
1	A Survey of Computer Graphics	2
1-1	Graphs and Charts	3
1-2	Computer-Aided Design	5
1-3	Virtual-Reality Environments	10
1-4	Data Visualizations	12
1-5	Education and Training	19
1-6	Computer Art	23
1-7	Entertainment	28
1-8	Image Processing	31
1-9	Graphical User Interfaces	32
1-10	Summary	33
	References	33

2	Overview of Graphics Systems	34
2-1	Video Display Devices	35
	• Refresh Cathode-Ray Tubes	36
	• Raster-Scan Displays	39
	• Random-Scan Displays	41
	• Color CRT Monitors	42
	• Flat-Panel Displays	44
	• Three-Dimensional Viewing Devices	47
	• Stereoscopic and Virtual-Reality Systems	48

2-2	Raster-Scan Systems	50
	• Video Controller	50
	• Raster-Scan Display Processor	52
2-3	Graphics Workstations and Viewing Systems	54
2-4	Input Devices	57
	• Keyboards, Button Boxes, and Dials	57
	• Mouse Devices	57
	• Trackballs and Spaceballs	59
	• Joysticks	59
	• Data Gloves	60
	• Digitizers	60
	• Image Scanners	62
	• Touch Panels	64
	• Light Pens	65
	• Voice Systems	65
2-5	Hard-Copy Devices	66
2-6	Graphics Networks	68
2-7	Graphics on the Internet	68
2-8	Graphics Software	69
	• Coordinate Representations	69
	• Graphics Functions	71
	• Software Standards	72
	• Other Graphics Packages	73
2-9	Introduction to OpenGL	73
	• Basic OpenGL Syntax	74
	• Related Libraries	74
	• Header Files	75
	• Display-Window Management Using GLUT	76
	• A Complete OpenGL Program	77

2-10	Summary	81
	References	82
	Exercises	82

3 Graphics Output Primitives **84**

3-1	Coordinate Reference Frames	86
	• Screen Coordinates	86
	• Absolute and Relative Coordinate Specifications	87
3-2	Specifying a Two-Dimensional World-Coordinate Reference Frame in OpenGL	87
3-3	OpenGL Point Functions	88
3-4	OpenGL Line Functions	91
3-5	Line-Drawing Algorithms	92
	• Line Equations	93
	• DDA Algorithm	94
	• Bresenham's Line Algorithm	95
	• Displaying Polylines	99
3-6	Parallel Line Algorithms	99
3-7	Setting Frame-Buffer Values	101
3-8	OpenGL Curve Functions	102
3-9	Circle-Generating Algorithms	103
	• Properties of Circles	103
	• Midpoint Circle Algorithm	105
3-10	Ellipse-Generating Algorithms	109
	• Properties of Ellipses	109
	• Midpoint Ellipse Algorithm	110
3-11	Other Curves	117
	• Conic Sections	117
	• Polynomials and Spline Curves	119
3-12	Parallel Curve Algorithms	119
3-13	Pixel Addressing and Object Geometry	120
	• Screen Grid Coordinates	120
	• Maintaining Geometric Properties of Displayed Objects	121
3-14	Fill-Area Primitives	123
3-15	Polygon Fill Areas	124
	• Polygon Classifications	124
	• Identifying Concave Polygons	125
	• Splitting Concave Polygons	125

	• Splitting a Convex Polygon into a Set of Triangles	127
	• Inside-Outside Tests	127
	• Polygon Tables	129
	• Plane Equations	131
	• Front and Back Polygon Faces	132
3-16	OpenGL Polygon Fill-Area Functions	134
3-17	OpenGL Vertex Arrays	139
3-18	Pixel-Array Primitives	142
3-19	OpenGL Pixel-Array Functions	143
	• OpenGL Bitmap Function	143
	• OpenGL Pixmap Function	145
	• OpenGL Raster Operations	146
3-20	Character Primitives	147
3-21	OpenGL Character Functions	149
3-22	Picture Partitioning	151
3-23	OpenGL Display Lists	151
	• Creating and Naming an OpenGL Display List	151
	• Executing OpenGL Display Lists	152
	• Deleting OpenGL Display Lists	153
3-24	OpenGL Display-Window Reshape Function	154
3-25	Summary	157
	Example Programs	160
	References	168
	Exercises	168

4

Attributes of Graphics Primitives

172

4-1	OpenGL State Variables	174
4-2	Color and Gray Scale	174
	• RGB Color Components	174
	• Color Tables	175
	• Gray Scale	176
	• Other Color Parameters	176
4-3	OpenGL Color Functions	177
	• The OpenGL RGB and RGBA Color Modes	177
	• OpenGL Color-Index Mode	178

• OpenGL Color Blending	179
• OpenGL Color Arrays	180
• Other OpenGL Color Functions	182
4-4 Point Attributes	183
4-5 Line Attributes	183
• Line Width	183
• Line Style	185
• Pen and Brush Options	186
4-6 Curve Attributes	187
4-7 OpenGL Point-Attribute Functions	189
4-8 OpenGL Line-Attribute Functions	190
• OpenGL Line-Width Function	190
• OpenGL Line-Style Function	190
• Other OpenGL Line Effects	192
4-9 Fill-Area Attributes	193
• Fill Styles	193
• Color-Blended Fill Regions	194
4-10 General Scan-Line Polygon-Fill Algorithm	196
4-11 Scan-Line Fill of Convex Polygons	200
4-12 Scan-Line Fill for Regions with Curved Boundaries	201
4-13 Fill Methods for Areas with Irregular Boundaries	201
• Boundary-Fill Algorithm	201
• Flood-Fill Algorithm	205
4-14 OpenGL Fill-Area Attribute Functions	205
• OpenGL Fill-Pattern Function	206
• OpenGL Texture and Interpolation Patterns	207
• OpenGL Wire-Frame Methods	207
• OpenGL Front-Face Function	210
4-15 Character Attributes	211
4-16 OpenGL Character-Attribute Functions	213
4-17 Antialiasing	214
• Supersampling Straight-Line Segments	215
• Subpixel Weighting Masks	217
• Area Sampling Straight Line Segments	217
• Filtering Techniques	217
• Pixel Phasing	218
• Compensating for Line-Intensity Differences	218

	• Antialiasing Area Boundaries	219
4-18	OpenGL Antialiasing Functions	221
4-19	OpenGL Query Functions	222
4-20	OpenGL Attribute Groups	223
4-21	Summary	224
	References	226
	Exercises	227

5 Geometric Transformations 230

5-1	Basic Two-Dimensional Geometric Transformations	232
	• Two-Dimensional Translation	232
	• Two-Dimensional Rotation	234
	• Two-Dimensional Scaling	236
5-2	Matrix Representations and Homogeneous Coordinates	237
	• Homogeneous Coordinates	238
	• Two-Dimensional Translation Matrix	239
	• Two-Dimensional Rotation Matrix	239
	• Two-Dimensional Scaling Matrix	239
5-3	Inverse Transformations	240
5-4	Two-Dimensional Composite Transformations	241
	• Composite Two-Dimensional Translations	241
	• Composite Two-Dimensional Rotations	241
	• Composite Two-Dimensional Scalings	242
	• General Two-Dimensional Pivot-Point Rotation	242
	• General Two-Dimensional Fixed-Point Scaling	243
	• General Two-Dimensional Scaling Directions	244
	• Matrix Concatenation Properties	244
	• General Two-Dimensional Composite Transformations and Computational Efficiency	245

	• Two-Dimensional Rigid-Body Transformation	247
	• Constructing Two-Dimensional Rotation Matrices	248
	• Two-Dimensional Composite-Matrix Programming Example	248
5-5	Other Two-Dimensional Transformations	253
	• Reflection	253
	• Shear	255
5-6	Raster Methods for Geometric Transformations	257
5-7	OpenGL Raster Transformations	258
5-8	Transformations Between Two-Dimensional Coordinate Systems	259
5-9	Geometric Transformations in Three-Dimensional Space	261
5-10	Three-Dimensional Translation	262
5-11	Three-Dimensional Rotation	263
	• Three-Dimensional Coordinate-Axis Rotations	264
	• General Three-Dimensional Rotations	266
	• Quaternion Methods for Three-Dimensional Rotations	272
5-12	Three-Dimensional Scaling	275
5-13	Composite Three-Dimensional Transformations	278
5-14	Other Three-Dimensional Transformations	281
	• Three-Dimensional Reflections	281
	• Three-Dimensional Shears	281
5-15	Transformations Between Three-Dimensional Coordinate Systems	282
5-16	Affine Transformations	283
5-17	OpenGL Geometric-Transformation Functions	283
	• Basic OpenGL Geometric Transformations	284
	• OpenGL Matrix Operations	285
	• OpenGL Matrix Stacks	287
	• OpenGL Geometric-Transformation Programming Examples	288
5-18	Summary	291

References	293
Exercises	293

6 Two-Dimensional Viewing **296**

6-1	The Two-Dimensional Viewing Pipeline	297
6-2	The Clipping Window	299
	• Viewing-Coordinate Clipping Window	300
	• World-Coordinate Clipping Window	300
6-3	Normalization and Viewport Transformations	301
	• Mapping the Clipping Window into a Normalized Viewport	301
	• Mapping the Clipping Window into a Normalized Square	303
	• Display of Character Strings	305
	• Split-Screen Effects and Multiple Output Devices	305
6-4	OpenGL Two-Dimensional Viewing Functions	305
	• OpenGL Projection Mode	306
	• GLU Clipping-Window Function	306
	• OpenGL Viewport Function	307
	• Creating a GLUT Display Window	307
	• Setting the GLUT Display-Window Mode and Color	308
	• GLUT Display-Window Identifier	309
	• Deleting a GLUT Display Window	309
	• Current GLUT Display Window	309
	• Relocating and Resizing a GLUT Display Window	309
	• Managing Multiple GLUT Display Windows	310
	• GLUT Subwindows	311
	• Selecting a Display-Window Screen Cursor Shape	311
	• Viewing Graphics Objects in a GLUT Display Window	311
	• Executing the Application Program	312
	• Other GLUT Functions	312
	• OpenGL Two-Dimensional Viewing Program Example	313

6-5	Clipping Algorithms	315
6-6	Two-Dimensional Point Clipping	315
6-7	Two-Dimensional Line Clipping	316
	• Cohen-Sutherland Line Clipping	317
	• Liang-Barsky Line Clipping	322
	• Nichol-Lee-Nichol Line Clipping	325
	• Line Clipping Using Nonrectangular Polygon Clip Windows	328
	• Line Clipping Using Nonlinear Clipping-Window Boundaries	329
6-8	Polygon Fill-Area Clipping	329
	• Sutherland-Hodgman Polygon Clipping	331
	• Weiler-Atherton Polygon Clipping	335
	• Polygon Clipping Using Nonrectangular Polygon Clip Windows	337
	• Polygon Clipping Using Nonlinear Clipping-Window Boundaries	338
6-9	Curve Clipping	338
6-10	Text Clipping	339
6-11	Summary	340
	References	342
	Exercises	343

7

Three-Dimensional Viewing

344

7-1	Overview of Three-Dimensional Viewing Concepts	345
	• Viewing a Three-Dimensional Scene	345
	• Projections	346
	• Depth Cueing	346
	• Identifying Visible Lines and Surfaces	347
	• Surface Rendering	348
	• Exploded and Cutaway Views	348
	• Three-Dimensional and Stereoscopic Viewing	348
7-2	The Three-Dimensional Viewing Pipeline	348
7-3	Three-Dimensional Viewing-Coordinate Parameters	351
	• The View-Plane Normal Vector	351

	• The View-Up Vector	352
	• The uvn Viewing-Coordinate Reference Frame	353
	• Generating Three-Dimensional Viewing Effects	353
7-4	Transformation from World to Viewing Coordinates	355
7-5	Projection Transformations	356
7-6	Orthogonal Projections	357
	• Axonometric and Isometric Orthogonal Projections	358
	• Orthogonal Projection Coordinates	358
	• Clipping Window and Orthogonal-Projection View Volume	359
	• Normalization Transformation for an Orthogonal Projection	360
7-7	Oblique Parallel Projections	362
	• Oblique Parallel Projections in Drafting and Design	362
	• Cavalier and Cabinet Oblique Parallel Projections	364
	• Oblique Parallel-Projection Vector	364
	• Clipping Window and Oblique Parallel-Projection View Volume	366
	• Oblique Parallel-Projection Transformation Matrix	366
	• Normalization Transformation for an Oblique Parallel Projection	367
7-8	Perspective Projections	368
	• Perspective-Projection Transformation Coordinates	368
	• Perspective-Projection Equations: Special Cases	369
	• Vanishing Points for Perspective Projections	370
	• Perspective-Projection View Volume	371
	• Perspective-Projection Transformation Matrix	373
	• Symmetric Perspective-Projection Frustum	374
	• Oblique Perspective-Projection Frustum	378
	• Normalized Perspective-Projection Transformation Coordinates	380
7-9	The Viewport Transformation and Three-Dimensional Screen Coordinates	382

7-10	OpenGL Three-Dimensional Viewing Functions	383
	• OpenGL Viewing-Transformation Function	383
	• OpenGL Orthogonal-Projection Function	384
	• OpenGL Symmetric Perspective-Projection Function	386
	• OpenGL General Perspective-Projection Function	386
	• OpenGL Viewports and Display Windows	387
	• OpenGL Three-Dimensional Viewing Program Example	387
7-11	Three-Dimensional Clipping Algorithms	389
	• Clipping in Three-Dimensional Homogeneous Coordinates	389
	• Three-Dimensional Region Codes	390
	• Three-Dimensional Point and Line Clipping	391
	• Three-Dimensional Polygon Clipping	394
	• Three-Dimensional Curve Clipping	395
	• Arbitrary Clipping Planes	395
7-12	OpenGL Optional Clipping Planes	397
7-13	Summary	398
	References	400
	Exercises	400

8 Three-Dimensional Object Representations **402**

8-1	Polyhedra	404
8-2	OpenGL Polyhedron Functions	404
	• OpenGL Polygon Fill-Area Functions	404
	• GLUT Regular-Polyhedron Functions	404
	• Example GLUT Polyhedron Program	406
8-3	Curved Surfaces	408
8-4	Quadric Surfaces	408
	• Sphere	408
	• Ellipsoid	408
	• Torus	409

8-5	Superquadrics	410
	• Superellipse	410
	• Superellipsoid	411
8-6	OpenGL Quadric-Surface and Cubic-Surface Functions	411
	• GLUT Quadric-Surface Functions	412
	• GLUT Cubic-Surface Teapot Function	413
	• GLU Quadric-Surface Functions	414
	• Example Program Using GLUT and GLU Quadric-Surface Functions	416
8-7	Bloppy Objects	418
8-8	Spline Representations	420
	• Interpolation and Approximation Splines	420
	• Parametric Continuity Conditions	421
	• Geometric Continuity Conditions	422
	• Spline Specifications	423
	• Spline Surfaces	424
	• Trimming Spline Surfaces	424
8-9	Cubic-Spline Interpolation Methods	425
	• Natural Cubic Splines	426
	• Hermite Interpolation	426
	• Cardinal Splines	429
	• Kochanek-Bartels Splines	431
8-10	Bézier Spline Curves	432
	• Bézier Curve Equations	433
	• Example Bézier Curve-Generating Program	435
	• Properties of Bézier Curves	437
	• Design Techniques Using Bézier Curves	438
	• Cubic Bézier Curves	439
8-11	Bézier Surfaces	441
8-12	B-Spline Curves	442
	• B-Spline Curve Equations	442
	• Uniform Periodic B-Spline Curves	444
	• Cubic Periodic B-Spline Curves	447
	• Open Uniform B-Spline Curves	448
	• Nonuniform B-Spline Curves	451
8-13	B-Spline Surfaces	452
8-14	Beta Splines	452
	• Beta-Spline Continuity Conditions	452

	• Cubic Periodic Beta-Spline Matrix Representation	453
8-15	Rational Splines	454
8-16	Conversion Between Spline Representations	456
8-17	Displaying Spline Curves and Surfaces	457
	• Horner's Rule	457
	• Forward-Difference Calculations	458
	• Subdivision Methods	459
8-18	OpenGL Approximation-Spline Functions	461
	• OpenGL Bézier-Spline Curve Functions	462
	• OpenGL Bézier-Spline Surface Functions	465
	• GLU B-Spline Curve Functions	467
	• GLU B-Spline Surface Functions	469
	• GLU Surface-Trimming Functions	471
8-19	Sweep Representations	473
8-20	Constructive Solid-Geometry Methods	474
8-21	Octrees	476
8-22	BSP Trees	479
8-23	Fractal-Geometry Methods	479
	• Fractal Generation Procedures	481
	• Classification of Fractals	481
	• Fractal Dimension	482
	• Geometric Construction of Deterministic Self-Similar Fractals	484
	• Geometric Construction of Statistically Self-Similar Fractals	487
	• Affine Fractal-Construction Methods	489
	• Random Midpoint-Displacement Methods	490
	• Controlling Terrain Topography	493
	• Self-Squaring Fractals	495
	• Self-Inverse Fractals	506
8-24	Shape Grammars and Other Procedural Methods	507
8-25	Particle Systems	510
8-26	Physically Based Modeling	511
8-27	Visualization of Data Sets	514
	• Visual Representations for Scalar Fields	514

	• Visual Representations for Vector Fields	517
	• Visual Representations for Tensor Fields	519
	• Visual Representations for Multivariate Data Fields	520
8-28	Summary	521
	References	524
	Exercises	525

9**Visible-Surface Detection Methods****528**

9-1	Classification of Visible-Surface Detection Algorithms	529
9-2	Back-Face Detection	530
9-3	Depth-Buffer Method	531
9-4	A-Buffer Method	534
9-5	Scan-Line Method	535
9-6	Depth-Sorting Method	537
9-7	BSP-Tree Method	540
9-8	Area-Subdivision Method	541
9-9	Octree Methods	543
9-10	Ray-Casting Method	544
9-11	Comparison of Visibility-Detection Methods	545
9-12	Curved Surfaces	545
	• Curved-Surface Representations	546
	• Surface Contour Plots	546
9-13	Wire-Frame Visibility Methods	547
	• Wire-Frame Surface-Visibility Algorithms	547
	• Wire-Frame Depth-Cueing Algorithm	548
9-14	OpenGL Visibility-Detection Functions	549
	• OpenGL Polygon-Culling Functions	549
	• OpenGL Depth-Buffer Functions	549
	• OpenGL Wire-Frame Surface-Visibility Methods	551
	• OpenGL Depth-Cueing Function	552
9-15	Summary	552
	References	553
	Exercises	554

10	Illumination Models and Surface-Rendering Methods	556
10-1	Light Sources	558
	• Point Light Sources	558
	• Infinitely Distant Light Sources	559
	• Radial Intensity Attenuation	559
	• Directional Light Sources and Spotlight Effects	560
	• Angular Intensity Attenuation	561
	• Extended Light Sources and the Warn Model	562
10-2	Surface Lighting Effects	563
10-3	Basic Illumination Models	563
	• Ambient Light	563
	• Diffuse Reflection	564
	• Specular Reflection and the Phong Model	567
	• Combined Diffuse and Specular Reflections	571
	• Diffuse and Specular Reflections from Multiple Light Sources	571
	• Surface Light Emissions	571
	• Basic Illumination Model with Intensity Attenuation and Spotlights	573
	• RGB Color Considerations	573
	• Other Color Representations	575
	• Luminance	575
10-4	Transparent Surfaces	576
	• Translucent Materials	576
	• Light Refraction	577
	• Basic Transparency Model	578
10-5	Atmospheric Effects	579
10-6	Shadows	580
10-7	Camera Parameters	581
10-8	Displaying Light Intensities	581
	• Distributing System Intensity Levels	581
	• Gamma Correction and Video Lookup Tables	582
	• Displaying Continuous-Tone Images	584
10-9	Halftone Patterns and Dithering Techniques	585
	• Halftone Approximations	585
	• Dithering Techniques	588

10-10	Polygon-Rendering Methods	591
	• Constant-Intensity Surface Rendering	591
	• Gouraud Surface Rendering	592
	• Phong Surface Rendering	595
	• Fast Phong Surface Rendering	595
10-11	Ray-Tracing Methods	597
	• Basic Ray-Tracing Algorithm	597
	• Ray-Surface Intersection Calculations	601
	• Ray-Sphere Intersections	602
	• Ray-Polyhedron Intersections	603
	• Reducing Object-Intersection Calculations	604
	• Space-Subdivision Methods	605
	• Simulating Camera Focusing Effects	607
	• Antialiased Ray Tracing	610
	• Distributed Ray Tracing	612
10-12	Radiosity Lighting Model	615
	• Radiant-Energy Terms	616
	• The Basic Radiosity Model	616
	• Progressive Refinement Radiosity Method	620
10-13	Environment Mapping	623
10-14	Photon Mapping	624
10-15	Adding Surface Detail	625
10-16	Modeling Surface Detail with Polygons	627
10-17	Texture Mapping	628
	• Linear Texture Patterns	628
	• Surface Texture Patterns	629
	• Volume Texture Patterns	632
	• Texture Reduction Patterns	633
	• Procedural Texturing Methods	633
10-18	Bump Mapping	634
10-19	Frame Mapping	637
10-20	OpenGL Illumination and Surface-Rendering Functions	637
	• OpenGL Point Light-Source Function	637
	• Specifying an OpenGL Light-Source Position and Type	638
	• Specifying OpenGL Light-Source Colors	639
	• Specifying Radial-Intensity Attenuation Coefficients for an OpenGL Light Source	639

	• OpenGL Directional Light Sources (Spotlights)	640
	• OpenGL Global Lighting Parameters	641
	• OpenGL Surface-Property Function	642
	• OpenGL Illumination Model	643
	• OpenGL Atmospheric Effects	644
	• OpenGL Transparency Functions	645
	• OpenGL Surface-Rendering Functions	646
	• OpenGL Halftoning Operations	647
10-21	OpenGL Texture Functions	648
	• OpenGL Line-Texture Functions	648
	• OpenGL Surface-Texture Functions	651
	• OpenGL Volume-Texture Functions	653
	• OpenGL Color Options for Texture Patterns	653
	• OpenGL Texture-Mapping Options	654
	• OpenGL Texture Wrapping	655
	• Copying OpenGL Texture Patterns from the Frame Buffer	655
	• OpenGL Texture-Coordinate Arrays	655
	• Naming OpenGL Texture Patterns	656
	• OpenGL Texture Subpatterns	657
	• OpenGL Texture Reduction Patterns	657
	• OpenGL Texture Borders	658
	• OpenGL Proxy Textures	659
	• Automatic Texturing of Quadric Surfaces	659
	• Homogeneous Texture Coordinates	659
	• Additional OpenGL Texture Options	660
10-22	Summary	660
	References	664
	Exercises	665

11

Interactive Input Methods and Graphical User Interfaces

668

11-1	Graphical Input Data	669
11-2	Logical Classification of Input Devices	669
	• Locator Devices	670
	• Stroke Devices	670
	• String Devices	670

	• Valuator Devices	671
	• Choice Devices	671
	• Pick Devices	672
11-3	Input Functions for Graphical Data	673
	• Input Modes	674
	• Echo Feedback	674
	• Callback Functions	674
11-4	Interactive Picture-Construction Techniques	675
	• Basic Positioning Methods	675
	• Dragging	675
	• Constraints	675
	• Grids	676
	• Rubber-Band Methods	676
	• Gravity Field	677
	• Interactive Painting and Drawing Methods	678
11-5	Virtual-Reality Environments	679
11-6	OpenGL Interactive Input-Device Functions	679
	• GLUT Mouse Functions	680
	• GLUT Keyboard Functions	684
	• GLUT Tablet Functions	689
	• GLUT Spaceball Functions	689
	• GLUT Button-Box Function	690
	• GLUT Dials Function	690
	• OpenGL Picking Operations	690
11-7	OpenGL Menu Functions	696
	• Creating a GLUT Menu	696
	• Creating and Managing Multiple GLUT Menus	699
	• Creating GLUT Submenus	700
	• Modifying GLUT Menus	703
11-8	Designing a Graphical User Interface	703
	• The User Dialogue	703
	• Windows and Icons	704
	• Accommodating Multiple Skill Levels	704
	• Consistency	705
	• Minimizing Memorization	705
	• Backup and Error Handling	705
	• Feedback	705
11-9	Summary	706
	References	709
	Exercises	709

12	Color Models and Color Applications	712
12-1	Properties of Light	713
	• The Electromagnetic Spectrum	713
	• Psychological Characteristics of Color	715
12-2	Color Models	716
	• Primary Colors	716
	• Intuitive Color Concepts	716
12-3	Standard Primaries and the Chromaticity Diagram	717
	• The XYZ Color Model	717
	• Normalized XYZ Values	718
	• The CIE Chromaticity Diagram	718
	• Color Gamuts	719
	• Complementary Colors	719
	• Dominant Wavelength	719
	• Purity	720
12-4	The RGB Color Model	720
12-5	The YIQ and Related Color Models	722
	• The YIQ Parameters	722
	• Transformations Between RGB and YIQ Color Spaces	722
	• The YUV $Y_C C_b$ Systems	723
12-6	The CMY and CMYK Color Models	723
	• The CMY Parameters	723
	• Transformations Between CMY and RGB Color Spaces	724
12-7	The HSV Color Model	724
	• The HSV Parameters	724
	• Selecting Shades, Tints, and Tones	726
	• Transformations Between HSV and RGB Color Spaces	726
12-8	The HLS Color Model	728
12-9	Color Selection and Applications	728
12-10	Summary	730
	References	731
	Exercises	731

13 Computer Animation **732**

13-1	Raster Methods for Computer Animation	734
------	---------------------------------------	-----

• Double Buffering	734
• Generating Animations Using Raster Operations	735
13-2 Design of Animation Sequences	735
13-3 Traditional Animation Techniques	737
13-4 General Computer-Animation Functions	737
13-5 Computer-Animation Languages	738
13-6 Key-Frame Systems	739
• Morphing	739
• Simulating Accelerations	742
13-7 Motion Specifications	745
• Direct Motion Specification	745
• Goal-Directed Systems	745
• Kinematics and Dynamics	746
13-8 Articulated Figure Animation	747
13-9 Periodic Motions	748
13-10 OpenGL Animation Procedures	749
13-11 Summary	752
References	754
Exercises	754

14 Hierarchical Modeling 756

14-1 Basic Modeling Concepts	757
• System Representations	757
• Symbol Hierarchies	759
14-2 Modeling Packages	760
14-3 General Hierarchical Modeling Methods	762
• Local Coordinates	763
• Modeling Transformations	763
• Creating Hierarchical Structures	763
14-4 Hierarchical Modeling Using OpenGL Display Lists	765
14-5 Summary	765
References	766
Exercises	766

15 Graphics File Formats 768

15-1 Image-File Configurations	769
15-2 Color-Reduction Methods	770

	• Uniform Color Reduction	770
	• Popularity Color Reduction	771
	• Median-Cut Color Reduction	771
15-3	File-Compression Techniques	771
	• Run-Length Encoding	772
	• LZW Encoding	772
	• Other Pattern-Recognition Compression Methods	773
	• Huffman Encoding	773
	• Arithmetic Encoding	776
	• Discrete Cosine Transform	776
15-4	Composition of the Major File Formats	778
	• JPEG: Joint Photographic Experts Group	779
	• CGM: Computer-Graphics Metafile Format	780
	• TIFF: Tag Image-File Format	781
	• PNG: Portable Network-Graphics Format	781
	• XBM: X Window System Bitmap Format & XPM: X Window System Pixmap Format	781
	• Adobe Photoshop Format	782
	• MacPaint: Macintosh Paint Format	782
	• PICT: Picture Data Format	782
	• BMP: Bitmap Format	782
	• PCX: PC Paintbrush File Format	783
	• TGA: Truevision Graphics-Adapter Format	783
	• GIF: Graphics Interchange Format	783
15-5	Summary	783
	References	784
	Exercises	784

A

Mathematics for Computer Graphics 787

A-1	Coordinate Reference Frames	787
	• Two-Dimensional Cartesian Screen Coordinates	787
	• Standard Two-Dimensional Cartesian Reference Frames	788
	• Polar Coordinates in the xy Plane	788

	• Standard Three-Dimensional Cartesian Reference Frames	789
	• Three-Dimensional Cartesian Screen Coordinates	790
	• Three-Dimensional Curvilinear-Coordinate Systems	790
	• Solid Angle	791
A-2	Points and Vectors	792
	• Point Properties	792
	• Vector Properties	792
	• Vector Addition and Scalar Multiplication	794
	• Scalar Product of Two Vectors	794
	• Vector Product of Two Vectors	795
A-3	Tensors	796
A-4	Basis Vectors and the Metric Tensor	796
	• Determining Basis Vectors for a Coordinate Space	796
	• Orthonormal Basis	797
	• Metric Tensor	798
A-5	Matrices	799
	• Scalar Multiplication and Matrix Addition	800
	• Matrix Multiplication	800
	• Matrix Transpose	801
	• Determinant of a Matrix	801
	• Matrix Inverse	802
A-6	Complex Numbers	802
	• Basic Complex Arithmetic	803
	• Imaginary Unit	803
	• Complex Conjugate and Modulus of a Complex Number	804
	• Complex Division	804
	• Polar-Coordinate Representation for a Complex Number	805
A-7	Quaternions	805
A-8	Nonparametric Representations	807
A-9	Parametric Representations	807
A-10	Rate-of-Change Operators	808
	• Gradient Operator	809
	• Directional Derivative	809
	• General Form of the Gradient Operator	810
	• Laplace Operator	810
	• Divergence Operator	810
	• Curl Operator	811

A-11	Rate-of-Change Integral Transformation Theorems	811
	• Stokes's Theorem	811
	• Green's Theorem for a Plane Surface	812
	• Divergence Theorem	813
	• Green's Transformation Equations	814
A-12	Area and Centroid of a Polygon	814
	• Area of a Polygon	814
	• Centroid of a Polygon	815
A-13	Calculating Properties of Polyhedra	817
A-14	Numerical Methods	817
	• Solving Sets of Linear Equations	817
	• Finding Roots of Nonlinear Equations	819

• Evaluating Integrals	820
• Solving Ordinary Differential Equations	822
• Solving Partial Differential Equations	824
• Least-Squares Curve-Fitting Methods for Data Sets	825
Bibliography	827
Subject Index	839
OpenGL Function Index	856
• Core Library Functions	856
• GLU Functions	857
• GLUT Functions	857