

# Contents

<b>Preface</b>	<b>XX</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Organization of the Book . . . . .	1
<b>2 Fundamentals of Light</b>	<b>3</b>
2.1 Introduction . . . . .	3
2.2 Electromagnetic Radiation . . . . .	5
2.3 Principles of Light Generation . . . . .	6
2.3.1 Thermal Radiation . . . . .	9
Radiation, Absorption and Efficiency . . . . .	10
2.3.2 Applications of Thermal Radiation Laws . . . . .	16
2.3.3 Open Systems and the Greenhouse Effect . . . . .	18
2.3.4 Color Temperature . . . . .	20
2.3.5 Bremsstrahlung . . . . .	22
2.3.6 Photon Energies . . . . .	24
2.3.7 Electron Excitation . . . . .	25

## *Contents*

---

2.3.8	Gas Discharge . . . . .	27
	Plasma Lamps . . . . .	28
	Arc Lamps . . . . .	28
	Phosphors . . . . .	29
	Fluorescent lamps . . . . .	31
	Other Forms of Luminescence . . . . .	31
2.3.9	Electro Luminescence . . . . .	32
	LED . . . . .	32
	OLED . . . . .	33
2.4	Measuring Light . . . . .	34
2.4.1	Radiometry . . . . .	34
	Angular Range . . . . .	35
	Lambert Emitters . . . . .	35
	Solid Angle and Angular Density . . . . .	35
	The Ulbricht Sphere . . . . .	37
2.4.2	Photometry . . . . .	40
2.4.3	Luminous Efficiency of Light Sources . . . . .	42
2.4.4	Durability of Light Sources . . . . .	44
2.5	Physics of Light . . . . .	45
2.5.1	Interference . . . . .	45
2.5.2	Quantum Effects . . . . .	46
2.5.3	The Double Slit Experiment . . . . .	51
	The Uncertainty Relation . . . . .	58

## *Contents*

---

2.5.4	Fourier Spectrum . . . . .	61
2.5.5	Radiation Processes Revisited . . . . .	63
2.5.6	Tunneling . . . . .	64
2.5.7	Quantum Dots . . . . .	66
2.5.8	Polarization . . . . .	67
	Polarizer Filters . . . . .	69
	Polarization and Quantum Physics . . . . .	69
	Turning Polarization . . . . .	72
2.5.9	Circular Polarization . . . . .	73
	Producing Circular Polarized Light . . . . .	74
2.6	Summary . . . . .	76
<b>3</b>	<b>Principles of Optics</b>	<b>77</b>
3.1	Introduction . . . . .	77
3.2	Wave Optics . . . . .	79
3.3	Lasers . . . . .	85
	3.3.1 Stimulated Emission . . . . .	85
	3.3.2 Laser Beam Divergence . . . . .	91
3.4	Geometric Optics . . . . .	95
	3.4.1 Light Modulation . . . . .	96
	Scattering . . . . .	96
	Refraction . . . . .	98
	3.4.2 Homogeneous vs. Inhomogeneous Media . . . . .	102
	3.4.3 Snell's Law Vectorized . . . . .	104

## *Contents*

---

3.5	Formation of Point Images . . . . .	107
3.5.1	Reflective Optics . . . . .	109
	Planar Mirrors . . . . .	109
	Spherical Mirrors . . . . .	110
	Concave Parabolic Mirrors . . . . .	112
	Convex Parabolic Mirrors . . . . .	113
	Varifocal Mirrors . . . . .	113
3.5.2	Refractive Optics . . . . .	114
	Lenses . . . . .	115
	Converging Lenses . . . . .	117
	Diverging Lenses . . . . .	119
	Plane Parallel and Curved Parallel Lenses . . . . .	119
	Apertures . . . . .	120
	Vignetting . . . . .	123
	Varifocal Lenses . . . . .	123
	Fresnel Lenses . . . . .	125
	Lens Resolution . . . . .	126
	Depth of Field . . . . .	128
3.5.3	The Plenoptic Function . . . . .	129
3.6	Summary . . . . .	133
<b>4</b>	<b>Basics of Visual Perception</b>	<b>135</b>
4.1	Introduction . . . . .	135
4.2	The Human Visual System . . . . .	137

## *Contents*

---

4.2.1	The Eye as an Optical System . . . . .	137
4.2.2	Saccades . . . . .	138
4.2.3	Temporal Response . . . . .	139
4.2.4	Contrast and Dynamic Range . . . . .	140
4.2.5	Resolution . . . . .	144
4.3	Colorimetry . . . . .	146
4.3.1	CIE Color Matching Functions . . . . .	150
4.3.2	The CIE Chromaticity Diagram . . . . .	152
4.3.3	Color Separation of the Eye . . . . .	154
4.3.4	Color Recording . . . . .	156
4.3.5	Neuro-Physiological Results . . . . .	159
	Retinal Image Processing . . . . .	161
4.4	Depth Perception . . . . .	163
4.4.1	The Human Visual Field . . . . .	165
4.4.2	Depth Cues . . . . .	166
	Convergence . . . . .	168
	Retinal Disparity . . . . .	168
	Accommodation . . . . .	170
	Focus Effects . . . . .	173
	Haze . . . . .	174
	Color . . . . .	174
	Motion Parallax and Motion Dynamics . . . . .	175
4.4.3	Stereo Picture Recording . . . . .	179

## *Contents*

---

4.5	Motion Pictures . . . . .	180
4.5.1	Pitfalls . . . . .	181
4.5.2	Film Projection . . . . .	182
4.6	Summary . . . . .	183
<b>5</b>	<b>Holographic Principles</b>	<b>185</b>
5.1	Introduction . . . . .	185
5.2	Holography: An Executive Summary . . . . .	188
5.2.1	Holographic Object Recognition . . . . .	190
5.2.2	A Basic Hologram Setup . . . . .	191
5.3	Interference and Diffraction . . . . .	194
5.3.1	The Grating Equation . . . . .	197
5.3.2	Holographic Point Formation in Detail . . . . .	199
5.3.3	Phase Holograms . . . . .	202
5.3.4	Embossed Holograms . . . . .	204
5.3.5	Color Dispersion . . . . .	205
5.3.6	Volume Gratings . . . . .	206
	Volume Grating Construction . . . . .	206
	Volume Grating Reconstruction . . . . .	208
	Resolution Requirements . . . . .	212
	Bragg's Law . . . . .	213
	Color Dependency . . . . .	214
5.3.7	Hologram Efficiency . . . . .	215
5.3.8	Holograms and Displays - Basic Considerations . . . . .	216

*Contents*

---

5.3.9	Temporal Coherence . . . . .	218
5.3.10	Spatial Coherence . . . . .	221
5.3.11	Laser Speckle . . . . .	223
5.4	Holographic Optical Elements (HOE) . . . . .	224
5.4.1	Headup Displays . . . . .	225
5.4.2	Construction of an HOE . . . . .	227
	A Detailed Construction Setup . . . . .	228
5.4.3	HOE Angular and Frequency Response . . . . .	230
5.4.4	HOE's vs. Conventional Optics . . . . .	232
5.4.5	Camera Lenses with HOE's . . . . .	236
5.4.6	Virtual HOE's . . . . .	236
5.4.7	Spatial Light Modulators . . . . .	236
5.4.8	Beam Splitters and Diverters . . . . .	237
	Switched HOE's . . . . .	238
5.4.9	Holographic Projection Screens . . . . .	238
5.4.10	Visual Perception of Holograms . . . . .	245
5.4.11	'Keyhole' Holograms . . . . .	248
5.5	Optical Holography . . . . .	249
5.5.1	Optical Distortion . . . . .	253
5.5.2	Transmission Holograms . . . . .	256
5.5.3	Reflection Holograms . . . . .	257
5.5.4	Rainbow Holograms . . . . .	260
5.5.5	Color Holograms . . . . .	264

## *Contents*

---

5.5.6	Multi-Channel Holograms . . . . .	269
5.5.7	Holographic Stereograms . . . . .	271
5.5.8	Digital Volumetric Holograms . . . . .	276
5.6	Summary . . . . .	277
<b>6</b>	<b>Display Basics</b>	<b>279</b>
6.1	Introduction . . . . .	279
6.2	Fundamental Measures . . . . .	280
6.2.1	Resolution . . . . .	281
6.2.2	Interlacing . . . . .	287
6.2.3	TV Standards . . . . .	290
	Eye Resolution and Displays . . . . .	293
6.2.4	Brightness . . . . .	296
6.2.5	Contrast and Dynamic Range . . . . .	297
6.2.6	Gamma . . . . .	299
6.2.7	Angular Range . . . . .	301
	Viewing Cone . . . . .	302
6.2.8	Speed . . . . .	304
6.3	Color and Intensity Production . . . . .	306
6.3.1	Color Gamut . . . . .	306
6.3.2	Wide Color Gamut Displays . . . . .	307
6.3.3	Multi Color Displays . . . . .	309
6.3.4	Additive and Subtractive Color Mixing . . . . .	311
	Subtractive Color Mixing . . . . .	311



## *Contents*

---

6.3.5	YUV-Formats . . . . .	313
6.3.6	Dyes and Filters . . . . .	316
6.3.7	Light Sources . . . . .	317
6.3.8	Luminescent vs. Light Valve Displays . . . . .	317
6.3.9	Test Pictures . . . . .	319
6.4	Electronics . . . . .	321
6.4.1	Signal Transmission . . . . .	322
6.4.2	Signal Processing . . . . .	324
6.4.3	Anti-Aliasing . . . . .	325
6.4.4	Moiré . . . . .	327
6.4.5	Image Processing . . . . .	328
	Resizing . . . . .	328
	Noise Reduction . . . . .	329
6.4.6	Image Compression . . . . .	330
6.4.7	De-interlacing . . . . .	333
6.4.8	Semiconductors . . . . .	338
6.4.9	Passive Matrix Displays . . . . .	343
6.4.10	Multiplexing and Connection . . . . .	344
	Connection . . . . .	348
6.4.11	Active Matrix Displays . . . . .	348
6.5	Assembly . . . . .	353
6.5.1	Panel Construction . . . . .	354
6.5.2	Backlighting . . . . .	355

## *Contents*

---

6.5.3	Anti-Reflective Coatings . . . . .	356
	Sol-Gel Coating . . . . .	359
6.5.4	Touch Screens . . . . .	360
	Force Detection . . . . .	361
	Surface Wave Detection . . . . .	362
	Light Grid and Optical Imaging . . . . .	363
	Bi-Directional Display Touch Detection . . . . .	364
	Resistive Panels . . . . .	365
	Percolation . . . . .	365
	Quantum Tunneling Composite (QTC) . . . . .	365
	Location Sensing . . . . .	366
	Surface Capacitance . . . . .	367
	Projected Capacitance (PCT) . . . . .	367
	Inductive Touch Panels . . . . .	369
6.5.5	Flexible Electronics . . . . .	369
6.5.6	Transparent Circuits . . . . .	371
	Inorganic Transparent Conductors and Semiconductors . .	372
	Carbon Nanotubes . . . . .	373
6.5.7	Printed Displays . . . . .	377
6.6	Summary . . . . .	379
<b>7</b>	<b>Spatial Light Modulation</b>	<b>380</b>
7.1	Introduction . . . . .	380
7.2	Transmissive Displays . . . . .	382

## *Contents*

---

7.2.1	LCD . . . . .	382
	Driving LC Displays . . . . .	386
	Driver Structures . . . . .	386
	LCD and Motion . . . . .	387
7.2.2	FLC . . . . .	389
7.2.3	TMOS . . . . .	389
7.2.4	Dyed Guest Host Displays . . . . .	390
7.2.5	Other . . . . .	391
7.3	Reflective Displays . . . . .	392
7.3.1	LCOS . . . . .	392
	F-LCOS . . . . .	393
	Phase Shifting LCD . . . . .	395
7.3.2	Bi-Stable LC displays . . . . .	395
7.3.3	DMD . . . . .	399
	Driving DMDs . . . . .	402
7.3.4	Advanced Driving Techniques . . . . .	404
7.3.5	PISTON Type Micro Mirror Displays . . . . .	406
7.3.6	MLM . . . . .	408
7.3.7	GLV . . . . .	408
7.3.8	Polymer Displays . . . . .	410
	Electrochromic Polymers . . . . .	410
7.3.9	E-Ink . . . . .	410
7.3.10	Electrowetting Displays . . . . .	413

## *Contents*

---

7.3.11	Electrofluidic Displays . . . . .	413
7.3.12	iMOD Displays . . . . .	414
7.3.13	Refractive Index Modulation . . . . .	415
7.3.14	Electronic Paper . . . . .	416
7.4	Transflective Displays . . . . .	418
7.5	Emissive Displays . . . . .	421
7.5.1	CRT . . . . .	421
	Deflection . . . . .	428
7.5.2	FED and SED . . . . .	429
7.5.3	Plasma Displays . . . . .	431
	ALIS . . . . .	432
7.5.4	Electroluminescence Displays . . . . .	434
7.5.5	LED . . . . .	435
7.5.6	OLED . . . . .	436
	Transparent OLED . . . . .	439
	OLED on CMOS . . . . .	439
7.5.7	Vacuum Fluorescence Displays . . . . .	440
7.5.8	Cold Cathode Tubes . . . . .	440
7.6	High Dynamic Range Displays . . . . .	441
7.6.1	Rendering for HDR LCD Displays . . . . .	445
7.7	Bi-Directional Displays . . . . .	447
7.8	Projection Displays . . . . .	448
7.8.1	Projector Optics Overview . . . . .	450

## *Contents*

---

7.8.2	Projection Lenses . . . . .	456
	Offset Projection . . . . .	457
7.8.3	Projector Lamps . . . . .	458
7.8.4	CRT and OLED Projectors . . . . .	461
7.8.5	LCD Projectors . . . . .	464
7.8.6	DLP and GLV Projectors . . . . .	466
7.8.7	Eidophor Projector . . . . .	467
7.8.8	Dichroic Combiners . . . . .	468
7.8.9	Fourier Holographic Projector . . . . .	469
7.8.10	Projection Screens . . . . .	471
7.8.11	Rear Projection . . . . .	473
7.8.12	Wedge Displays . . . . .	475
7.8.13	Collimated Displays . . . . .	477
7.8.14	'Quantum' Displays . . . . .	478
7.8.15	Laser Projectors . . . . .	481
	Far-Field Laser Projectors . . . . .	483
	MEMS Scanners . . . . .	484
7.8.16	Beam Deflection Modes . . . . .	487
7.9	Summary . . . . .	489
<b>8</b>	<b>Projector-Camera Systems</b>	<b>491</b>
8.1	Introduction . . . . .	491
8.2	Challenges of Non-Optimized Surfaces . . . . .	494
8.3	Geometric Registration . . . . .	496

## *Contents*

---

8.3.1	Uniformly Colored Surfaces of Known Geometry . . . . .	496
8.3.2	Textured Surfaces and Surfaces of Unknown Geometry . .	501
8.3.3	Embedded Structured Light . . . . .	503
8.4	Radiometric Compensation . . . . .	508
8.4.1	Static Techniques . . . . .	509
8.4.2	Dynamic Surfaces and Configurations . . . . .	517
8.4.3	Dynamic Image Adaptation . . . . .	521
8.4.4	Enhancing Contrast . . . . .	526
8.5	Correcting Complex Light Modulations . . . . .	527
8.5.1	Interreflections . . . . .	528
8.5.2	Specular Reflections . . . . .	532
8.5.3	Radiometric Compensation through Inverse Light Trans- port . . . . .	533
8.6	Overcoming Technical Limitations . . . . .	538
8.6.1	Increasing Depth of Field . . . . .	539
8.6.2	Super-Resolution . . . . .	545
8.6.3	High Dynamic Range . . . . .	551
8.6.4	High Speed . . . . .	557
8.7	Summary . . . . .	563
<b>9</b>	<b>Three-Dimensional Displays</b>	<b>565</b>
9.1	Introduction . . . . .	565
9.2	Three-Dimensional Displays: Basic Considerations . . . . .	570
9.2.1	Orientation . . . . .	570

## *Contents*

---

9.2.2	Distance and Depth . . . . .	571
9.2.3	Perspective . . . . .	576
9.2.4	3D TV vs. 3D Cinema . . . . .	578
9.2.5	Toward Light Field Displays . . . . .	581
9.3	Spatial Stereoscopic Displays . . . . .	583
9.3.1	Stereo-Channel Separation . . . . .	584
9.3.2	Projection Screens . . . . .	595
9.3.3	Screen Configurations and Rendering . . . . .	597
9.3.4	Stereoscopic Multi-Viewer Techniques . . . . .	601
9.4	Autostereoscopic Displays . . . . .	605
9.4.1	Parallax Displays . . . . .	606
	Barrier Displays . . . . .	606
	Lenticular Displays . . . . .	609
	Time-Multiplexed Displays . . . . .	613
	Multi-Viewer Techniques . . . . .	615
	Basic Categories . . . . .	618
9.4.2	Volumetric Displays . . . . .	619
	Swept Volume Displays . . . . .	620
	Static Volume Displays . . . . .	622
9.5	Light Field Displays . . . . .	624
9.5.1	Parameterization . . . . .	627
9.5.2	Light Fields vs. Holograms . . . . .	629
9.5.3	Light Field Display Implementations . . . . .	632

## *Contents*

---

9.5.4	An Adaptive Approach to Light Field Displays . . . . .	634
	Electrowetting Prisms and other approaches . . . . .	640
9.5.5	Light Field Focus Synthesis . . . . .	641
9.5.6	Depth Of Field and Light field Recording . . . . .	643
9.6	Computer-Generated Holograms . . . . .	644
9.6.1	Displaying Computed Fringe Patterns . . . . .	645
9.6.2	Computing a Hologram . . . . .	645
9.6.3	Fourier Hologram Synthesis . . . . .	649
9.6.4	Adaptive Holographic Displays . . . . .	652
	Discussion . . . . .	661
9.7	3D Media Encoding . . . . .	662
9.7.1	Light Field Encoding . . . . .	663
9.7.2	Camera Array (Multi-View) Encoding . . . . .	664
9.7.3	Holographic 'Millimeter Wave' Encoding . . . . .	667
9.8	Summary . . . . .	670
<b>10</b>	<b>Near-Eye Displays</b>	<b>676</b>
10.1	Introduction . . . . .	676
10.2	Examples of Near-Eye Displays . . . . .	678
10.2.1	View-Covering Head-Attached Displays for Virtual Real- ity and Personal Video Viewing . . . . .	679
10.2.2	Semi-Covering Head-Attached Displays for Personal In- formation Presentation . . . . .	680
10.2.3	Optical See-Through Displays . . . . .	682



## *Contents*

---

10.3	Eye Physiological Aspects . . . . .	684
10.4	Economy and Ecology . . . . .	688
10.4.1	Brightness of Virtual Displays . . . . .	688
10.5	Micro Display Technologies . . . . .	690
10.6	An Optical Design Study . . . . .	693
10.6.1	Exit Pupil . . . . .	698
10.6.2	Self-Adaptation . . . . .	699
10.7	Laser Displays . . . . .	703
10.7.1	A Classical Laser Scanner Design . . . . .	704
10.7.2	A More Versatile Laser Display Design . . . . .	705
10.7.3	Exit Pupil . . . . .	708
10.8	Advanced Laser Scanning . . . . .	709
10.8.1	Holographic Scanners . . . . .	714
10.9	Holographic Near-Eye Displays . . . . .	718
10.10	Beam Combiners . . . . .	720
10.10.1	Dichroic Combiners . . . . .	721
10.10.2	Holographic Combiners . . . . .	724
10.10.3	Advanced HOE Designs . . . . .	726
10.10.4	Contact Lens Displays . . . . .	727
10.11	Geometry Adaptive Displays and Eye Tracking . . . . .	733
10.11.1	Adaptation Requirements . . . . .	734
10.11.2	Eye Tracking . . . . .	736
	Optical Constructions with Eye Trackers . . . . .	739

## Contents

---

Combining Eye Tracking with SLMs . . . . .	740
10.11.3 Retina Tracking . . . . .	742
10.11.4 Dynamic Image Linearization . . . . .	749
10.11.5 Micro Motors . . . . .	750
10.12 Image Integration . . . . .	753
10.12.1 Optical Compensation . . . . .	753
10.12.2 Eyetaps and Video-See-Trough . . . . .	754
10.12.3 Mask Displays . . . . .	756
Technologies for Mask Displays . . . . .	764
10.13 Summary . . . . .	766
<b>11 Discussion and Outlook</b>	<b>768</b>
<b>Appendix: Image Processing for Displays</b>	<b>769</b>
A The Fixed Function Graphics Pipeline . . . . .	770
A.1 Transformations . . . . .	772
A.2 Rasterization . . . . .	774
A.3 Framebuffer Operations . . . . .	775
B The Programmable Graphics Pipeline . . . . .	776
C Graphics Hardware . . . . .	778
D GPU Programming Languages . . . . .	780
D.1 High Level Shading Languages . . . . .	781
GLSL . . . . .	781
Cg . . . . .	782

## *Contents*

---

	Other Languages: . . . . .	782
D.2	General Purpose Computation on the GPU . . . . .	783
	Nvidia CUDA . . . . .	783
	ATI Stream . . . . .	784
	DirectX Compute Shaders . . . . .	784
	OpenCL . . . . .	784
E	An Introduction to GPU Programming by Example . . . . .	785
F	The Swiss Army Knife of GPU Image Processing . . . . .	789
F.1	Basics Shaders . . . . .	790
F.2	Homography Warping via Vertex Shading . . . . .	796
F.3	Compensation of Interreflection via Dependent Texture Lookups . . . . .	798
F.4	Histogram Calculations with Geometry Shading . . . . .	800
F.5	Anaglyph Rendering via Fragment Shading . . . . .	802
F.6	Color Space Conversion via Fragment Shading . . . . .	805
F.7	Image Undistortion via Fragment Shading . . . . .	809
F.8	Convolution via Fragment Shading . . . . .	811
F.9	Fast Fourier Transformations via CUDA . . . . .	813