
10.4 Generation of the three synthesized images.	159
10.5 The three synthesized images in gray scale.	159
10.6 The three synthesized images in color models.	160
10.7 The three synthesized images in color icons and LOCS.	161
10.8 The three synthesized images in color icons and separate scales.	162
10.9 The three synthesized images in color icons.	163
10.10MR brain with malignant glioma.	165
10.11Brain MR images in color models.	166
10.12A color icon integrated image of the two brain sections. Two parameter-to-color-scale mappings are shown. T1 in LOCS, T2 in heated-object scale.	167
10.12Another color icon integration of the same section; T1 in heated-object, T2 in LOCS. (See Web site for color versions.)	168
10.13One-Limb Configuration.	170
10.14Two-Limb Configuration.	171
10.15Three-Limb Configuration.	172
10.16Four-Limb Configuration.	173
10.17Original images used to implement the iconographic technique for sensor fusion. (See Web site for color version.)	179
10.18Visible and thermal image integration.	180
10.19An integrated image of the FBI homicide database.	181

10.20	Four raw satellite images of the great lakes. (See also a version on the Web site.)	183
10.21	Two color icon integrated images.	184
10.22	Three parameter color icon integration.	185
10.23	Four-parameter color icon integration.	186

## **Chapter 11**

---

# LIST OF TABLES

## Chapter 1

- 1.1 Physical vs. Perceptual Terms. 8

## Chapter 2

- 2.1 Color specification systems summary. 34  
2.2 HSL in CIELUV and CIELAB. 43

## Chapter 3

- 3.1 Comparison of lightness in LHS models. 55  
3.2 Computer graphics models in GLHS. 57

## Chapter 4

- 4.1 Average difference values. 79

## Chapter 5

## Chapter 6

## Chapter 7

- 7.1 The  $\Delta(j)$  operators. 121  
7.2 Results of experiments. 129

## Chapter 8

## Chapter 9

## Chapter 10

10.1 Synthesized data generation.

158

**Chapter 11**

---

## PREFACE

Imagine a world in which the colors you see do not necessarily represent the correct ones. Imagine, when you approach a traffic light, you cannot tell what color the light is. Imagine the colors of traffic lights changing from one block to the next one. Could you?

If you can't, just go to your computer. In the world of visual computing, you cannot be sure what the colors will be. Even today. And today, the awareness of computer professionals to color has grown orders of magnitude.

When I got introduced to some interesting color problems in medical imaging back in 1984 (and thus reintroduced to color, which I had researched and explored in the seventies), it seemed like nobody really bothered; there were very few publications that attempted to understand the relationship between color and the computer.

Within a few years, that number grew significantly. Finally, people were beginning to realize that, just as colors play such an important role in our day-to-day life, they are important on our computer displays. And, thus, color should be studied, and the appropriate usage on computer displays should be explored, understood, and *practiced*. I cannot say we have reached that stage, yet, but I am glad to report that progress has been made.

This book is the result of over a dozen years of research, teaching, consulting, and advising, first at the Medical Image Processing Group, Department of Radiology, the University of Pennsylvania, and then here at the Institute for Visualization and Perception Research and the Graphics Research Laboratory at the University of Massachusetts Lowell.

I started putting the material presented here together the first time for a half-day color tutorial I taught at the IEEE Visualization '91 conference in San Diego. The success of that tutorial suggested that it should be expanded from a half-day to a full-day course, and that inviting other color experts to contribute their expertise would strengthen it. As a result, I invited Philip Robertson (then of CSIRO, Canberra, Australia, and now with Canon Research in Sydney) and Bernice Rogowitz (IBM Research, Yorktown Heights, NY) to join me. We took our "show" to SIGGRAPH '92 in Chicago, and again to IEEE Visualization '92 in Boston. Phil's and Bernice's contributions to the tutorial, and thereby to this book, were numerous and significant. I am grateful to them for lending me their vast knowledge and experience.

Since then I have taught a similar tutorial at several other conferences, and have used parts of this material in my visualization tutorials, as well as in my computer graphics and visualization courses here at Lowell.

Over the years, many people have asked me for advice about their color graphics applications. At some point, I got convinced that many others, who haven't had the opportunity to take the tutorial, and who couldn't ask me questions, could use some of the material presented here. Thus came the idea for of this book.

The goal of this book is not to teach you everything you need to know about color; numerous publications are available to do that. It is not even to teach you everything you need to know about color computer graphics; no, there aren't numerous publication available to do that. The goal of this book is to convince you that it is important to pay attention to color (if you are not convinced yet); to give you the basic fundamentals of color vision in general, and as related to visual computing in particular; to make you aware of the repercussions of your color choices; and to stimulate you to further explore this topics. One not-so-hidden agenda: I'd like to encourage students to pick color as their doctoral research topic.

To help us accomplish these goals, we have established a World-Wide Web (<http://www.cs.uml.edu/~haim/ColorCenter>) site, where you can find all the color images, more information, examples, tools, and links to other related sites. As all good Web sites should be (forever), this site is under construction, and will hopefully remain so. What you will find on the Web site are all the color figures in the book, additional example images, recommended color scales, some useful software tools, an extended, annotated bibliography, and links to other relevant sites.

We would like you to visit the site, and take advantage of what is available there. To make the most of it, we suggest the use of an automatic monitor (such as URL-minder at <http://www.netmind.com/URL-minder/URL-minder.html>) to alert you to changes in the site.

We would also appreciate your comments, suggestions, contributions, and critique.

This book would not have materialized if not for many people who have helped me, directly or indirectly, make it happen.

More than fifteen years ago, my colleague and friend Yair Censor influenced to a large degree the direction of my academic career. Gabor Herman, my doctoral



dissertation advisor, colleague, and friend, made significant contributions to the material presented in this book. Ron Pickett found me at a job I did not enjoy, and together with Georges Grinstein and Stu Smith, brought me over to Umass Lowell, where I have had a wonderful time ever since. Giam Pecelli, our previous Department Chair, and Jim Canning, our current Chair, have both provided me enormous support here; they, together with the rest of the Computer Science Department faculty, have made it so wonderful to work here.

Many extremely capable and dedicated students have worked over the years on projects, the results of which can be found in this book and on the Web site: Kerry Shetline wrote the first versions of MCMTRANS and MCMIDS (and suffered through my notorious bug-finding ability). Nupur Kapoor and Bogdan Pytlik implemented the first version of the color icon. David Gonthier developed the new version of the color icon, and incorporated it in NewExvis, our visualization environment. He was helped by Jude Fatyol, Omar Hoda, and Lisa Masterman. Rob Erbacher developed the parallel implementation of the color icon and the GLHS color model. Krishnan Seetharaman added three-dimensional spaceball navigation to the GLHS color model, and made numerous other contributions, too numerous to list them all. Alex Gee, Pat Hoffman, J.P. Lee, Dave Pinkney, and Marjan Trutschl, have all helped make life at IVPR as pleasant as it is, in many different ways, but mostly in their eagerness to do whatever is necessary, whenever it is necessary. When one is blessed with having so many wonderful students, it is inevitable to forget someone; my apologies to those I have not mentioned: your contributions have been as important and as appreciated.

My family in Israel, Colombia, and here in the US, all deserve my thanks for all they have given me over the years.

Finally, no thanks could be enough to Ea, Merav, and Shir, with whom I should be spending this weekend, instead of in front of my computer, writing this. It's wonderful to have you!

*Lowell, Massachusetts  
January 1997*

*Haim Levkowitz*