

Index

Numbers

- (0,2)-sequences, 368–372
 - 2D sample generation, 370
 - defined, 368
 - elementary intervals, 370
 - illustrated, 369
 - low-discrepancy sampler, 372
 - random scrambling, 370, 371
 - sample generation, 371
 - sequence length, 370
 - stratification, 368
 - unscrambled, 370
 - use of, 378
- See also* low-discrepancy sampling
- 1D sample patterns, 344
- 2×2 linear systems, 1020
- 2D sample patterns, 343, 347
- 2D (u , v) mapping, 514–515
- 3D grids, 592–594
 - defined, 592
 - implementations, 593
 - local density computation, 594
 - voxel coordinates/offsets computation, 594
- 3D mapping, 518–519
- 3D sample patterns, 343
- 3D viewing problem, 305
- 4×4 matrices, 1020–1021

A

- absorption, 575, 576–578
 - cross section, 576
 - defined, 575
 - effect, 577–578
 - illustrated, 577
 - radiance and, 577–578
 - total fraction of light, 578
- absorption coefficient
 - defined, 435
 - of gold, 436
- abstract base classes, 15, 41
- abstraction
 - efficiency versus, 991
 - radiative transfer, 281

- of shapes, 107
- acceleration structures
 - bounding volume hierarchies (BVHs), 208–227
 - defined, 183
 - goal, 192
 - grid accelerators, 195–208
 - implementation, 172
 - KD-tree accelerator, 227–245
 - octrees for, 1022
 - primitive subdivision-based, 250
 - in ray-object intersection, 8
 - specialized, 992
- acceptance probability, 653
- across tangents, 172
- adaptive sampling, 334, 341, 385–389
 - challenge, 386
 - criteria example, 390
 - defined, 334
 - implementation, 385, 386
 - tests, 388–389
- See also* sampling
- affine space, 55
- affine transformations, 97
- aggregates, 191–195
 - bugs, 245–246
 - bugs, finding, 246–249
 - bugs, fixing, 249–250
 - debugging, 245–250
 - implementation testing, 246–247
 - intersections, 192–193
 - performance bugs, 250
 - ray-box intersections, 193–195
 - volume, 596–598
- aliases, 331
- aliasing, 331, 331–332
 - checkerboard textures, 548
 - defined, 324
 - illustrated, 332
 - from point sampling, 333
 - shading, 336
 - sources, 336–337
 - texture, 501, 502
 - visual impact, 501
- alpha masks, 144

- ambient occlusion (AO), 926, 927
 - common use, 927
 - defined, 926
 - illustrated, 926
- See also* precomputed light transport
- angle measure conversion, 1001
- angle rotation, 81, 83
- animated shapes, 1065, 1066, 1067, 1068
- animation
 - keyframe matrix, 90
 - primitives, 189–191
 - transformation, 90–100
- anisotropic microfacet model, 457–460
 - defined, 457
 - distribution function, 458
 - exponents, 459
 - sampling, 699–701
 - spheres rendered from, 459
- See also* microfacet models
- anisotropic phase functions, 584
- anisotropic surfaces, 425
- antialiasing
 - adaptive sampling, 334
 - checkerboard textures, 548
 - fractional Brownian motion, 561
 - mix textures and, 521
 - nonuniform sampling, 334
 - polka dots, 559
 - prefiltering, 334–335
 - procedural texturing, 545, 551
 - ray differentials and, 46, 68–69
 - scale texture and, 521
 - techniques, 332–335
 - texture, 503–513
- application programming interfaces (APIs)
 - cleanup, 1053, 1056
 - function definitions, 1054, 1055, 1057, 1058, 1060, 1063, 1065, 1069, 1070, 1072
 - initialization, 1053, 1056, 1060
 - local classes, 1054, 1056, 1059, 1060
 - macros, 1053, 1055, 1063
 - rendering option functions, 1057
 - routine subsets, 1052

- application programming interfaces (APIs) (*continued*)
 - shape recreation, 1073
 - states, 1052
 - static data, 1052, 1054, 1055, 1056, 1060
- area
 - differential, 291, 292, 293
 - integrals over, 292–293
- area lights, 623–627
 - creation, 1065
 - in current graphics state, 1067
 - defined, 623–625
 - diffuse, 718
 - emitted power, 626
 - illumination illustration, 624
 - incident illumination, 627
 - infinite, 627–631, 724–730, 943–949
 - interface, 625
 - projection, 943–949
 - protected data, 626
 - sampling, 358, 377–378, 715–722
 - sampling methods, 717–719
 - See also* light sources; light(s)
- arena-based allocation, 1014–1017
 - advantages, 1014
 - defined, 1014
 - memory areas, 1014–1017
 - See also* memory allocation; memory management
- arithmetic logic units (ALUs), 993
- asymmetry parameter, 585, 586
- atomic operations, 1036–1038
 - add of floating-point values, 1038
 - compare and swap, 1037
 - implementation of, 1036
 - lock-free algorithm, 1038
- atomics, 38–39
 - defined, 38
 - mutexes versus, 39
- attenuation
 - coefficient, 579, 874
 - geometric, 453, 455
 - light, 13
- attribute stacks, 1059
- axis-aligned bounding boxes (AABBs)
 - defined, 70
 - homogeneous volumes, 590
 - illustrated, 71
 - world space, 587

B

- back-scattering, 585
- balance heuristic, 691, 693

- band-limited functions, 329, 330, 509
- barycentric coordinates
 - computation, 141, 142
 - computation for points, 147
 - defined, 140
 - intersection point, 140
 - less than zero/greater than one, 142
- base-2 logarithms, 1001–1002
- basis functions, 927–932
 - advantages, 928
 - dual of, 930
 - efficiency, 928
 - integral of, 931
 - orthonormal, 928, 930–932
 - piecewise-constant, 928–930
 - projection onto, 930
 - SPD representation, 261
 - for spectral representation, 263
 - spherical harmonics (SH), 932
 - theory, 927–932
- basis vectors, 55–56, 82
- beam transmittance, 580–581
 - defined, 580
 - illustrated, 581
 - multiplicative property, 581
 - properties, 580–581
- best-candidate algorithm, 379
- best-candidate sampling pattern, 378–385
 - defined, 379
 - integrator sample computation, 385
 - sample generation, 385
 - stratified sampling pattern
 - comparison, 382
 - table, 380
 - tiled sample patterns, 384
 - toroidal topology, 379
- bias
 - compensation for bounding geometry, 781, 783
 - compensation, trace ray for, 783
 - introduction of, 784
 - photon mapping, 828
 - start-up, 655–656
 - in variance reduction, 686–687
- bidirectional path tracing, 770–771
 - defined, 762, 770
 - as generalization of standard
 - path-tracing algorithm, 770
 - IGI correspondence, 775
 - path instances construction, 851–852
 - radiance along path computation, 846–847
 - refinements, 771
 - See also* path tracing

- bidirectional reflectance distribution functions (BRDFs), 294–296
 - adapter, 430–431
 - defined, 10
 - delta distribution, 439–440
 - energy conservation, 295
 - Fresnel incidence effects, 460
 - illustrated, 295
 - implementation, 428
 - interface, 428–432
 - Lambertian model, 446
 - low-level, 477
 - measured, 462–470
 - memory management, 482–483
 - microfacet-based models, 447
 - parameterized models, 462
 - path, 757
 - public data, 429
 - reciprocity, 295
 - scaling adapter, 431–432
 - specular reflection, 439
 - utility functions, 435
- bidirectional scattering distribution functions (BSDFs), 477–483
 - BRDF reuse adapter, 430–431
 - class representation, 477
 - complex material property surfaces, 43
 - defined, 11, 296
 - destructor, 482
 - for final gathering, 824
 - implementations, 428, 479
 - inline functions, 426
 - interface, 428–432
 - interface setting, 426
 - matrix, 977–979
 - memory allocation, 187
 - pointer storage, 705
 - random variables, 705
 - sample initialization, 705
 - sample offsets, 706
 - sample values, 705
 - sampled directions, 707–708
 - sampling, 705–708
 - sampling distribution, 979
 - sampling PDF computation, 707
 - scaling adapter, 431–432
 - special handling, 429
 - transfer matrix, 978
 - utility functions, 435
 - values, 46
- bidirectional scattering-surface reflectance distribution function (BSSRDF), 296–297, 598–600
- BRDF reflectance correspondence, 912

- computation, 885
 - defined, 296
 - diffuse reflectance conversion to, 908
 - evaluation, 885, 908
 - illustrated, 297
 - lower-level scattering properties, 598
 - properties, 598
 - scattering equation, 296
 - special handling, 429
 - subsurface scattering materials, 599–600
 - in volume scattering, 598–600
 - bidirectional transmittance distribution functions (BTDFs)
 - defined, 295
 - denotation, 295
 - low-level, 477
 - specular transmission, 442, 443
 - bilinear interpolation texture, 522–523
 - defined, 522
 - See also* texture(s)
 - binary space partitioning (BSP) trees
 - defined, 227
 - KD-trees, 227–245
 - octrees, 227
 - Blinn microfacet distribution, 455–457
 - defined, 455
 - exponent variation effect, 458
 - functions, 696
 - implementations, 695
 - interface, 695
 - Killeroo, 456
 - normalized functions, 456–457
 - sampling, 695–699
 - See also* microfacet models
 - blocked 2D arrays, 1017–1020
 - arrangement in memory, 1017
 - block size, 1017
 - natural layout, 1018
 - blurring, 398
 - bootstrapping samples, 853, 856, 857
 - boundary vertices, 156
 - determining, 157
 - limit rule, 171
 - odd, 167
 - one-ring, 164–165
 - subdivision and, 162
 - tangent computation, 172–173
 - valance computation, 158–159
 - bounding
 - cylinder, 126
 - disk, 130–131
 - shape interface, 109–110
 - sphere, 116
 - subdivision surfaces, 160
 - bounding boxes
 - axis-aligned (AABBs), 70, 71, 587, 590
 - BVH nodes, 226
 - grid, 202
 - oriented (OBBs), 70
 - overlapping kd-tree nodes, 238
 - points, 71, 72
 - primitive, 201
 - processing expense, 70
 - radiance probes, 959
 - ray intersection with, 193
 - sphere, 73
 - surface area computation, 72–73
 - in texture space, 542
 - three-dimensional, 70–74
 - transforming, 88
 - world space, 109, 139
 - bounding spheres, 893
 - bounding volume hierarchies (BVHs), 208–227
 - binary, 208
 - bounds computation, 213
 - characteristics, 208–209
 - compact, for traversal, 222–224
 - construction, 210–217
 - defined, 208
 - definition of, 209
 - efficiency, 208
 - illustrated example, 209
 - implementation, 225–226
 - interior nodes, 213, 224, 226
 - leaf nodes, 211, 213, 226
 - linear layout in memory, 223
 - nodes, 211, 212, 223, 224
 - nodes, bounding boxes, 226
 - nodes, checking ray against, 225
 - nodes, following ray through, 225
 - partition axis, 214
 - performance, 226
 - primitive storage, 210
 - surface area heuristic, 217–222
 - traversal, 224–227
 - box filter, 394–396
 - defined, 394
 - graph, 395
 - isotropic triangle, 536–539
 - mip map, 536
 - reconstruction, 395
 - See also* filters; reconstruction
 - BRDF. *See* bidirectional reflectance distribution function
 - BSDF. *See* bidirectional scattering distribution function
 - BSSRDF. *See* bidirectional scattering-
 - surface reflectance distribution function
 - BTDF. *See* bidirectional transmittance distribution function
 - bugs (aggregates), 245–250
 - causes, 249
 - challenge, 245
 - finding, 246–249
 - fixing, 249–250
 - performance, 250
 - bugs, pbrt, 50
 - bump mapping, 490–496
 - appearance, 490–492
 - application effect, 490, 492
 - defined, 490
 - displacement texture evaluation, 495
 - implementations, 494
 - offset position computation, 495
 - offsets selection, 495–496
 - in shading normals computation, 492
 - in Sponza atrium model, 493
 - support, 492
 - See also* materials
 - bumpy textures, 565–566
 - BVHs. *See* bounding volume hierarchies
- ## C
- cache coherency, 1034
 - cache-friendly memory usage, 1012–1013
 - caching
 - geometry, 992
 - texture, 524–527
 - camera paths, 845
 - connecting, 849
 - radiance computation, 849
 - vertex, reflected light computation, 850
 - camera space
 - defined, 304
 - origin, 304
 - points in, 308, 311
 - world space transformation to, 304
 - See also* coordinate spaces
 - cameras, 5–7
 - class, 301–302
 - coordinate spaces, 303–305
 - defined, 4
 - environment, 318–319
 - implementation, 303
 - interface, 303
 - models, 301–321
 - orthographic, 306–310
 - perspective, 310–313

- cameras (*continued*)
 - physical lens system simulation, 302
 - pinhole, 5, 6, 316
 - projective, 305–318
 - ray computation, 303
 - real-world, 302, 313
 - simulator, 6–7
- candelas, 287
- candidate points distribution algorithm, 892
- canonical uniform random variables, 639
- Cartesian coordinates, 661
- caustic lighting
 - computation, 817
 - illustrated, 818
 - photon map, 802, 803, 817
 - rendering of, 802
- caustic photons, 813
- checkerboard textures
 - aliasing, 548
 - antialiasing, 548
 - application illustration, 547
 - check function frequency, 547
 - closed-form box-filtered, 549
 - defined, 546
 - filtering, 549
 - sampling method comparison, 348
 - solid, 552–553
 - step function integration, 550
 - supersampling, 551
 - texture coordinates, 514, 546
 - See also* texture(s)
- child octree nodes, 899
- circle of confusion, 313, 314
- clamping, 561
 - function, 1000
 - Monte Carlo integration and, 782
- classes
 - abstract base, 15, 41
 - geometric, 55
 - reentrant methods, 40–41
 - relationships, 27, 42
 - summarization, 26
 - surface integration, 42
 - synchronization, 31
- closed mesh, 152
- code, this book
 - bugs, 50
 - optimization, 49
 - pointer versus reference, 48
 - using/understanding, 48–50
- coherent shared memory, 36
- color(s)
 - out-of-gamut, 413
 - RGB, 273–279
 - tristimulus theory, 270
 - XYZ, 270–273
- communication with user, 1004–1006
 - error reporting, 1005
 - float file reader, 1006
 - reporting progress, 1005–1006
- compare and swap, 1037
- concentric mapping, 666, 667
- conditional density function, 662
- conductors, 434, 435
- cones, 133–134
 - implicit form, 133
 - parametric form, 133
 - partial derivatives, 133–134
 - See also* shapes
- constant texture, 520
- continuous coordinates, 337, 338
- continuous random variables, 639–640
- continuous transformations, 74
- control mesh, 148, 149, 150
 - consistently ordered, 154
 - directed edge, 154
 - See also* subdivision mesh
- convex hull property, 160, 163
- convolution
 - computing, 327
 - Fourier transform, 329
 - operation, 327
 - shah function, 329, 330
 - in spatial domain, 329
- coordinate spaces
 - camera space, 304, 308, 311
 - illustrated, 304
 - normalized device coordinate (NDC)
 - space, 304
 - object space, 115, 138, 303
 - raster space, 304, 309, 384
 - screen space, 39, 304
 - world space, 56, 109, 139, 191, 199, 303
- coordinate systems, 55–57
 - defined, 55
 - frame, 55, 56
 - handedness, 56–57, 89
 - left-handed, 56, 57
 - reflection, 425
 - right-handed, 56, 57
 - shading, 425, 427
 - from vectors, 63
 - world space, 56
- cosine-weighted hemisphere sampling, 668–670
- CPUs
 - cache coherence protocol, 1034
 - design, 993
 - packet tracing on, 995
 - performance improvement, 993
 - SIMD width, 995
- Cramer's rule, 140
- Cranley-Patterson rotations, 384
- critical angle, 439
- cross product, 61–62
 - defined, 61
 - in left-handed coordinate system, 61
 - of perpendicular unit vectors, 62
 - “up” vector, 85
- cross-referencing, 3–4
- cube maps, 945–946
- cumulative distribution function (CDF)
 - constructing, 643–644
 - defined, 639
 - discrete, 644
 - integral, 644
 - inversion, 644, 648
 - monotonically increasing, 648
 - normalization, 649
 - PDF and, 640
 - piecewise-constant 1D functions, 647–650
 - segments computation, 649
 - value storage, 648
- current transformation matrices (CTMs), 1053–1055
 - active, 1053
 - for initialization, 1058
 - named copies of, 1055
 - pbrrt maintenance, 1053
 - selective modification, 1053
 - use of, 1054
- curse of dimensionality
 - defined, 350
 - stratified sampling and, 684–685
- cylinders, 124–129
 - basic setting, 125
 - bounding, 126
 - coefficients computation, 127
 - construction, 125–126
 - hit point computation, 127
 - illustrated, 126
 - implementation, 125
 - implicit form, 126
 - infinitely long, 126
 - intersection, 126–127
 - parametric form, 125
 - partial, 127–128
 - partial derivatives, 128
 - sampling, 719
 - surface area, 129
 - See also* shapes

cylindrical mapping, 517

D

dart throwing, 378

data races

coordination and, 36–40
defined, 36

See also parallelization

debugging

aggregates, 245–250

decomposition

function, 3
matrix, 91
in pbrt image rendering, 28
polar, 97
screen-space, 39
transformation, 97

delta distributions, 327, 439

Dirac, 439, 702
in integrand, 757–758
light, 608

density estimation, 827–833

defined, 828
example illustration, 829
kernel methods, 828
PDF construction, 828

depth of field, 313–318

circle of confusion and, 313, 314
defined, 314
focal distance, 314
illustrated, 314, 316
lens aperture size, 314, 315
orthographic camera, 309
pinhole cameras and, 316
projective cameras, 314

design

abstraction versus efficiency, 991
CPU, 993
graphics API, 1046
retrospective, 989–993
triangles-only alternative, 991–992

detailed balance, 653

dielectric media, 434

differential area, 291, 292, 293

differential geometry

defined, 101
illustrated, 101

differential irradiance, 8

See also irradiance

differential radiance, 295

See also radiance

diffuse area lights, 718

diffuse precomputed radiance transfer
(PRT), 969–973

diffuse reflection, 970

reflected radiance computation, 972

diffuse reflection

defined, 424
illustrated, 425
Oren-Nayar, 449–451

diffuse subsurface reflectance, 906, 908

diffusion approximation, 901–908

diffusion equation, 902–904

digital difference analyzer (DDA), 203

dipole approximation, 905

basic setting for, 906

boundary condition, 905

Dirac delta distribution, 439, 702

direct lighting, 741–751, 802, 848

BSDF directions, 743

computation, 744, 768, 853

computation strategies, 741

defined, 45

estimating, 745

implementation, 744

importance sampling, 748

integral, estimating, 747–751

integrator, 741, 742, 744, 746

light source sampling parameters,
743

for Metropolis path vertex, 848

in Metropolis sampling, 854, 855

multiple importance sampling, 749,
750

photon map, 803

reflection from, 848

sampling, 741, 744

scene rendering, 742

strategy, applying, 744

See also indirect lighting; lighting

direct photons, 810

Direct3D, 1045

directional lights

infinite light direction, 715
light direction point offset, 715
outgoing ray direction, 714
sampling, 713–715

directional sampling, 664

directions

differential reflected, 513
half-angle, 469
incident, computation, 697
incident light, 427
incident radiance, 294
normalized, 43
normals, 103
ray, 248
sampling, 708
specular reflection, 441
spherical coordinate representation,
661–662

transformation into shading space,
479

transmitted, 45

transmitted ray, 445–446

vector representation, 57

voxel stepping, 205

discrepancy

box, 360

computing, 359–360

defined, 359–361

Halton sequence, 363

star, 360–361

van der Corput sequence, 362

See also low-discrepancy sampling

discrete coordinates, 337, 338

discrete random media, 915

disks, 129–132

basic setting, 129

bounding, 130–131

construction, 130

generalized to annulus, 129–130

hit point computation, 131–132

illustrated, 130

intersection, 131–132

parameterization, inverting, 132

parametric form, 130

partial, 129

partial derivatives, 132

plane intersection computation, 131

sampling, 665–668, 718–719

surface area, 132–133

See also shapes

dispersion, 432

displacement textures, 494, 495

display pixels, 323–324

distant lights, 621–623

defined, 621

power approximation, 622

See also light sources; light(s)

distributions

Blinn microfacet, 455–457, 695–699

conditional sampling, 672

delta, 327, 439, 608, 757–758

exponential, 646

fluence, 905

geometric, 8

half-angle, 698, 700

image, 384

joint, 662

light, 8–9, 15, 902–903

marginal sampling, 673

particle, 805

photon, 801

piecewise-constant 1D, 647–650

piecewise-constant 2D, 671–674

Poisson, 888–896

distributions (*continued*)
 power, 645–646
 radiometric, 8
 spectral power (SPD), 261–271, 275, 280
 stationary, 653
 transforming between, 660–662
 dot product, 60–61
 absolute value, 61
 angle relationship, 61
 computation between normals and vectors, 66
 defined, 60
 vector, 556

E

efficiency
 abstraction versus, 991
 bias and, 686–687
 BVHs, 208
 estimator definition, 679
 importance sampling and, 688–693
 Monte Carlo estimator, 747
 Monte Carlo integration, 679–737
 rejection method, 650
 Russian roulette and, 680–681
 sample placement and, 682–686
 sampling reflection functions, 693–708
 splitting and, 681–682
 elementary intervals, 370
 elliptically weighted average (EWA), 539–544
 coordinates conversion, 541
 ellipse axes computation, 540
 ellipse bounding box computation, 542
 ellipse coefficients computation, 542
 ellipse eccentricity, 540
 filter illustration, 539
 filter table lookup, 543
 filter weights initialization, 544
 filtering algorithm, 509
 image pyramid, 541
 lookup detail, 541
 unified resampling filter, 539
 emission, 575, 578, 578–579
 defined, 575
 differential equation, 578
 illustrated, 579
 emission-only integrator, 876–882
 defined, 877
 scene rendering, 878
 stepping, 880–881
See also volume integrators

energy balance, 52, 751
 energy conservation
 BRDF, 295
 light, 282
 environment camera, 318–319
 defined, 318
 ray coordinate computation, 319
 rendering example, 319
See also cameras
 environment maps
 changing, 629
 for illumination, 630
See also infinite area lights
 environmental projection, 318
 equation of transfer, 873–875
 defined, 873
 diffusion approximation, 901–908
 incident radiance, 875
 Monte Carlo integration and, 730
 radiance effects, 875
 error reporting, 1005
 Euler decomposition, 953–956
 even vertices, 162
 boundary rule application for, 165
 one-ring rule for, 163
 EWA. *See* elliptically weighted average
 exitant radiance, 286–287
 computing from photons for diffuse surface, 832
 computing from photons for glossy service, 832
 computing with radiance photons, 824, 826
 defining, 754
See also radiance
 expected values, 640, 641, 654
 exponential density, 594–596
 defined, 594
 illustrated, 595
 perpendicular projection, 596
 exponential distribution, 646
 extraordinary vertices
 defined, 152
 determination, 157
See also vertices

F

false sharing, 1035
 film, 402–413
 effect of, 402
 image, 404–412
 image output, 412–413
 implementations, 402, 404
 interface, 403–404

filters
 box, 394–396, 536
 extent in each direction, 393
 functions, 393–402
 Gaussian, 396–398
 Mitchell, 398–400
 pbrt implementations, 393, 394
 pixel reconstruction, 393
 reconstruction, 531
 sinc, 392, 400–402
 support, 394
 triangle, 396
 unified resampling, 539
 weight table computation, 407
 width definition, 393
See also reconstruction
 final gathering, 819–827
 BSDF for, 824
 defined, 802
 illustrated, 819
 one-bounce, 819
 photon mapping with/without, 820
 ray direction selection, 821
 rays, 826–827
 fixed-function graphics hardware, 995
 float file reader, 1006
 floating-point
 error, 112
 integer conversion, 1002
 weights, 32
 fluence distribution, 905
 fluorescence, 282
 flux. *See* radiant flux
 focal distance, 314
 focal plane, 317–318
 foreshortening
 defined, 306
 perspective projection, 310
 forward differencing, 494
 Fourier analysis, 329
 concept, 325–327
 defined, 324
 equation, 326
 pairs, 327
 use of, 326
 Fourier transform, 325–327
 convolution, 329
 defined, 325, 326
 inverse, 326
 one-dimensional function, 326
 product of two functions, 329
 shah function, 329
 fractional Brownian motion, 561–562
 antialiasing, 561
 graphs, 562
 implementation, 561

- noise, 563
- noise octave computation, 563
- fragments
 - \pm symbol, 3
 - content expansion, 3
 - defined, 2
 - initialization, 2–3
 - page numbers, 4
 - series of, 3
- frames
 - defined, 55
 - standard, 56
 - transformation of, 74
- frequency domain
 - defined, 325
 - sampled signal, 329
 - transforming to spatial domain, 326
- Fresnel equations
 - for conductors, 434, 435, 436
 - defined, 434
 - for dielectric media, 434, 437
- Fresnel incidence effects, 460–462
 - diffuse term derivation, 461
 - illustrated, 461
 - spectra, 460
- Fresnel interface, 439
- Fresnel reflectance, 434–439
 - computation for dielectric, 434
 - for conductors, 434, 436–437
 - for dielectric media, 434, 437–439
 - diffuse, 905
 - for parallel polarized light, 434
 - for unpolarized light, 435
 - See also* reflectance
- Fresnel transmittance, 909
- functions
 - angle measure conversion, 1001
 - band-limited, 329, 330, 509
 - base-2 logarithm, 1001–1002
 - checkerboard, 550
 - clamping, 1000
 - conditional density, 662–663
 - decomposition, 3
 - expected value, 640
 - floating-point to integer conversion, 1002
 - fractional Brownian motion, 561–562
 - frequency, 326
 - frequency space representation, 326
 - image contribution, 836
 - image texture, 538
 - importance, 799
 - incident radiance, 981
 - linear interpolation, 1000
 - lookup, 1032, 1033, 1050
 - marginal density, 663

- memory allocation, 1013
- microfacet distribution, 456–457, 696
- modulus, 1001
- noise, 553–554
- phase, 582, 583–587
- piecewise-constant 1D, 647–650
- ray-casting, 752
- reentrant, 41
- reflectance distribution, 424
- rendering option, 1057
- sampling reflection, 693–708
- scalar contribution, 837
- as series of fragments, 3
- smooth interpolating, 563
- spectrum, 329, 330, 331
- texture, 501, 509–510
- transformation, 1054
- turbulence, 563–565
- utility, 1000–1003
- variance of, 640, 641
- future, 995

G

- gamma correction, 526
- garbage collection, 107–108
- Gauss-Jordan elimination, 1021
- Gaussian filter, 396–398
 - defined, 396
 - graph, 397
 - utility functions, 398
 - See also* filters; reconstruction
- generalized nth nearest-neighbor
 - estimate, 829
- geometric attenuation, 453, 455
- geometric classes, 55
- geometric distribution, 8
- geometric optics
 - defined, 281
 - linearity assumption, 295
 - as reflection model source, 424
- geometric primitives, 187–189
 - allocation, 187
 - with animated transformation, 100
 - collection, 22–23
 - methods, 188–189
- geometry
 - caching, 992
 - differential, 101–103
 - shading, 112–113
 - specular transmission, 445
 - surface, approximating, 506
- Gibbs phenomenon, 336, 337
- glass material, 490
- global illumination
 - algorithms, 751
 - bidirectional path tracing, 770–771
 - instant, 772–784
 - irradiance caching, 784–797
 - Metropolis light transport, 833–861
 - path tracing, 760–771
 - photon mapping, 797–833
 - See also* indirect lighting
- global include files, 999, 1000
- global variables, 2–3
- glossy precomputed radiance transfer (PRT), 974–982
 - BSDF matrix, 977–979
 - defined, 974
 - implementations, 980
 - integrator, 979–982
 - rendering with, 975
 - steps, 974
 - transfer matrix, 975–977
- glossy specular reflection
 - defined, 424
 - illustrated, 425
 - See also* specular reflection
- goniophotometric diagram lights, 618–621
 - defined, 618
 - example, 619
 - for real-world light sources, 619
 - sampling, 713
 - scene rendering, 620
- gradients
 - contributions, 557
 - vectors, 556
- graphics processing units (GPUs), 993
- graphics state, 1059–1061
 - current, 1060
 - defined, 1059
 - hierarchical, 1059–1061
 - methods, 1067
 - pushed, 1071
 - storage, 1059
- grid accelerator, 195–208
 - creation, 197–202
 - defined, 195
 - grid bounding box, 202
 - grid resolution, 198
 - grid size, 198
 - implementation, 196
 - initialization, 196
 - number of voxels, 198, 199
 - performance, 196
 - ray entrance, 202
 - space division, 196
 - “teapot in a stadium” problem, 196
 - traversal, 202–208
 - See also* acceleration structures

H

half-angle vectors, 452, 697, 700
 Halton sampler, 363–366
 stratified sampler comparison, 365
 Halton sequences, 362–368
 characteristics, 363
 discrepancy, 363
 drawbacks, 366
 points, 364
 randomized, 366–368
 sample generation with, 365–366
 Hammersley sequences, 362
 drawbacks, 366
 points, 364
 hemispherical-directional reflectance, 430, 447
 hemispherical-hemispherical reflectance, 430
 estimation, 704
 Lambertian BRDF, 447
 Henyey-Greenstein phase function, 585–586
 asymmetry parameter, 585, 586
 defined, 585
 plot, 587
 weighted sum, 586
 heterogeneous scattering, 886
 hierarchical graphics state, 1059–1061
 hierarchical integration, 908–912
 in refraction evaluation, 908, 910
 rendering with, 908–912
 histogramming, 828
 homogeneous coordinates, 75–76
 defined, 75
 transformation, 75–76
 weight, 75
 homogeneous volumes, 589–591
 AABBs, 590
 hyperboloids, 134–135

I

ideal sampling, 327–331
 identity matrix, 76, 87
 identity transformation, 76
 illumination algorithms, 751
 image contribution function, 836
 image file input/output, 1003–1004
 image film, 404–413
 color alternatives, 406
 configuration, 405
 crop window, 405–406
 discrete integer pixels, 409
 extent computation, 406
 filter table offsets, 410

 filter weight table computation, 407
 looping, 409, 410
 mutex use, 410
 pixel updates, 411
 pixel values, 408
 pixel weight, 409
 storage allocation, 407
 XYZ color, 406
 image pixels, 323
 image pyramids
 defined, 529
 EWA filter, 541
 implementation, 530
 image sampling interface, 338–346
 image textures, 523–544
 caching, 524–527
 defined, 523
 elliptically weighted average (EWA), 539–544
 example illustration, 523
 function value computation, 538
 isotropic triangle filter, 536–539
 memory requirements, 524
 memory use, 534
 mip maps, 528–536
 parameterization, 524
 See also texture(s)
 image(s)
 distribution, 384
 filtering, 391
 reconstruction, 389–402
 resampling, 531
 resizing, 531
 resolution, 340, 342, 531
 synthesis, 335–336
 tile shapes, 341
 implicit form
 cones, 133
 cylinders, 126
 hyperboloids, 134
 paraboloids, 134
 spheres, 114
 importance functions, 799
 importance sampling, 688–693, 734
 defined, 679
 direct lighting, 748
 ease of use, 690
 Monte Carlo estimator convergence, 688
 multiple, 690–693
 variance and, 688
 in-scattering, 581–582, 581–583
 defined, 579
 illustrated, 583
 phase function, 582

 radiance increase, 582
 source term, 582
 See also scattering
 incident light, 427
 incident photons, 831
 incident radiance, 286–287, 288, 442, 744
 as continuous function, 323
 convolving, 968
 direction, 294
 equation of transfer, 875
 function, 981
 function projection, 949–950
 sampled direction and, 819
 SH coefficients computation, 964
 incident radiance probes, 963
 include files
 global, 999, 1000
 main, 999–1000
 index of refraction
 for conductors, 435
 defined, 432
 of gold, 436
 variance, 432
 indexing, 3–4, 153
 indirect lighting, 784, 802
 component example, 785
 estimating, 789
 illumination computation, 783
 irradiance cache and, 789
 photon map, 803
 photon map integrator, 818
 rendering, 772
 sampling, 776
 See also direct lighting; global illumination; lighting
 indirect photons, 810, 812, 813, 821, 823
 inequality operators, 1021
 infinite area lights, 627–631, 943–949
 cube maps with, 948
 defined, 627
 for environment lighting, 627
 illumination illustration, 628
 PDF initialization, 724–725
 projection, 943–949
 ray PDF computation, 730
 sample point conversion to direction, 728
 sampled direction PDF computation, 728
 sampling, 724–730
 sampling steps, 724
 total power, 631
 utility classes, 948

- See also* area lights; light sources; light(s)
- initialization
 - APIs, 1053, 1056
 - with CTM, 1058
 - current graphics state, 1060
- instancing, object, 189–191
 - defined, 189
 - memory use, 189
 - in scene description, 169–170
 - shapes with, 183
- instant global illumination (IGI)
 - integrator, 772–784
 - bidirectional path tracing and, 775
 - computation, 773
 - defined, 772
 - indirect lighting rendering, 772
 - local structures, 779
 - number of light sets variation with, 774
 - parameters, 773
 - path connections, 775
 - virtual light source creation, 775–780
- integrals
 - basis function, 931
 - direct lighting, 747–751
 - estimating with Metropolis sampling, 656
 - evaluation, 759
 - over area, 292–293
 - over paths, 755–757
 - over points, 756
 - over projected solid angles, 289–290
 - over spherical coordinates, 290–292
 - of product of three or more functions, 932
 - radiometric, 288–293
 - triple product, 984
 - XYZ color, 280
- integrand
 - delta distributions in, 757–758
 - partitioning, 758–759
- integrators
 - defined, 739
 - direct lighting, 741, 742, 744, 746
 - emission-only, 876–882
 - glossy PRT, 979–982
 - instant global illumination (IGI), 772–784
 - interfaces, 740
 - irradiance caching, 786–788
 - multiple sample use, 354
 - path, 763, 766–767
 - path tracing, 760
 - photon, 800–803
 - radiance probes, 966
 - sample patterns and, 344
 - samples for, 343, 354, 376
 - simulating light propagation, 26
 - single scattering, 882–885
 - stratified sample generation for, 356
 - subsurface, 887–888
 - surface, 42, 739
 - utility functions, 709
 - volume, 876–885
 - for Whitted ray tracing, 41–47
- intensity, 284–285
 - defined, 284
 - equation, 285
 - solid angle and, 284–285
- interior BVH nodes, 213, 224, 226
- interior kd-tree nodes
 - field usage, 229
 - information access, 229
 - initialization, 234
 - memory, 229
 - processing, 242
 - split access position, 236
 - storage, 230–231
- interior octree nodes, 900, 901
- interior vertices, 162
 - limit rule, 171
 - one-ring vertices for, 164
 - tangent computation, 172
 - updating positions of, 162
- interpolation
 - barycentric, 146
 - keyframe matrix, 90, 91
 - linear, 1000
 - mip map level, 537
 - photon, 827–833
 - rotations, 91, 99
 - scale, 91
 - scale matrix, 99
 - SPDs, 265
 - spherical linear, 94–96
 - translation, 91
- interreflection
 - microfacet models and, 448
 - Oren-Nayar model and, 449
- intersections
 - aggregate, 192–193
 - existence of, 23
 - inconsistencies between, 249
 - information, 111
 - photon-surface, 808
 - ray-box, 193–195
 - ray-cylinder, 126–127
 - ray-disk, 131–132
 - ray-object, 7–8
 - ray-plane, 507
 - ray-primitive, 34, 43
 - ray-shape, 112
 - ray-triangle, 140–145
 - routines, reading/writing, 110–111
 - self, 111–112
 - shadow rays, 208
 - shape interface, 110–111
 - sphere, 116–119
 - testing for, 183
 - time spent finding, 990
- inverse Fourier transform, 326
- inverse transformations, 74
- inversion method, 643–650
 - defined, 644
 - exponential distribution example, 646
 - generalization of, 661
 - piecewise-constant 1D functions, 647–650
 - power distribution example, 645–646
 - use illustration, 645
 - See also* random variables
- irradiance, 282–284
 - candidate samples, 792, 793
 - computation, 794
 - defined, 282
 - differential, 582
 - equations, 283, 284
 - estimation, 795–796
 - integral, 290, 292, 293
 - Lambert's law, 283
 - at points, 288, 898
 - sample region determination, 796–797
 - sample storage, 792
 - sample weighting, 794
 - samples, 791–797, 898
- irradiance caching, 784–797
 - BSDF partitioning, 789
 - defined, 784
 - design issues, 784
 - implementation, 785
 - indirect lighting and, 789
 - integrator, 786–788
 - lookup and interpolation, 791–794
 - path tracing, 795
 - prime, 788
 - rendering with, 789–791
 - sample storage, 788
 - values, adding, 794–797
- irregular isotropic measured BRDFs, 463–466
 - defined, 463
 - mapping function, 464
 - shortcomings, 464
 - See also* measured BRDFs

isotropic phase functions, 583
 isotropic surfaces, 424–425
 isotropic triangle filter, 536–539

K

kd-tree accelerator, 227–245
 defined, 227
 illustrated, 228
 traversal, 240–245
 tree-building algorithm, 231
 See also acceleration structures
 kd-trees, 1027–1033
 as binary trees, 229
 building of, 228
 child node initialization, 240
 child node processing, 1033
 construction, 231–240, 1029
 creation to store set of points, 1030
 defined, 227, 1027
 depth, 232, 233, 240
 depth-first traversal, 1033
 interior nodes, 229, 230
 intersection tests, 244–245
 kd-tree accelerator versus, 1028
 leaf nodes, 229, 230, 1030
 lookups, 1032
 node allocation, 233
 node array, 241
 node, bounding boxes overlapping, 238
 node children pointers, 243
 node layout, 231
 node memory, 230–231, 232, 233
 node storage, 230
 node surface area, 236
 node type decision, 232
 nodes, allocating, 1031
 parameterization, 1029
 parameters, 232–233
 photon storage, 821
 primitive indices, 232
 representation, 229–231
 split axis selection, 236
 split preference, 234
 traversal of rays through, 241
 working memory allocation, 235–236, 240
 kernel methods, 828
 keyframe matrices, 90, 91
 Killeroo model
 Blinn microfacet distribution, 456
 Lambertian model, 450
 measured BRDFs, 463
 metal material, 491
 Oren-Nayar model, 450

plastic material, 486
 specular reflection, 433
 specular refraction, 433
 subdivision surfaces, 148–149
 subsurface material, 491
 Torrance-Sparrow, 456
 Kronecker delta function, 930

L

Lambertian reflection, 43, 446–447
 BRDF, 446
 Killeroo model, 450
 See also reflection
 Lambert's law, 283
 Lanczos window, 400
 lat-long map projection, 944
 Latin hypercube sampling (LHS)
 advantage, 355
 defined, 355
 illustrated, 355
 sample generation, 356
 sample permutation, 356
 stratified sampling versus, 356
 See also sampling
 leaf BVH nodes, 211, 213, 226
 leaf kd-tree nodes
 creation, 233, 1030
 dynamic memory allocation and, 230
 field usage, 229
 initialization, 230
 intersection tests, 244–245
 memory, 229
 overlapping primitives, 229
 primitive checking in, 244
 primitive id storage, 230
 storage, 230
 leaf octree nodes, 899, 900, 901
 left-handed coordinate system
 cross product in, 61
 defined, 56
 illustrated, 57
 rotation matrix, 80–81
 transformations changing, 89
 Legendre polynomials, 932
 computation steps, 937
 implementation, 936
 recurrence, 938, 939
 values computation, 936
 LHS. *See* Latin hypercube sampling
 light distribution, 8–9
 after many scattering events, 903
 defined, 4
 geometric, 8
 in media with high albedos, 902
 radiometric, 8
 spotlight, 15
 light sampling, 709–730
 directional lights, 713–715
 goniophotometric lights, 713
 interface, 709–711
 lights with singularities, 711–815
 methods, 710–711
 point lights, 711–712
 projection lights, 713
 spotlights, 712–713
 light sources, 605–634
 area lights, 8, 623–627, 943–949
 directional lights, 713–715
 distant lights, 621–623
 general, 942–943
 goniophotometric lights, 618–621, 713
 illumination detection, 608
 implementations, 605
 incident direction, 607
 infinite area lights, 627–631
 interface, 605–608
 intersection between ray origin and, 9
 isotropic, 610
 point lights, 285, 711–712, 942
 primitives as, 188
 projection, 941–949
 projection lights, 713
 sample default number, 606
 sampling, 708–730
 scene, 23
 scene definition, 1064–1065
 spotlights, 611–614, 712–713
 surface energy, 10
 texture projection lights, 614–618
 total power emitted, 611
 virtual, 775–780
 visibility testing, 608–609
 light transport equation (LTE), 751–760
 analytic solutions, 753–754
 basic derivation, 751–752
 brevity, 753
 closed form, 739
 conservation of power, 751
 defined, 11, 751
 delta distribution in integrand, 757–758
 energy balance, 751, 752
 equation of transfer and, 873
 evaluation of, 751
 integral over paths, 755–757
 measurement equation and, 759–760
 outgoing radiance distribution, 753
 partitioning integrand, 758–759
 path of multiple rays, 67
 path tracing, 760–771
 surface form, 754–755, 754–757

- unbiased, 784
 - volume, 13
 - lighting
 - caustic, 802, 803, 817
 - direct, 45, 741–751, 802
 - indirect, 772, 776, 802
 - volumetric. *See* radiance probes
 - light(s)
 - area, 623–627, 715–722
 - arrival direction, 607
 - attenuation, 13
 - behavior at wavelengths, 282
 - cosine falloff, 8
 - delta distribution, 608
 - differential flux, 284
 - directional, 713–715
 - directional distribution, 285
 - distant, 621–623
 - energy, 8
 - energy conservation, 282
 - fluorescence and, 282
 - goniophotometric, 618–621, 713
 - incident, 427
 - infinite area, 627–631
 - leaks, 480
 - linearity behavior, 282
 - multiple, 9
 - paths, 850, 851
 - phosphorescence and, 282
 - point, 609–621, 711–712, 942
 - polarization and, 282
 - projection, 713
 - propagation, simulating, 25
 - in ray radiance, 35
 - with singularities, 711–715
 - spotlights, 15, 611–614, 712–713
 - steady state behavior, 282
 - subsurface transport, 187
 - texture projection, 614–618
 - total emitted power, 608
 - linear interpolation, 1000
 - linear transformations, 74
 - linearity
 - geometric optics, 295
 - light behavior, 282
 - of light transport, 926
 - literate programming, 1–4
 - cross-referencing, 3–4
 - defined, 1
 - as enhanced macro substitution package, 3
 - features, 2
 - indexing, 3–4
 - influences, 2
 - local exploration, 833
 - local illumination algorithms, 751
 - local support, 163
 - lock-free algorithm, 1038
 - look-at transformation, 84–85
 - defined, 84
 - finding entries of, 84
 - See also* transformations
 - lookup functions, 1032, 1033, 1050
 - Loop subdivision surfaces, 150
 - convex hull property, 160
 - implementation, 152
 - local support, 163
 - manifold control mesh, 152
 - modified rules, 160
 - refinement process, 150
 - rules, 150
 - scheme, 152
 - vertices, 150
 - weights, 150
 - low-discrepancy sampler, 372–378
 - (0,2) sequence, 372
 - for area lighting sampling, 377–378
 - defined, 372
 - drawbacks, 378
 - sample copies, 376
 - sample generation, 375
 - sample value computation, 375–376
 - scrambled van der Corput sequences, 373
 - stratified sampler comparison, 373
 - low-discrepancy sampling, 359–378
 - (0,2)-sequences, 368–372
 - Halton sequence, 362–368
 - Hammersley sequence, 363
 - radical inverse, 361–363
 - Sobol' sequence, 372
 - underlying uniformity, 361
 - van der Corput sequence, 362, 368, 372
 - See also* sampling
 - luminance, 287–288
 - defined, 272, 287
 - representative values, 288
 - spectral response curve and, 287
 - units, 287
- M**
- main rendering loop, 26–35
 - beginning of, 27–28
 - class relationships, 26, 27
 - defined, 26
 - tasks, number of, 28–30
 - See also* pbrt rendering system
 - Malley's method, 669
 - marble, 567–569
 - defined, 567
 - illustrated, 568
 - parameters, 568
 - See also* noise; texture(s)
 - masking
 - microfacet models and, 448
 - Oren-Nayar model and, 449
 - materials, 477–499
 - bump mapping, 490–496
 - default, 1064
 - description, 1063–1064
 - displacement function association, 492
 - glass, 490
 - interface/implementations, 483–490
 - matt, 484–486
 - measured, 489
 - metal, 490, 491
 - mirror, 490
 - mix, 487–488
 - parameters, 1061–1062, 1064
 - plastic, 486–487
 - shape, 1067
 - substrate, 490
 - subsurface, 490, 491
 - translucent, 483, 490
 - uber, 490
 - mathematical routines, 1020–1021
 - 2×2 linear systems, 1020
 - 4×4 matrices, 1020–1021
 - matrix decomposition, 91
 - matte material, 484–486
 - defined, 484
 - texture evaluation, 486
 - See also* materials
 - Maxwell's equations, 281, 584
 - mean free paths, 807
 - measured BRDFs, 462–470
 - forms, 463
 - irregular isotropic, 463–466
 - Killeroo model, 463
 - regular half angle, 467–470
 - rendering with, 462
 - See also* bidirectional reflectance distribution functions (BRDFs)
 - measured material, 489–490
 - measurement equation, 759–760
 - defined, 759
 - in pixel measurements, 760
 - memory
 - atomic operations, 38–39
 - barrier instructions, 1034
 - blocked layout, 1017
 - BSDF, management, 482–483
 - cache-friendly usage, 1012–1014
 - coherence models, 1034–1035
 - coherent shared, 36

- memory (*continued*)
 - image maps, 524, 534
 - kd-tree nodes, 229, 230–231, 232, 233
 - linear layout of BVH in, 223
 - object instancing and, 189
 - overhead, reducing, 992
- memory allocation
 - arena-based, 1014–1017
 - BSDF, 187
 - custom routines, 201
 - functions, 1013
 - preallocation, 340
 - samples, 345–456
 - variable stack, 1009
- memory arenas, 1014–1017
 - defined, 1014
 - function, 1015
 - getting block of memory for, 1016
 - vectors, 1015
- memory management, 1009–1020
 - arena-based allocation, 1014–1017
 - blocked 2D arrays, 1017–1020
 - cache-friendly memory usage, 1012–1014
 - complexity, 1009
 - reference-counted objects, 1010–1012
 - variable stack allocation, 1009
- metal material, 490, 491
- metamers, 270
- Metropolis Light Transport (MLT), 833–861
 - advantages, 833
 - bootstrapping, 856
 - defined, 833
 - implementation, 857, 859
 - light-carrying paths, 833
 - local exploration, 833
 - mutations, 839–842
 - path contributions, 845–852
 - path generation, 842–844
 - path tracing comparison, 834, 835
 - path vertex, 848
 - rendering, 857–861
 - sample generation, 853
 - sample representation, 838–839
 - sample structure, 838, 839
 - sample variables, 858
 - in sample vector generation, 836
- Metropolis renderer, 852–857
 - responsibilities, 853
- Metropolis sampling, 652–659
 - acceptance probability, 653
 - algorithm pseudocode, 653–654
 - basic algorithm, 652–654
 - defined, 652
 - detailed balance property, 653
 - direct lighting in, 854, 855
 - disadvantages, 652
 - expected values, 654
 - graph illustration, 657
 - integrals estimation, 656
 - mutation strategies, 654–655, 657
 - one-dimensional setting example, 656–659
 - PDFs and, 655
 - sample generation, 658
 - start-up bias, 655–656
 - starting, 853
 - stationary distribution, 653
 - strategies comparison, 659
 - See also* sampling
- microfacet models, 447–460
 - anisotropic, 457–460
 - Blinn, 455–457
 - components, 448
 - defined, 447
 - function, 448
 - geometric effects, 448
 - interreflection and, 448
 - masking and, 448
 - Oren-Nayar, 449–451
 - reflection computation, 448
 - shadowing and, 448
 - Torrance-Sparrow, 43, 452–455
 - See also* reflection; reflection models
- microfacets
 - defined, 447
 - differential area of, 452
 - half-angle vector, 452
 - surface comprised of, 447
- Mie scattering, 584
- mip maps, 528–536
 - box filter, 536
 - defined, 528–529
 - filter weights, 533
 - image pyramid, 529, 530
 - image resampling weights computation, 533
 - level computation, 537
 - level initialization, 534, 536
 - level selection, 537
 - level trilinear interpolation, 537
 - operation support, 529
 - parameterization, 529
 - projection light, 616
 - reconstruction filter, 531
 - texels, 532, 534, 535
 - See also* image textures
- mirror material, 490
- Mitchell filter, 398–400
 - defined, 398
 - graph, 397
 - illustrated, 399
 - negative lobes, 398
 - one-dimensional filter function, 398–399
 - ringing/blurring trade-off, 398
 - See also* filters; reconstruction
- mix material, 487–489
 - defined, 487
 - See also* materials
- mix textures, 521–522
 - defined, 521
 - evaluation, 521
 - See also* texture(s)
- MLT. *See* Metropolis Light Transport
- Möbius strip, 154
- modulus function, 1001
- Monte Carlo algorithms, 46, 608
 - improvements to, 640
 - results averaging, 637
- Monte Carlo estimator, 641–643
 - convergence, 643
 - convergence rate, 643
 - defined, 641
 - efficiency, 747
 - error, 643
 - evaluation, 643
 - expected value, 641
 - extending to multiple dimensions, 642
 - multiple import sampling, 691
 - for scattering equation, 702
- Monte Carlo integration, 24–25, 458, 637–737
 - background, 638–641
 - clamping and, 782
 - concepts, 637–676
 - defined, 638
 - disadvantage, 638
 - efficiency improvement, 679–737
 - equation of transfer and, 730
 - integral estimation, 789, 977
 - random samples for, 745
 - randomness, 637
 - SH coefficient value estimation, 942
- Monte Carlo sampling, 441, 630
 - artifacts, 638
 - random samples for, 481
- multidimensional transformations, 662–674
 - conditional density function, 662–663
 - cosine-weighted hemisphere sampling example, 668–670
 - piecewise-constant 2D distributions example, 671–674
 - sphere sampling example, 663–665
 - triangle sampling example, 670–671
 - unit disk sampling example, 665–668

See also transformations
 multiple importance sampling (MIS),
 690–693
 balance heuristic, 691, 693
 defined, 691
 direct lighting, 749, 750
 Monte Carlo estimator, 691
 power heuristic, 692, 693
 sample weighting, 691
 variance reduction, 691
 weight computation, 825–826, 827
See also importance sampling
 multipoles, 915
 mutation strategies, 654–655, 657
 mutexes, 1038–1039
 instances, 1038
 locks, 1039
 reader-writer, 1039
 mutual exclusion, 37, 38

N

n-rooks sampling. *See* Latin hypercube
 sampling (LHS)
 nearest-neighbor techniques, 829
 noise, 553–569
 as band-limited function, 560
 for fractional Brownian motion, 563
 frequency content, 560
 functions, 553–554
 idioms, 560–565
 marble, 567–569
 octave of, 561
 Perlin, 554–558
 random polka dots, 558–560
 turbulence, 563–565
 value, 554
 windy waves, 566–567
 non-a-number (NaN) values, 57–58
 nonuniform sampling, 334, 391
 nonuniform scaling, 79
 normalization
 CDF, 649
 factor, 932, 941
 vector, 62–63
 normalized device coordinate (NDC)
 space, 304, 319
 normalized directions, 43
 normals, 65–66
 for closed shapes, 103
 defined, 65
 dot product computation between, 66
 implementation, 65
 microfacet, 448
 orientation, reversing, 103
 partial derivative of, 121–122

 shading, 146, 480, 481
 transforming, 86–88
 noweb system, 2
 Nyquist frequency, 332, 389
 Nyquist limit, 334, 562

O

object instancing, 189–191
 defined, 189
 memory use, 189
 in scene description, 1069–1070
 shapes with, 183
 object space
 defined, 303
 spheres in, 115
 triangle mesh, 138
See also coordinate spaces
 object subdivision, 192
 object(s)
 default material, 1064
 foreshortening, 306, 310
 implementations, adding, 1073
 instances, 1068
 layout in memory, 1013
 reference-counted, 1010–1012
 scene, 1072
 octave, noise, 561
 octrees, 1022–1027
 for acceleration structures, 1022
 applications, 1022
 callback, 1027
 child node numbering scheme, 1026,
 1027
 child nodes, 899, 1026
 clustered irradiance samples,
 898
 declaration, 1022–1023
 defined, 227, 1022
 interior nodes, 900, 901
 of irradiance points, 910
 leaf nodes, 899, 900, 901
 quadtree, 1025
 sample point, 896–901
 odd vertices, 162
 offset rays, 505
 one-ring
 for boundary vertex, 164–165
 defined, 162
 for even vertex, 163
 for interior vertex, 164
 rule, 162
 one-to-one transformations, 74
 open mesh, 152
 OpenEXR standard, 1003–1004
 OpenGL, 1045

optical thickness, 581
 computing, 731–733
 defined, 731
 estimation, 732
 Oren-Nayar diffuse reflection, 449–451
 cosine term computation, 451
 defined, 449
 Killerloo model, 450
 shadowing, masking, interreflection
 and, 449
 sine and tangent term computation,
 451
See also microfacet models; reflection
 organization, this book, 47–48
 oriented bounding boxes (OBBs), 70
 orthogonal matrix, 80
 orthogonality, 930
 orthographic camera, 306–310
 church model image, 308
 defined, 306
 depth of field, 309
 differential rays computation, 307
 illustrated, 307
 ray creation, 309
 viewing transformation, 307
See also cameras; projective camera
 models
 orthographic projection, 307
 orthonormal basis functions, 930–932
 properties, 928, 930
 space of functions representation, 931
 out-of-gamut colors, 413
 out-scattering, 579–581
 beam transmittance, 580–581
 defined, 579
 illustrated, 580
 probability, 579
 radiance and, 580
See also scattering

P

packet tracing, 995
 paraboloids, 134
 parallelism, 1033–1041
 atomic operations, 1036–1038
 expression style, 1040
 memory coherence models and
 performance, 1034–1135
 mutexes, 1038–1039
 task system, 1040–1041
 parallelization, 35–41
 challenge, 35–36
 conventions, 39–40
 data races and coordination, 36–39
 reentrancy expectations, 40–41

- parallelization (*continued*)
 - See also* pbrt rendering system
- parallelograms, 62
- parameter sets, 1047–1051
 - adding to, 1048–1049
 - defined, 1047
 - item structure, 1048
 - methods, 1050
 - parameters, 1047
 - values, looking up, 1049–1051
- parametric form
 - cones, 133
 - cylinders, 125
 - disks, 130
 - hyperboloids, 134–135
 - paraboloids, 134
 - rays, 7, 67
 - spheres, 114
 - triangles, 142, 143–144
- partial cylinders, 127–128
- partial derivatives
 - cone, 133–134
 - cylinder, 128
 - disk, 132
 - estimation with offset rays, 505
 - hyperboloid, 135
 - paraboloid, 134
 - parametric, 120
 - position and normal, 102
 - shading normal, 146
 - sphere, 121–122
 - triangle, 142, 143
- partial spheres, 119–121
- participating media, 575
- particle tracing, 798–800
 - defined, 797
 - illustrated, 798
 - samples of illumination, 798
 - theoretical basis, 798–800
- particles
 - distribution, 805
 - intersections, 807
 - paths, 803
 - weights, 799, 805
- partitioning
 - integrands, 758–759
 - irradiance cache integrator, 789
 - photon mapping, 801, 817
 - radiance photons, 816
- partitioning primitives, 213–217
 - with approximate SAH, 219
 - axis selection, 213–214
 - bucket boundary, 221
 - equally-sized subsets, 217
 - goal, 214
 - interior nodes, 213
 - through node midpoint, 215–216
 - See also* bounding volume hierarchies (BVHs)
- path tracing, 760–771
 - bidirectional, 762, 770–771
 - defined, 760
 - implementation, 765–770
 - incremental path construction, 765
 - integrator, 760
 - irradiance cache integrator, 795
 - Metropolis Light Transport (MLT)
 - comparison, 834, 835
 - overview, 762–763
 - path sampling, 763–764
 - process, 762
 - scene rendering, 761
- paths
 - bidirectional, weight computation, 852
 - BSDF, 757
 - camera, 845, 849
 - connecting, 775, 849
 - contributions, 845–852
 - generating, 842–844
 - incremental construction, 765
 - indirect visibility, 961
 - integral over, 755–757
 - integrator, 763, 766–767
 - length, 849, 850
 - light, 851, 852
 - light-carrying, 833
 - mean free, 807
 - Metropolis, 850
 - particle, 803
 - photon, 806, 808, 811
 - radiance computation along, 846
 - random ray, 891
 - ray, vertex generation, 843
 - sampling, 763–764
 - termination, 769, 780, 807, 844
 - total number of, 804
 - vertex, finding, 769–770
 - vertex information, 844
- pbrt rendering system
 - abstract base classes, 15
 - bugs, 50
 - code use, 48–50
 - conventions in, 39–40
 - integrator for Whitted ray tracing, 41–47
 - interface types, 16
 - main() function, 18–19
 - main rendering loop, 26–35
 - overview, 15–47
 - parallelization of, 35–41
 - parsing phase, 16–17
 - phases of execution, 16–17
 - reconstruction in, 391
 - reentrancy expectations in, 40–41
 - rendering loop, 17
 - scene file format, 16–17
 - scene representation, 18–24
 - source code distribution, 16
 - volumetric primitives support, 23
- perfect specular reflection
 - defined, 424
 - illustrated, 425
- performance bugs, aggregate, 250
- Perlin noise, 554–558
 - characteristics, 555
 - computation, 554
 - data, 557
 - defined, 554
 - gradient weights computation, 556
 - illustrated, 555
 - implementation, 555
 - nested permutations, 557
 - weights interpolation computation, 558
 - See also* noise
- perspective camera, 310–313
 - implementation, 310
 - rendering example, 308
 - See also* cameras; projective camera models
- perspective projection
 - distances/angles and, 310
 - foreshortening, 310
 - offset ray computation, 313
 - parallel lines and, 310
 - perspective viewing, 310
 - ray origination, 312
 - transformation matrix, 311
 - transformation steps, 311–312
- phase functions, 582, 583–587
 - anisotropic, 584
 - defined, 582
 - Henyey-Greenstein, 585–586
 - implementations, 584
 - isotropic, 583
 - probability density for sampling, 731
 - reciprocal property, 583
 - sampling, 731
 - Schlick, 586–587
 - weighted sum, 586
 - writing convention, 584
- phenomenological reflection models, 423
- phosphorescence, 282
- photometry, 287
- photon integrator, 800–803
 - caustic photon map, 817

- defined, 800
- illumination strategies, 802
- indirect lighting computation, 818
- initial photon subset selection, 813
- local definitions, 822
- merging photon data in, 812
- parameters, 802–803
- shared photon map data structures, 811
- photon mapping
 - bias, 828
 - defined, 797
 - final gathering, 802, 819–827
 - partitioning, 801, 817
 - photon weights and, 805
 - scene rendering, 801
- photon maps, 803–827
 - building, 803–817
 - caustics, 803
 - defined, 800
 - direct lighting, 803
 - indirect lighting, 803
 - lookup, 831
 - populating, 809
 - precomputed radiance values, 813–817
 - shared data structure updates, 811–813
 - types of, 803
 - update determination, 809
 - using, 817–827
- photon-surface intersections, 808
- photons
 - caustic, 813
 - close to lookup point, 821
 - density, 801
 - depositing at surface, 809–810
 - direct, 810
 - directions, copying, 823
 - distribution, 801
 - for final gather ray, 826
 - incident, 831
 - incident directions, 820
 - indirect, 810, 812, 813, 821, 823
 - interpolation, 827–833
 - local definitions, 830, 831
 - merging, 806
 - object arrays, 804
 - organization with heap, 822
 - path determination, 811
 - paths, 806, 808
 - radiance, 810, 813–817
 - ray direction samples, 810–811
 - recording, 808
 - representation, 805
 - scattering, 811
 - searching for, 821
 - shooting, 805–807, 815
 - storage with kd-tree, 821
 - storage with local arrays, 806
 - structure, 804
 - unordered array of, 823
 - weights, 805, 811
- photorealistic rendering
 - goal, 4
 - ray-tracing algorithm and, 4–15
 - See also* rendering
- physical (wave) optics, 424
- piecewise constant basis functions, 928–930
 - defined, 928
 - illustrated, 929
- piecewise-constant 1D functions, 647–650
 - PDF, 647
 - See also* inversion method
- piecewise-constant 2D functions, 671–674
 - illustrated, 674
- pinhole cameras
 - defined, 5
 - depth of field and, 316
 - elements, 5
 - illustrated, 6
 - simulation, 6
 - See also* cameras
- pixels
 - addressing, 338
 - coordinates, 349, 532
 - discrete integer, 409
 - display, 323–324
 - display values and, 526
 - image, 323
 - in low-discrepancy sampler, 374
 - measurements, 760
 - reconstruction filter, 393
 - sampling range, 341
 - splat values, 411, 413
 - understanding, 337–338
 - weight, 409
- planar mapping, 518
- plastic material, 486–487
 - Killeroo rendered with, 486
 - modeling, 486
 - parameters, 486
 - See also* materials
- point lights, 609–621
 - goniophotometric diagram, 618–621
 - intensity, 285
 - positioning, 610
 - projection, 942
 - sampling, 711–712
 - scene rendering, 610
 - spotlights, 611–614
 - texture projection, 614–618
 - total power emitted, 611
 - See also* light sources; light(s)
- point repulsion algorithms, 888
- points, 63–65
 - adding, 64
 - auxiliary intersection, 507
 - barycentric coordinate computation for, 147
 - bounding box, 71, 72
 - in camera space, 308, 311
 - candidate, 891, 892, 896
 - defined, 63
 - denoting, 63
 - distance between, 65
 - Halton sequence, 364
 - Hammersley sequence, 364
 - height, in object space, 596
 - homogeneous, 75
 - indirect visibility between, 961
 - integral over, 756
 - irradiance at, 288, 898, 910
 - low-discrepancy, 810
 - optical thickness between, 581
 - Poisson, 890, 891
 - Poisson distribution of, 888–896
 - sampled, 888, 889, 896–901
 - samples, 325, 333, 962
 - in sphere, 721
 - sphere sample, on spherical light source, 721
 - subtracting, 64
 - surface, 888–896
 - transforming, 85–86
 - translation and, 78
 - translucent surfaces, 894
 - weighted sums of, 65
- Poisson disk patterns, 378
- Poisson distribution, 888–896
- Poisson sphere
 - criterion cases, 889
 - implementation, 889–890
 - point computation, 890
 - in Poisson disk approximation, 888
 - test, 892
- polar coordinates, 661
- polar decomposition, 97
- polarization, 282
- polka dots, 558–560
 - antialiasing, 559
 - application illustration, 558
 - center, 560
 - declaration, 559
 - indices computation, 559

polka dots (*continued*)
 radius, 560
 postaliasing, 332
 power distribution, 645–646
 power heuristic, 692, 693
 prealiasing, 332
 precomputed light transport, 925–986
 ambient occlusion, 926, 927
 basis functions and, 927–932
 categories, 927
 defined, 925
 overview, 925–927
 precomputed diffuse transfer, 969–973
 precomputed glossy transfer, 974–982
 radiance probes, 956–969
 spherical harmonics, 932–956
 precomputed radiance transfer (PRT)
 diffuse, 969–973
 glossy, 974–982
 rendering with, 970
 techniques, 969
 prefiltering, 334–335
 prime irradiance cache, 788
 primitive interface, 184–191
 defined, 186
 methods, 186–187
 primitive subdivision, 208
 primitives
 adding to voxels, 199
 animated, 189–191
 as area light sources, 188
 bounding boxes, 201
 centroids, computing bounds of, 214
 geometric, 187–189
 groups, rejection of, 192
 instanced, 189
 lazy refinement, 197
 looping over, in voxel, 206, 207
 overlapping, kd-tree nodes, 229
 partitioning, 213–217
 refining, 186–187, 206
 splitting based on midpoint centroids, 216
 surface scattering inside, 187
 surface shader bound to, 477
 transformation, 190–191
 in voxel, 202
 world space bounds, 199
 principle of similarity, 901–902
 probability density, 44
 probability density functions (PDFs), 640
 CDF and, 640
 discrete, 644
 infinite area light, 729–730
 Metropolis sampling and, 655

photon-sampling of directions, 825
 piecewise-constant 1D functions, 647, 649
 power distribution, 645
 sampling direction towards spheres, 722
 sampling for infinite area light, 724–725
 shape sampling, 716–717
 spotlight illumination distribution, 712
 probes, 1006–1009
 data gathering, 1008
 defined, 1006
 options, 1007–1008
 statistics gathered during, 1071
 procedural texturing, 544–553
 antialiasing, 545, 551
 checkerboard, 546–552
 defined, 545
 fractional Brownian motion for, 561
 implications, 545
 implicit pattern definition, 553
 UV texture, 545–546
 See also texture(s)
 projected solid angles, 289–290
 determination, 289
 illustrated, 289
 integrals over, 289–290
 See also solid angles
 projection
 general light sources, 942–943
 incident radiance functions, 949–950
 infinite area lights, 943–949
 lat-long map, 944
 light sampling, 713
 light sources, 941–949
 point lights, 942
 with Reinmann integration, 944
 projective camera models, 305–318
 depth of field, 313–318
 implementation, 305
 orthographic, 306–310
 perspective, 310–313
 screen-to-raster, 305–306
 transformation matrix, 305
 pseudo-random number generator, 1002–1003

Q

quadratic equations, 118, 127
 quadrics
 checkerboard texture applied to, 547
 cone, 133–134
 cylinder, 124–129

 defined, 113
 disk, 129–132
 hyperboloid, 134–135
 paraboloid, 134
 polka dots applied to, 558
 sphere, 113–124
 surface area, 123
 UV texture applied to, 546
 quadrees, 1025
 quasi Monte Carlo, 685
 quaternions, 92–94
 addition, 93
 along animation path, 95
 defined, 92
 inner product, 93
 interpolation, 94–96
 multiplication, 92
 representation, 92
 rotation matrix, 93
 subtraction, 93

R

radiance, 285–286
 absorption and, 577–578
 along path, 846
 camera path, 849
 defined, 33, 285
 determination, 34
 differential, 295
 emitted, 293
 equation, 285
 exitant, 286–287, 754
 illustrated, 286
 impossible values, 33
 in-scattering and, 582
 incident, 286–287, 288, 294, 442, 744
 out-scattering and, 580
 outgoing, accumulating, 817
 outgoing, distribution, 753
 outgoing, reflected, 453
 over set of directions, 288
 properties, 285
 rays carrying, 35
 reflected, 791, 831
 surface integrator, 740
 total, 45, 579
 values, precomputing, 813–817
 Whitted integrator evaluation, 42
 radiance photons, 810
 creating, 814
 exitant radiance computation, 813, 824, 826
 partitioning, 816
 precomputing, 815
 process methods, 825

- radiance computation for, 816
- range computation, 816
- scene rendering with, 814
- structure, 815
- radiance probes, 956–969
 - bad placement artifacts, 960
 - bounding box, 959
 - coefficients, 966
 - computing at sample points, 962
 - contribution computation, 963
 - creating, 956–965
 - defined, 956
 - error sources, 956
 - incident, 963
 - integrator, 966
 - reflected lighting computation with, 966
 - rendering with, 957
 - using, 965–969
 - See also* precomputed light transport
- radiant exitance, 282
- radiant flux, 282
 - defined, 282
 - differential, 284
 - illustrated, 283
- radiative equilibrium, 913
- radiative transfer, 281
- radical inverse
 - computation, 362
 - defined, 361
 - positive integers, 363
 - sequences using, 362
- radiometric distribution, 8
- radiometric integrals, 288–293
 - evaluation of, 288
 - irradiance, 290, 292, 293
 - over area, 292–293
 - over projected solid angle, 289–290
 - over spherical coordinates, 290–292
 - working with, 288–293
- radiometry, 281–288
 - basic, 281–288
 - defined, 261, 281
 - flux, 282, 283
 - geometric optics, 281
 - intensity, 284–285
 - irradiance, 282–284
 - luminance, 287–288
 - Maxwell's equations and, 281
 - radiance, 285–286
 - radiant exitance, 282
 - radiative transfer, 281
- random number generator, 892, 1003
- random polka dots, 558–560
- random ray generation, 247
- random sampling, 684
- random variables
 - applying functions to, 639
 - BSDF, 705
 - canonical uniform, 639
 - CDF, 639
 - continuous, 639–640
 - defined, 638
 - discrete, 639
 - independent, 641
 - inversion method, 643–650
 - PDF, 640
 - rejection method, 650–652
 - sampling, 643–652
 - uniform, 665
- randomized Halton sequences
 - defined, 366
 - permutation tables, 367–368
 - See also* Halton sequences
- randomness, 637
- raster space
 - computing, 384
 - defined, 304
 - sample point, 309
 - See also* coordinate spaces
- ray differentials, 68–70
 - in antialiasing textures, 46
 - computation for specular reflection, 512
 - defined, 32
 - in finding filter regions, 510
 - offset rays in, 511
 - reflected, 510
 - tracking, 511
 - transmitted, 510
- ray propagation, 13–15
 - defined, 5
 - participating media, 13
- ray tracing
 - advantage, 318
 - early example, 12
 - environment camera, 318–319
 - high-performance CPU, 994
 - image projections, 318
 - photorealistic rendering and, 4–15
 - recursive, 5, 11–13
 - single low-level shape representation, 991
 - strength of, 992
- ray-box intersections, 193–195
 - defined, 193
 - illustrated, 193, 194
- ray-casting function, 752
- ray-cylinder intersections, 126–127
- ray-disk intersections, 131–132
- ray-object intersections, 7–8
 - acceleration structure, 8
 - brute-force approach, 7–8
 - defined, 4
 - execution time, 192
 - point, 7
 - sphere, 123
- ray-plane intersections, 507
- ray-primitive intersections, 34, 43
 - information about, 186
 - light-scattering properties, 187
- ray-shape intersections, 112
- ray-triangle intersections, 140–145
 - barycentric coordinates, 140, 142
 - cost of, 141
 - distance along ray, 142
- ray-voxel stepping algorithm, 203–204
- Rayleigh scattering, 584
- rays, 66–70
 - camera simulation and, 6–7
 - constructing, 68
 - defined, 66
 - denoting, 66
 - direction, 248
 - “epsilon” value, 248
 - final gather, 826–827
 - floating-point weights, 32
 - illustrated, 67
 - image location conversion to, 7
 - marching process, 879
 - offset, 505
 - parametric distance to intersection, 186
 - parametric form, 7, 67
 - parent, 68
 - path, vertex generation, 843
 - random, 247
 - sampling, 708
 - shadow, 9, 23
 - stepping through voxel grid, 203
 - testing for intersection, 183
 - time value, 67
 - transforming, 88
 - traversal through kd-tree, 241
 - tree of, 12
 - volume integration sampling, 881
 - world space, 117
- read for ownership (RFO), 1035
- reader-writer mutexes, 1039
- real spherical harmonics, 932–933
- reconstruction, 389–402
 - approximation, 324
 - artifacts, 332
 - box filter, 394–396
 - defined, 324
 - filter functions, 393–402
 - Gaussian filter, 396–398
 - ideal, 391

- reconstruction (*continued*)
 - Mitchell filter, 398–400
 - in *pbrt*, 391
 - pixel filter, 392
 - pixel values, 391
 - postaliasing, 332
 - sinc filter, 400–402
 - success key, 331
 - triangle filter, 328, 396
 - recursive ray tracing
 - defined, 5
 - illustrated, 13
 - mirror-reflection direction, 12
 - tree of rays, 12
 - See also* ray tracing
 - reduced extinction coefficient, 902
 - reduced scattering coefficient, 598, 902
 - reentrancy expectations, 40–41
 - reference-counted objects, 1010–1012
 - references
 - assignment, 1011
 - as pointers, 1011–1012
 - reflectance, 430
 - BRDF, 294–296, 912
 - conversion process for, 277–278
 - differential diffuse subsurface, 906
 - distribution function, 424
 - estimation, 703–704
 - Fresnel, 434–439, 905
 - hemispherical-directional, 430
 - hemispherical-hemispherical, 430, 704
 - Lambertian surface, 753
 - properties, 423
 - reflected radiance
 - computation, 791
 - computation with diffuse PRT, 972
 - estimating, 831
 - outgoing, 453
 - See also* radiance
 - reflection
 - BRDF, 294–296
 - BSSRDF, 296–297
 - categories, 424
 - computations, 425
 - coordinate system, 425
 - diffuse, 424, 425, 449–451
 - from direct lighting, 848
 - direction, 12
 - distribution properties, 423
 - equation, 296
 - evaluation with hierarchical
 - integration, 908, 910
 - glossy, 680
 - glossy specular, 424, 425
 - Lambertian, 446–447
 - mechanisms, 294
 - Oren-Nayar, 449–451
 - perfect specular, 424, 425
 - retro-reflective, 424, 425
 - specular, 45, 433, 439–441, 702–703
 - subsurface, 885
 - surface, 293–297, 739–871
 - total internal, 439
 - reflection models, 423–474
 - basic interface, 428–432
 - geometric setting, 425–428
 - implementations, 424
 - microfacet, 447–460
 - sources, 423–424
 - terminology, 424–425
 - refraction
 - index of, 432
 - indices for objects, 434
 - specular, 433
 - regular half angle measured BRDFs, 467–470
 - advantages, 467
 - defined, 467
 - regular vertices, 152
 - rejection method, 650–652
 - defined, 650
 - efficiency, 650
 - example, 651–652
 - sample generation, 651
 - sampling, 650
 - See also* random variables
 - Renderer interface, 24–26
 - rendering
 - aliasing sources, 336–337
 - APIs, 1045–1046
 - cleanup after, 1071
 - defined, 1
 - equation. *See* light transport equation
 - with hierarchical integration, 908–911
 - with irradiance cache, 789–791
 - loop, 17
 - main loop, 26–35
 - with measured BRDF data, 462
 - Metropolis Light Transport (MLT), 857–861
 - options, 1056–1058
 - photorealistic, 4–15
 - with radiance probes, 957
 - sample pattern effect on, 351
 - with virtual light sources, 780–784
 - volume, 873–922
 - world end and, 1070–1072
 - reporting, 1005–1006
 - error, 1005
 - progress, 1005–1006
 - retro-reflective reflection
 - defined, 424
 - illustrated, 425
 - RGB color, 273–279
 - coefficients, 275
 - conversion, 279
 - conversion table computation, 276
 - conversion to SPDs, 276
 - conversion to XYZ values, 275
 - device dependent, 412
 - emission curves, 274
 - image film, 406
 - LED/LCD displays, 273
 - output values, 413
 - reflectance spectrum conversion, 278
 - SPD display, 275
 - spectrum creation, 280
 - spectrum functions computation, 277
 - values, 274, 277
 - See also* spectral representation
 - Riemann integration, 944, 945
 - right-handed coordinate system, 56, 57
 - ringing
 - defined, 398
 - effect illustration, 950
 - reducing, 950–951
 - rotations, 80–83
 - angle, 81, 83
 - arbitrary axis, 82–83
 - Cranley-Patterson, 384
 - defined, 80
 - extracting, 98
 - interpolation, 91, 99
 - matrix, 93–94
 - orthogonal matrix, 80
 - properties, 80
 - spherical harmonics (SH), 951–956
 - x axis, 80–81
 - y axis, 81–82
 - z axis, 82
 - Russian roulette, 680–681
 - applying, 681
 - defined, 680
 - in path sampling termination, 766
 - thresholds, 774
 - variance and, 681
 - weights, 681
- ## S
- SAH. *See* surface area heuristic
 - sample placement, 682–686
 - quasi Monte Carlo, 685
 - stratified sampling, 682–685
 - warping samples and distortion, 685–686
 - sample points
 - generating, 888

- illustrated, 889
- octree, 896–901
- radiance probe computation, 962
- radiance values computation, 897
- raster space, 309
- sampled spectrum
 - arithmetic operations, 266
 - XYZ matching functions computation, 271–272
- samplers
 - adaptive, 385–389
 - best-candidate, 378–385
 - current pixel coordinates, 349
 - Halton, 363–366
 - implementations, 323, 338, 340
 - low-discrepancy, 372–378
 - main rendering loop interaction, 385–386
 - ray generation report, 341
 - stratified, 346
- samples
 - (0,2)-sequence, 370
 - accessing, 344
 - bootstrapping, 853
 - difference comparison, 389
 - discrete pixel, 353
 - distribution, 25
 - emitted rays from lights, 777
 - generation, 349, 350, 351, 353
 - implementations, 338
 - integrators, 343, 344, 354, 376
 - irradiance, 791–797, 898
 - LHS, 356
 - light source, 606
 - linear segments between, 267
 - maximum number of values, 340
 - memory allocation, 345–346
 - MLT, 838–839, 853, 858–860
 - nonuniform distribution, 335
 - number returned, 31
 - photon ray direction, 810–811
 - point, 325
 - position, 324
 - random, 2D mapping, 666
 - representation, 342–346
 - shape ids, 388
 - spacing, 504
 - SPD, 266, 267
 - spectral data, 266
 - storage, 342
 - stratified, 353
 - value, 324
 - vector, 836
 - warping, 685–686
- sampling
 - 1D patterns, 344
 - 2D patterns, 343, 347
 - 3D patterns, 343
 - adaptive, 334, 341, 385–389
 - aliasing and, 324, 331–332
 - anisotropic microfacet model, 699–701
 - antialiasing and, 332–335
 - approximation, 324
 - area lights, 358, 715–722
 - artifacts, 332
 - best-candidate, 378–385
 - Blinn microfacet distribution, 695–699
 - BSDFs, 705–708
 - cosine-weighted hemisphere, 668–670
 - cylinders, 719
 - directional, 664
 - directions, 708
 - disks, 665–668, 718–719
 - frequency minimum, 332
 - FresnelBlend class, 701
 - goniophotometric lights, 713
 - ideal, 327–331
 - image interface, 338–346
 - image synthesis application, 335–336
 - importance, 679, 688–693, 734
 - indirect lighting, 776
 - infinite area lights, 724–730
 - Latin hypercube, 355
 - light sources, 708–730
 - low-discrepancy, 359–378
 - method comparison, 348
 - Metropolis, 652–659
 - Monte Carlo, 441, 481, 630
 - nonuniform, 334, 391
 - paths, 763–764
 - pattern comparison, 346, 347, 379
 - patterns, 338
 - phase functions, 731
 - pixel, 341
 - point, 333
 - point lights, 711–712
 - prealiasing, 332
 - process, 327, 328
 - random, 684
 - random variables, 643
 - rays, 708
 - reflection functions, 693–708
 - rejection, 650–652
 - shape sets, 722–724
 - shapes, 716–717
 - spheres, 720–722
 - spotlights, 712–713
 - stratified, 346–359, 682–686
 - texture, 503–513
 - theorem, 332
 - theory, 323–331
 - triangles, 670–671, 719
 - uniform, hemisphere, 663–665
 - volume integration ray, 881
 - volume scattering, 730–733
- sampling rate
 - computation, 959
 - defined, 327
 - low, 332
 - texture, 503–509, 528
- saturation, 14
- scalar contribution function, 837
- scalars, 56
 - division, 59
 - multiplication, 59
 - reciprocal computation, 59
- scale texture, 520–521
 - antialiasing and, 521
 - defined, 520
 - See also* texture(s)
- scaling
 - BxDF adapter, 431–432
 - nonuniform, 79
 - properties, 79
 - transformation, 79–80
 - uniform, 79
 - vectors, 59–60
- scattering
 - back, 585
 - defined, 576
 - equation, 296
 - heterogeneous, 886
 - in, 581–583
 - Mie, 584
 - out, 579–581
 - Rayleigh, 584
 - subsurface, 297, 599–600, 885–913
 - surface, 5, 10–11
 - translucent media, 886
 - volume, 575–602, 730–733
- scene definition, 1058–1072
 - hierarchical graphics state, 1059–1061
 - light sources, 1064–1065
 - object instancing, 1069–1070
 - shapes and volume regions, 1065–1069
 - surface and material description, 1063–1064
 - texture and material parameters, 1061–1062
 - world end and rendering, 1070–1072
- scene description
 - approaches, 1045–1046
 - defined, 16
 - initialization and rendering options, 1051–1058
 - interface, 1045–1076

- scene description (*continued*)
 - new object implementations, 1073
 - parameter sets, 1047–1051
 - parsing, 16, 21, 30
 - scene definition, 1058–1072
 - state tracking, 1052–1053
 - transformations, 1053
- scenes
 - complexity, increased, 992–993
 - geometric object representation, 22–23
 - instance usage, 1069
 - light source, 23
 - representation, 18–24
- Schlick phase function, 586–587
 - defined, 586
 - plot, 587
 - See also* phase functions
- screen space
 - decomposition, 39
 - defined, 304
 - See also* coordinate spaces
- screen-to-raster projection, 305–306
- second fundamental form, 121–122
- self-illumination, 913
- self-intersections, 111–112
- self-shadowing
 - microfacet models and, 448
 - Oren-Nayar model and, 449
- semi-infinite media, 886
- separable approximations, 984
- shading aliasing, 336
- shading coordinate system, 425, 427
- shading geometry, 112–113
 - computing, 113
 - with interpolated normals, 112
 - triangles, 145–148
- shading normals, 146, 147
 - artifacts, 480
 - bump mapping and, 492
 - computation, 490
 - error types resulting from, 481
- shadow rays
 - defined, 9
 - existence of intersections, 23–24
 - intersections, 208
 - virtual light, 782
- shadows, 9
- shah function
 - convolution, 329, 330
 - Fourier transform, 329
- shape sets
 - acceleration structure, 724
 - defined, 722
 - PDF value computation, 723
 - sampling, 722–724
- shapes, 107–181
 - abstraction of, 107
 - animated, 1065, 1066, 1067, 1068
 - with animated transformation
 - matrices, 183
 - API creation, 1073
 - bounding, 109–110
 - closed, 103
 - cone, 133–134
 - creation, 1066–1067
 - cylinder, 124–129
 - definition of, 108
 - disk, 129–132
 - hyperboloid, 134
 - id, 108–109, 388
 - incorrect self-intersections, 111–112
 - interface, 107–113, 716
 - intersection, 110–111
 - material, 1067
 - normals, 103
 - with object instancing, 183
 - paraboloid, 134
 - parametric description, 102
 - as placeholders, 110
 - pointers, 108
 - refinement, 110
 - sampling, 716–717
 - shading geometry, 112–113
 - sidedness, 113
 - sphere, 113–124
 - surface area, 113
 - tetrahedron, 148
 - triangle, 135–148
- shared data, updating, 39–40
- sidedness, 113
- simulation, 423–424
- sinc filter, 400–402
 - finite extent, 400
 - graphs, 401
 - infinite support, 392
 - Lanczos window, 400
 - ringing, 392
 - use results, 401
 - See also* filters; reconstruction
- single instruction, multiple data (SIMD)
 - processing, 994
- single scattering integrator, 882–885
 - defined, 882
 - implementation, 882
 - sample pattern computation, 884
 - source term computation, 884
 - visual effect, 883
 - See also* volume integrators
- Snell's law, 432
 - derivation of, 473
 - for transmitted directions, 45
- Sobol' sequence, 372
- solid angles
 - defined, 284
 - differential, 291, 292, 293
 - illustrated, 285
 - intensity and, 284–285
 - measure relationship, 289
 - projected, 289–290
- solid checkerboard, 552–553
 - defined, 552
- solid textures, 544–553
 - checkerboard, 552–553
 - defined, 544
 - representation problem, 544–545
 - See also* texture(s)
- spatial domain, 325
 - convolution in, 329
 - equivalent process, 331
 - frequency space representation, 327
 - functions, 327
- spatial subdivision, 192
- spectral matching curves, 270
- spectral power distributions (SPDs)
 - arbitrary, 270, 280
 - basis function representation, 261
 - coefficient computation, 263
 - coefficient representation, 263
 - computations with, 261
 - debugging routine, 265
 - defined, 261
 - of fluorescent light, 262
 - linear interpolation, 265
 - real-world objects, 261
 - representations, 270–271
 - resampling, 268
 - RGB color, 275
 - samples, 266, 267
- spectral representation, 261–266
 - basis functions, 263
 - class, 263–266
 - design advantages, 263
 - hiding details of, 263
 - RGB color, 273–279
 - Spectrum type, 263
 - value zero, 264
 - XYZ color, 270–273
- spectral synthesis, 560–565
- spectrum
 - clamping, 265
 - equality/inequality tests, 264
 - initialization, 264
 - luminance, 272
 - sampled, 266–279
 - shah function, 329
 - square root, 265

- specular reflection, 439–441
 - BRDF, 439
 - direction, 441
 - effect computation, 45
 - implementation, 439
 - Killeroo model, 433
 - modulation, 443
 - ray differential computation for, 512
 - texture filtering, 510, 511
 - vector, 439, 440
 - See also* reflection
- specular refraction, 433
- specular transmission, 442–446
 - BTDF for, 442, 443
 - direction computation, 445–446
 - effect computation, 45
 - geometry, 445
 - modulation, 443
 - vector, 443
- spheres, 113–124
 - basic setting, 114
 - bounding, 116, 893
 - bounding box, 73
 - center, 115, 720
 - construction, 115–116
 - cosine-weighted sampling, 668–670
 - defined, 113
 - DifferentialGeometry initialization, 122–123
 - illustrated, 115
 - implementation, 115
 - implicit form, 114
 - intersection, 116–119
 - object space, 115
 - parameterization, 114–115
 - parametric definition, 120
 - parametric form, 114, 119
 - partial, 119–121
 - partial derivatives of normal vectors, 121–122
 - Poisson, 888–892
 - profile curve, 124
 - radius, 115, 720
 - ray-object intersection, 123
 - sample points, 721
 - sampling, 720–722
 - second fundamental form, 121–122
 - spinning, 90–100
 - stratified uniform distribution of rays
 - over, 689
 - surface area, 123–124
 - texture mapping, 114, 115
 - uniform sampling of, 663–665
 - See also* shapes
- spherical coordinates, 661–662
 - direction vectors and, 290
 - formula, 319
 - integrals over, 290–292
- spherical harmonics (SH), 932–956
 - basis, 932–933
 - coefficient rotation, 955
 - coefficient vector pointers, 960
 - coefficients, 933, 941, 954, 956, 976
 - defined, 932
 - efficient evaluation, 935–941
 - environmental map representation, 934
 - function definitions, 935
 - function smoothness, 933
 - incident radiance function projection, 949–950
 - light source projection, 941–949
 - local definitions, 936, 939, 940, 968
 - normalization factor, 932, 941
 - as orthonormal, 933
 - point light source projection to, 942
 - real, 932–933
 - ringing reduction, 950–951
 - rotation matrices, 951, 952, 953
 - rotational invariance, 951
 - rotations, 951–956
 - rotations via Euler decomposition, 953–956
 - sine/cosine terms for rotations, 956
 - See also* precomputed light transport
- spherical linear interpolation (SLERP), 94–96
- spherical mapping, 515–517
- splits
 - access position, 236
 - axis selection, 236
 - edge, 166
 - preferences, 234
- splitting, 681–682
 - data structures, 1014
 - defined, 681
 - integral estimator and, 682
 - node plane, 242, 243
 - primitives, 216
 - surface area heuristic (SAH), 220–221
- spotlights, 611–614
 - angles, 612, 613
 - defined, 611
 - falloff computation, 614
 - lighting distribution, 15
 - sampling, 712–713
 - scene rendering, 612
 - strength computation, 613
 - See also* light(s); point lights
- square-to-circle mapping, 686
- star discrepancy
 - bounds, 361
 - defined, 360
 - of sequence, 360–361
- start-up bias, 655–656
 - defined, 655
 - removing, 656
- state tracking, 1052–1053
- stationary distribution, 653
- statistics, 1007–1009
- steady state, light, 282
- strata
 - compact, 684
 - defined, 346, 682
 - jittering center point, 346
 - number of, 349
 - variance, 683
- stratified samples
 - generation, 353, 356
 - initialization, 354
 - shifting to pixel coordinates, 353
 - See also* samples
- stratified sampling, 346–359, 682–686
 - 1D, 352
 - 2D, 352
 - area light samples, 358
 - best-candidate sampling comparison, 382
 - curse of dimensionality, 350, 684–685
 - drawbacks, 378, 684–685
 - example effect, 684
 - function definitions, 352
 - Halton sampler comparison, 365
 - Latin hypercube sampling (LHS)
 - versus, 356
 - low-discrepancy sampler comparison, 373
 - next pixel advance, 357
 - pattern transformation to points, 686
 - sample generation, 349, 350, 351, 353
 - sample shifting to pixel coordinates, 353
 - strata, 346, 682
 - uniform, over hemisphere, 689
 - uniform random distribution versus, 684
 - utility routines, 352
 - worst-case situation, 355
 - See also* sampling
- subdivision, 160–174
 - applying fixed number of times, 160
 - on boundary edge, 165
 - illustrated, 161
 - levels of, 160
 - limit surface and output, 170–174
 - main loop, 161
 - mesh topology update, 168–170
 - object, 192

- subdivision (*continued*)
 - primitive, 208
 - refinement process, 150
 - rule for edge split, 166
 - rules, 148, 170
 - rules application, 160
 - spatial, 192
 - steps, 148
 - tetrahedron, 148
 - subdivision mesh
 - boundaries, 152
 - closed, 152
 - consistently ordered, 154
 - control, 148, 149, 150, 154
 - data structures, 151
 - extraordinary vertices, 152
 - faces, 150, 151, 154
 - in Loop subdivision scheme, 150
 - manifold, 152, 154
 - open, 152
 - representation, 151–160
 - split edges, 166
 - topology initialization, 162
 - topology update, 168–170
 - triangular face pointers, 153
 - subdivision surfaces, 148–174
 - advantages, 150
 - applied to Killeroo model, 148–149
 - bounds, 160
 - convex hull property, 160, 163
 - definition of, 148
 - illustrated, 149
 - Loop, 150
 - mesh representation, 151–160
 - methods, 150
 - smooth, 150
 - subdivision, 160–174
 - triangle meshes, 137
 - See also* surfaces
 - substrate material, 490
 - subsurface integrator, 887–888
 - subsurface light transport, 187, 294
 - subsurface material, 490, 491
 - subsurface reflectance, 885, 906, 908
 - subsurface scattering, 885–913
 - basis, 297
 - dipole diffusion approximation, 901–908
 - illustrated, 887
 - materials, 599
 - Poisson distribution of sample points, 888–896
 - properties, 885
 - properties, setting, 912–913
 - rendering with hierarchical integration, 908–911
 - sample point octree, 896–901
 - supersampling, 551
 - surface area
 - cylinders, 129
 - disks, 132
 - kd-tree node, 236
 - shape interaction, 113
 - spheres, 123–124
 - triangles, 145
 - surface area heuristic (SAH), 217–222
 - computational expense, 217
 - concept, 218
 - defined, 217
 - partitioning primitives with, 219
 - splitting at bucket boundaries, 220–221
 - splitting plane selection, 220
 - See also* bounding volume hierarchies (BVHs); kd-tree accelerator
 - surface integrators
 - class relationships, 42
 - interface, 740
 - outgoing radiance, 740
 - See also* integrators
 - surface normals. *See* normals
 - surface reflection, 293–297
 - BRDF, 294–296
 - BSSRDF, 296–297
 - modeling effects, 293
 - translucent, 294
 - surface scattering, 10–11
 - BRDF, 10
 - BSDF, 11
 - defined, 5
 - determination, 10
 - geometry, 11
 - inside primitive, 187
 - surface shader, 424, 477
 - surfaces
 - anisotropic, 425
 - area density of flux arriving/leaving, 282
 - composition, 423
 - description, 1063–1064
 - diffuse, 424, 425
 - glossy specular, 424, 425
 - implicit form, 114
 - isotropic, 424–425
 - light transport beneath, 297
 - limit, 148
 - microfacets, 447
 - Möbius strip, 154
 - parametric form, 114
 - perfect specular, 424, 425
 - properties, 424
 - quadrics, 113
 - retro-reflective, 424, 425
 - smooth, 432
 - subdivision, 148–174
 - translucent, 894
- ## T
- tangents, 136, 137, 142
 - across, 172
 - computing for boundary vertices, 172–173
 - computing for interior vertices, 172
 - shading, 147
 - transverse, 172–173
 - task queue, 36
 - task system, 36, 1040–1041
 - tasks
 - adding to work queue, 1041
 - class synchronization for, 31
 - cleanup, 1041
 - execution of, 28
 - functions, 30
 - implementation, 1041
 - number determination, 28–29
 - run time distribution, 29
 - shared data updating, 39–40
 - variables, 31
 - “teapot in a stadium” problem, 196
 - testing
 - aggregate implementation, 246–247
 - ray intersection, 183
 - voxel overlap, 200
 - tetrahedron subdivision, 148
 - texture coordinates, 513–519
 - 2D (u, v) mapping, 514–515
 - 3D mapping, 518–519
 - checkerboard textures, 546
 - cylindrical mapping, 517
 - differential change, 519
 - differentials for sphere, 517
 - discontinuity, 516
 - floating-point, 538
 - planar mapping, 518
 - selection methods, 513
 - spherical mapping, 515–517
 - texture filtering
 - elliptical weighted average, 539
 - problem, 509
 - for specular reflection, 510, 511
 - triangular filter, 536
 - texture maps
 - AO values in, 927
 - defined, 523
 - filtering, 529
 - procedural texturing and, 545
 - See also* image textures

- texture projection lights, 614–618
 - defined, 614
 - directions behind, discarding, 617
 - mip map creation, 616
 - projection matrix initialization, 616
 - scene rendering, 615
 - setting illustration, 615
 - See also* light(s); point lights
 - texture space, 542
 - texture(s), 501–573
 - aliasing, 501, 502
 - alpha mask, 136
 - antialiasing, 503–513
 - bilinear, 522–523
 - bumpy, 565–566
 - caching, 524–527
 - checkerboard, 348, 514, 546–552
 - constant, 520
 - displacement, 494, 495
 - functions, 501
 - functions, filtering, 509–510
 - as high-frequency variation source, 501
 - ideal resampling, 509
 - image, 523–544
 - implementations, 514
 - inline functions, 563
 - interface, 519–520
 - marble, 567–569
 - mix, 521–522
 - noise, 553–569
 - parameters, 1061–1062
 - in pbrt, 501
 - polka dot, 558–560
 - procedural, 544–553
 - sampling, 503–513
 - sampling rate, 503–509, 528
 - scale, 520–521
 - solid, 544–553
 - solid checkerboard, 552–553
 - UV, 545–546
 - windy waves, 566–567
 - wrinkled, 565–566
 - three-dimensional bounding boxes, 70–74
 - throughput processors, 993–996
 - Torrance-Sparrow model, 43, 452–455
 - derivation of, 452, 453
 - Fresnel term, 455
 - geometric attenuation, 453, 455
 - half-angle vector, 452
 - implementation, 454
 - Killeroo model, 456
 - reflected outgoing radiance, 453
 - terms evaluation, 455
 - for two outgoing directions, 468
 - See also* microfacet models
 - total internal reflection, 439
 - transfer function, 971, 977
 - transfer matrix, 975–977
 - BSDF, 978
 - SH radiance, 981
 - transformations, 74–85
 - affine, 97
 - animating, 90–100
 - applying, 85–89
 - array, 1054
 - benefits, 74
 - of bounding boxes, 88
 - composite matrices, 96–97
 - composition of, 88–89, 97
 - continuous, 74
 - coordinate system handedness and, 89
 - decomposition, 97
 - defined, 74
 - between distributions, 660–662
 - of the frame, 74
 - functions, 1054
 - homogeneous coordinates, 75–76
 - identity, 76
 - invertible, 74
 - keyframe, 90
 - linear, 74
 - look-at, 84–85
 - matrix, 77, 88
 - multidimensional, 662–674
 - multiple dimensions, 661
 - multiplying, 89
 - of normals, 86–88
 - from one frame to another, 74
 - one-to-one, 74
 - operations, 76–77
 - pointers, 1066
 - of points, 85–86
 - polar, 661
 - primitive, 190–191
 - of rays, 88
 - rotation, 80–83
 - scaling, 79–80
 - scene description, 1053–1056
 - translations, 77–79
 - of vectors, 86
 - world-to-object, 123
 - translations, 77–79
 - defined, 77
 - extracting, 97
 - interpolation, 91
 - matrix equation, 79
 - in matrix form, 78
 - points and, 78
 - properties, 78
 - in 2D, 78
 - translucent material, 483, 490, 894
 - transmission. *See* specular transmission
 - transmittance, 13
 - beam, 580–581
 - Fresnel, 909
 - transverse tangents, 172–173
 - traversal
 - bounding volume hierarchies (BVHs), 224–227
 - grid accelerator, 202–208
 - kd-tree accelerator, 240–245
 - triangle filter
 - defined, 396
 - graph, 395
 - See also* filters; reconstruction
 - triangle meshes
 - bound computation, 138
 - coordinate assignment, 137
 - defined, 135
 - illustrated, 136
 - object space bound, 138
 - shape transformation, 137
 - smooth-looking, 171
 - subdivision surfaces, 137
 - tangent vectors, 142
 - vertices, 152
 - triangles, 135–148
 - dual role, 136–137
 - intersection, 140–145
 - only, as design alternative, 991–992
 - parametric coordinates, 142
 - partial derivatives, 142, 143
 - sampling, 670–671, 719
 - as set of points, 142
 - shading geometry, 145–148
 - storage reduction, 139
 - surface area, 145
 - vertices, 139–140
 - world space bounding boxes, 109, 139
 - See also* shapes
 - triple product integral, 984
 - tristimulus theory, 270, 271
 - turbulence, 563–565
 - defined, 563
 - graphs of, 564
 - implementation, 563
 - noise octave computation, 565
 - See also* noise
- ## U
- uber material, 490
 - unified resampling filters, 539
 - uniform scaling, 79
 - unit vectors, 61, 62

utilities, 999–1043
 communication with user, 1004–1006
 functions, 1000–1003
 image file input/output, 1003–1004
 kd-trees, 1027–1033
 main include file, 999–1000
 mathematical routines, 1020–1021
 memory management, 1009–1020
 octrees, 1022–1027
 parallelism, 1033–1041
 probes and statistics, 1006–1009
 pseudo-random number generator, 1002–1003
 UV texture, 545–546
 application illustration, 546
 defined, 545

V

valence, 152
 value noise, 554
 van der Corput sequences, 362, 368, 372
 variable stack allocation, 1009
 variance reduction
 bias, 686–687
 importance sampling, 688–693
 multiple importance sampling, 690–693
 Russian roulette, 680–681
 sample placement, 682–686
 sampling reflection functions, 693–708
 splitting, 681–682
 variance
 of functions, 640, 641
 Monte Carlo ray tracing, 679
 random sampling and, 684
 strata, 683
 sum of, 641
 varying-density volumes, 591–596
 3D grids, 592–594
 exponential density, 594–596
 protected data, 592
 vectors, 57–63
 addition, 58
 arithmetic, 58–59
 basis, 55–56, 83
 coordinate system from, 63
 cross product, 61–62
 difference, 468
 direction, 57, 290
 division, 59
 dot product, 60–61, 556
 gradient, 556
 half-angle, 452, 697, 700
 homogeneous, 75

memory area, 1015
 multiplication, 59
 normal, 65–66, 86–88
 normalization, 62–63
 obtaining, 64
 rotation around arbitrary axis, 82
 sample, 836
 scaling, 59–60
 specular reflection, 439, 440
 specular transmission, 443
 subtraction, 58–59
 tangent, 136, 137, 142, 147
 transforming, 86
 unary negation operator, 60
 unit, 61, 62
 “up,” 85
 vertices
 boundary, 156, 162
 boundary, determining, 157
 boundary, valance computation, 158–159
 child faces, 170
 edge computation, 166
 edges rule application, 167–168
 even, 162
 extraordinary, 152, 157, 162
 indices of, 156, 170
 initialization, 157, 158, 162, 167
 interior, 162
 limit surface position, 171
 local support, 163
 neighboring faces, 154
 new position computation, 162–168
 next face, 157, 158
 nonboundary, valance computation, 158
 numbering scheme, 168
 odd, 162, 168
 one-ring rule, 162, 172
 parent, 169
 previous face, 157
 regular, 152, 162
 sorting, 155
 split edges computation, 161
 tangents computation, 171
 updating values, 170
 valance, 152, 157, 158
 weights, 163, 171
 viewing volume, 5
 virtual light sources
 creating, 775–780
 indirect illumination with, 780
 path termination, 780
 at ray intersection point, 779
 rendering with, 780–784
 sample ray leaving, 778

shadow ray, 782
 tentative contribution computation, 782
 weak singularity effect, 781
 visibility, 9–10
 defined, 5
 indirect, between two points, 961
 indirect, efficiently computing, 962
 visibility testing, 608–609
 defined, 608
 volume aggregates, 596–598
 defined, 596
 implementations, 597
 reasons for, 596
 volume integrators, 876–885
 emission-only, 876–882
 interface, 876
 multiple scattering, 886
 single scattering, 882–885
 stepping, 880–881
 uniform sampling, 730
 volume rendering, 873–922
 emission-only integrator, 876–882
 equation of transfer, 873–875
 single scattering integrator, 882–885
 subsurface scattering, 885–913
 volume integrator interface, 876
 volume scattering, 575–602, 730–733
 absorption, 575, 576–578
 BSSRDF, 598–600
 definitions, 585, 597, 598, 733, 913
 emission, 575, 578–579
 homogeneous properties, 576
 homogeneous volumes, 589–591
 illustrated, 576
 in-scattering, 581–583
 inhomogeneous properties, 576
 interface, 587–588
 local definitions, 912
 optical thickness computation, 731–733
 out-scattering, 579–581
 participating media, 575
 phase functions, 583–587, 731
 processes, 575–583
 properties, setting, 912–913
 sampling, 730–733
 varying-density volumes, 591–596
 volume aggregates, 596–598
 volumes
 homogeneous, 589–591
 light transport equation, 13
 regions, 730, 1072
 varying-density, 591–596
 volumetric lighting. *See* radiance probes
 volumetric primitives, 23

- voxel grids
 - resolution, 198
 - size, 198
 - stepping axis, 207
 - stepping ray through, 203, 205
- voxels
 - adding primitives to, 199
 - address computation, 204
 - allocating, 199
 - defined, 195
 - function of, 195
 - intersection checking in, 205
 - looping over primitives in, 206, 207
 - number of, 197, 198, 199
 - number of primitives in, 206
 - overlap testing, 200
 - primitive storage location
 - determination, 201
 - primitives in, 202
 - stepping direction, 205
 - stepping logic, 204
 - See also* grid accelerator

W

- warping samples, 685–686
- weak singularity, 781
- Web site, this book, 49
- Weingarten equations, 121, 128
- Whitted integrator, 41–47
 - functions, 41
 - geometric setting, 44
 - radiance evaluation, 42
 - scattered light and, 45
- windowed sinc filter, 400–402
- windy waves, 566–569
 - defined, 566–567
 - evaluation function, 567
 - See also* noise
- world end, 1070–1072
- world space, 56
 - AABB, 587
 - bounding boxes, 109, 139
 - defined, 303
 - primitive transformation to, 191

- rays, 117
- widths, 199

- wrinkled textures, 565–566

X

- XYZ color, 270–273
 - conversion, 279
 - converting RGB to, 275
 - image film, 406
 - integrals, 280
 - matching curves, 271
 - SPD representation, 270, 271
 - value computation, 271
 - values, 271
 - y coordinate, 272
 - See also* spectral representation