
Index

- 3DS Max*, 393, 414, 691
 - conventions, 28
- AABB, 304–311
 - closest point, 720
 - computing, 306
 - intersection with plane, 725
 - intersection with sphere, 731
 - representing, 305
 - transforming, 308–311
 - vs. bounding sphere, 307
- absolute measurements, 41
- absolute position, 39
- acceleration, 513–530
 - angular, *see* angular acceleration
 - constant, 516–530
 - derivative, 516
 - due to gravity, 564
 - is due to force, 555
 - of curve, 651
- active transformation, **94**, 137
- Adams, Douglass, xiii
- addition
 - of vectors, *see* vector, addition
- additive identity, 38
- additive inverse, 43
- addressing mode (texture mapping), 395
- adjacent triangle leg, 23
- adjoint, *see* classical adjoint
- Adobe Photoshop*, *see Photoshop*
- advertising, 88, 363
- aerospace
 - conventions, 28
 - terminology, 234
- affine transformation, 91, 137, **156**, 181
- airplane security, 75
- Airplane!*, 77
- Aitken's algorithm, **656–659**, 670, 711
- Aitken, Alexander, 656
- Aldrin, Buzz, 745
- algorithm as definition, 335
- aliasing
 - of Euler angles, 237
 - of exponential map, 245
 - of polar coordinates, 194–198
 - of quaternion, 249
 - of spherical coordinates, 207–210
- alpha blending, 441, 456
- alpha test, 441, 456
- altitude, 205
- altitude of triangle, 318
- Alvarado, Texas, 201
- ambient light, 398, **406**
- amplitude, 574
- analysis, 494
- anamorphic stretching, 364, 367
- angle
 - in standard position, 22
 - measuring in 2D, 21
 - measuring in 3D with dot product, 65
 - units, 21
- angle-preserving transformation, 157
- angular acceleration, **604**, 609, 613
- angular displacement, 218
- angular frequency, 544, 574
 - undamped, 577
- angular impulse, 610
- angular momentum, 608, 610, **613–615**
 - in 3D, 615
 - spin vs. orbital, 615
- angular velocity, 241, 604
 - and exponential map, 245, 548
 - integration of, 636
 - spin, *see* spin angular velocity
 - spin vs. orbital, 604, 615
 - vs. linear velocity, 548
- Animal Farm*, 81
- anisotropic reflection, 410
- anticommutative
 - cross product, 67
- antiderivative, 535
- apex, 523, 527
- Arcesilaus, 70

- Archimedes, 81
- area
 - and integral, **518**, 530, 534
 - measuring with cross product, 67
 - of circle, 304
 - of parallelogram, 67, 318
 - of triangle, 318
- Aristarchus, 80
- Aristotelian dynamics, 555
- Aristotle, 80
- array
 - compared to vector, 32
- array of structures (AOS), 449
- articulated model, 107
- aspect ratio
 - of display device, 363
 - of pixel, *see* pixel, aspect ratio
 - of render window, 367
- associative
 - cross product isn't, 67
 - dot product is, 59
 - matrix multiplication is, 120
 - quaternion multiplication is, 252
 - vector laws, 70
- astronomical unit, 483
- atan2, **200**, 212, 279
- atlas, 423
- attenuation, light, *see* light attenuation
- attitude, 220, 232
- authors, xvii
 - ignorance, 247
 - fallibility, xx
 - ignorance, 483, 621, 639
 - laziness, 491, 659, 695, 696
 - stunt, 479
- Autodesk 3DS Max*, *see* *3DS Max*
- average velocity, 486–490
- axis
 - of coordinate space, 7
 - of rotation, 16, 139, 546, 589, 604
 - z, 13
- axis-angle (orientation), 244–246, *see also* exponential map
- azimuth, 205, 232

- Babylonians, 21
- back buffer, 445
- backface culling, 440, 453–455
- ball-and-socket joint, 626
- bank, 218, 229
- barycentric coordinates
 - Bernstein basis, 675, 679
 - calculating, 324–329
 - conversion to Cartesian, 323
 - degrees of freedom, 321, 322
 - Hermite basis, 668
 - intro using triangles, 321
 - normalization constraint, 321
 - polynomial interpolation, 664
 - ray-triangle intersection, 737
 - use in interpolation, 324
- base of triangle, 318
- basis polynomial, 660
 - Hermite, *see* Hermite basis
 - Lagrange, *see* Lagrange polynomials
 - vs. basis vector, 662
- basis vectors
 - define coordinate frame, 97–106
 - for bump mapping, 100, **432–438**
 - orthogonal, 105
 - orthonormal, 105
 - rank of, 102
 - span of, 101
 - transformation of, 125
 - vs. basis polynomials, 662
- bear
 - developer-eating, 215
- Bernstein basis, 675, 677–682
- best fit plane, 314
- Bézier curve, 670–685
 - and Hermite form, 683
 - degree elevation, 690
 - subdivision, 688–690
- Bézier spline, 694–697
- Bézier, Pierre, 670
- bias (TCB spline), 710
- billboard, 390
- binding pose, 428
- binomial coefficients, 678
- binormal vector, 100, 433
- bitmap, 345
- Blinn specular model, 402–404
- Blinn-Phong, 352, **396–411**
 - equation, 407
 - Gouraud shading, 412
 - HLSL example, 459
 - limitations, 409–411
 - multiple lights, 408
- blossoming, 690
- body space, *see* object space
- bogey, 201
- bone, *see* skeletal animation
- bone space, 429
- bounding box, 303–311
 - axially aligned, *see* AABB
 - oriented, *see* OBB

- bounding sphere, 303
 - calculating, 307
 - vs. AABB, 307
- BRDF, 350–353, 396
 - accounting for color, 351
 - accounting for shininess, 351
 - Blinn-Phong, *see* Blinn-Phong
 - diffuse reflector, 406
 - in the rendering equation, 360
 - normalization constraint, 352
- Broom Bridge, 267
- buffer (rendering), 444
- bugs, xx
- Bullet Physics, 621, 639
- bump mapping, 431–438, *see also* normal mapping
 - computing basis vectors, 435–438
 - HLSL example, 469
 - mirrored texture maps, 437
 - tangent space, 432–435
 - vertex format, 448
- Burleson, Texas, 201
- C^n continuity, *see* parametric continuity calculus
 - derivative, *see* derivative
 - integral, *see* integral
 - prior knowledge of, xviii
 - what's left out, 480
- Calvin and Hobbes*, xxi
- Cambridge, MA, 83
- camera space, **83–84**, 370, 451
- canonical coordinates
 - Euler angles, 238
 - polar, 196
 - spherical, 208
- canonical view volume, 371
- Captain Oveur, 77
- Car Talk*, 83
- Cardinal spline, 711
- Cartesia, city of, 6, 80, 82
- Cartesian coordinates
 - 2D, 5–11
 - 3D, 12–19
- Catmull, Edwin, 704
- Catmull-Rom spline, 703–705
- Cayley-Klein parameters, 236
- Celsius, 41
- center of gravity, 586, *see also* center of mass
 - of triangle, 330
- center of mass, **586–589**
 - calculating, 587
 - measuring experimentally, 586
 - of dynamics body, 623
- center of mass coordinates, 86, 636
- center of projection, 183
- centigrade, 41
- centrifugal force, 546
 - Earth's rotation, 564
- centripetal acceleration, **544**, 551
 - gravity, 564
- centroid, of triangle, 330
- Cg (shading language), 457
- chain rule (differentiation), 511–513
- Chebyshev norm, 74
- Chicago, IL, 81
- circle, 303–304
 - closest point, 719
 - inscribed in triangle, 330
 - through three points, 332
 - unit circle, *see* unit circle
- circular motion, 542–549
 - 2D, 542–546
 - 3D, 546–549
- circumcenter of triangle, 331
- circumference, 304
- circumradius of triangle, 332
- Citroen, 671
- clamp addressing mode, **395**, 421
- classical adjoint, 169
- classical dynamics, *see* Newtonian dynamics
- clip matrix, 189, **371–378**
 - projection, 371–378
 - zoom, 375–378
- clip plane
 - view frustum, 364
- clip space, 93, **371–378**, 440, 451
- clipping, 440, 451–453
- closed intervals, *see* interval notation
- closest point
 - on AABB, 720
 - on circle, 719
 - on line, 717
 - on plane, 719
 - on ray, 718
- closest point tests, 717–720
- coefficient of friction, 567
- coefficient of restitution, **597**, 618
- cofactor, 164
- collision, 590–601
 - elastic, *see* elastic collision
 - elastic vs. inelastic, 591
 - inelastic, *see* inelastic collision
- collision detection, 563, 594, 627
- collision geometry, 623, 625

- collision law, *see* Newton's collision law
- collision response, 563, 593–601, 618–621
- color, 353–354
- color blindness, 353
- Columbus, Christopher, 82, 216
- commutative
 - cross product isn't, 67
 - matrix multiplication isn't, 120
 - quaternion multiplication isn't, 252
 - vector laws, 70
- complex exponentials, 551
- complex number
 - basic laws, 265
 - in exponent, 551
 - quaternion, 264
- complex polygon, 333
- compound interest, 511
- concatenation
 - of exponential map rotations, 246
 - of quaternion rotations, 253
 - of rotation matrices, 226
 - of transformations, 153
- concave polygon, 334
- condition number, 169
- conic section, 295
- conical joint, 626
- conical spot light, 415
- conjugate
 - of complex number, 266
 - of quaternion, 250
- conservation of momentum, **584–585**
 - angular, 614
 - in collision, 591, 596
- constant color, 458
- constant curve, 650
- constant rule (differentiation), 504
- constraint (physics), 625–627
- constraint force mixing (CFM), 627
- constructive solid geometry (CSG), 381
- contact constraint, 626, 627
- contact force, 563, 607, *see also* normal force
- continuity (spline), 697–702
 - geometric, *see* geometric continuity
 - parametric, *see* parametric continuity
- continuity (TCB spline), 707
- continuous vs. discrete, 3, 481
- contravariant vector, 391
- control point (curve)
 - vs. knot, 654, 670
- control system
 - first-order, 580
 - second-order, 578
- convex hull, 664, 680
- convex polygon, 334
- cookie, 416
- coordinate space
 - axes, 7
 - bone, *see* bone space
 - camera, *see* camera space
 - clip, *see* clip space
 - commonly used, 81–86
 - defined by basis vectors, 97–106
 - establishing, 7
 - handedness, *see* handedness
 - hierarchy, 106–108
 - left- vs. right-handed, *see* handedness
 - object, *see* object space
 - origin, 7
 - screen, *see* screen space
 - specifying, 96–97
 - tangent, *see* tangent space
 - transformation, *see* transformation
 - upright, *see* upright space
 - used in graphics, 369–381
 - why multiple, 80–81
 - world, *see* world space
- coordinates
 - Cartesian, *see* Cartesian coordinates
 - polar, *see* polar coordinates
- Copernicus, Nicolaus, 80, 191
- coscant, 23
- cosine
 - definition using unit circle, 22
 - derivative, 510
 - related to dot product, 64
 - Taylor series, 508
- cotangent (trigonometric function), 23
- Coulomb friction, *see* friction
- Coulomb's law of friction, 570
- Coulomb, Charles-Augustin, 567
- counting numbers, *see* numbers, natural
- couple, 610
- covariant vector, 391
- critical damping, 578
- cross product, 66–70
 - angular velocity, 547
 - area of triangle, 321
 - formula, 66
 - hand rule, 69
 - magnitude related to area, 67
 - quaternion, 251
- CRT, 346
- crunch time, 215
- cubic mapping, 393
- cubic polynomial curve, 648

- cuculoris, 416
- culling, *see* backface culling
- curvature, 653
- curve fitting, *see* polynomial interpolation
- cylindrical coordinates, 203–204
- cylindrical mapping, 393

- Dallas, Texas, 201
- damped oscillation, 576
 - critically damped, 578
 - overdamped, 578
 - underdamped, 577
- damping, 566, **576**
- damping ratio, 577
- da Vinci, Leonardo, 10
- de Casteljau algorithm, 671–676
 - subdivision, 688–690
- de Casteljau, Paul, 671
- de La Rochefoucauld, Francois, xiii
- decal shading, 457
- decibels, 42
- declination, 207
- deferred rendering, 348
- definite integral, 530
 - and antiderivative, 536
 - vs. indefinite integral, 539
- degree elevation, 690
- degree of polynomial, 647
- degrees, 194
 - converting to radians, 22
- Denton, TX, 81
- depth buffer, **347**, 441, 445
 - values in, 365, 377, 379
- depth test, 441, 456
- derivative, 490, 494
 - and integral, 535
 - definition, 498
 - examples, 496–497
 - graph of, 500
 - laws, 504–508
 - notation, 503–504
 - of acceleration, 516
 - of altitude, 496
 - of Bézier curve, 682–685
 - of composite function, 512
 - of constant, 504
 - of exponential function, 511
 - of Hermite curve, 665
 - of monomial curve, 651
 - of polynomial, 506–507
 - of position, 495
 - of rotating frame, 637
 - of sine and cosine, 510
 - of sum, 505
 - of velocity, 513
- derived quantities, 484
- Descartes, René, 1, 207, 490
- destination fragment, 348
- detaching faces, 390
- determinant, 161–168, 268
 - 2×2 , 162
 - 3×3 , 163
 - 4×4 , 165
 - arbitrary size, 164
 - geometric interpretation, 167
 - identities, 165
- diagonal matrix, 115
- diameter, 304
- differential equation, 572
 - second-order, 577
- diffuse color, 405, 439
- diffuse map, 412, 439
- diffuse reflection, 398, **404–407**, *see also*
 - Lambert's law
 - BRDF, 406
- dimensional analysis, 486, 581
- diminishing returns, 497
- Dirac delta, 358, 416, **601–602**
- Dire Straits, 425
- direction cosines matrix, 224–225
- direction vs. orientation, 218
- directional light, 416
- DirectX, 124, 343, 396, 409, 414, 475
 - clip matrix, 375
 - screen space conventions, 378
 - UV conventions, 393
- discrete vs. continuous, 3, 481
- displacement
 - in particular direction, 62
 - is a vector quantity, 35
 - vs. distance, 35, 488
- displacement
 - between points, 50
- display device
 - aspect ratio, 363
 - resolutions, 363
 - RGB color space, 354
 - widescreen, 363
- distance
 - between point and plane, 316
 - between two points, 55
 - is a scalar quantity, 35
 - signed, *see* signed distance
 - vs. displacement, 35
- divide and conquer, 656, 660
- Doctor Who, xv
- Doom 3* engine, 418

- Doom*-style light, *see* volumetric light
- dot notation, 504
- dot product, **56–66**, 104
 - and magnitude formula, 62
 - as projection, 58
 - formula, 57
 - matrix notation, 57
 - polygon convexity test, 335
 - quaternion, 255
 - related to cosine, 64
 - sign of, 65
- double**, 4
- double angle identities (trig), 26
- double buffering, 445
- driving force, 575, 579
- dry friction, *see* friction
- dual vector, 392
- Dunn, Riley, xiii
- dynamic intersection test, 721
- dynamics, 479–551
 - vs. kinematics, 483
- dynamics body, 622–625
- Dyslexia, city of, 80

- Eagles, 531
- earmuffs, 589
- edge of triangle mesh, 382
- edge vector (triangle), 317
- eggrolls, 481
- Einstein, Albert, 190
- elastic collision, 591
- elastic limit, 571
- elevation, 232
- Elmo's World*, 96
- Emerson, Ralph Waldo, 643
- emissive surface, 350, 398, 407
- energy, 480, 532
 - radiant, *see* radiant energy
- engineer vs. mathematician, 502
- errata, xx
- error (control system), 579
- error reduction parameter (ERP), 627
- Euclidian norm, 74
- Euler angles, 206, **229–243**
 - advantages, 236–237
 - aliasing, 237
 - and spherical coordinates, 232
 - canonical set, **238**, 278
 - conventions, 232–236
 - converting to matrix, 275–278
 - converting to quaternion, 287–288
 - definition, 229
 - disadvantages, 237–242
 - from matrix, 278–281
 - from quaternion, 288–291
 - interpolating, 239–242
 - joint, 626
 - proper, 235
 - symmetric, 235
 - vs. fixed-axis, 233
- Euler axis, 246
- Euler integration, 557, 579, **632–639**
- Euler's formula, 551, 784
- Euler's identity, 784
- Euler's rotation theorem, 244, 245, 255
- Euler, Leonard, 229, 244
- exponential function
 - derivative, 511
 - quaternion, 256
 - Taylor series, 510
- exponential map, **244–246**, 548
 - aliasing, 245
 - and angular velocity, 245
 - and quaternion logarithm, 256
 - vector addition, 246
- exponentiation of quaternion, 257
- exterior angle at polygon vertex, 335
- extrinsic rotations, 233
- eye space, *see* camera space

- fable, 486
- face of triangle mesh, 382
- factorial (!), 509, 679
- Fahrenheit, Gabriel, 41
- fake spot light, 421
- falloff angle (spot light), 415
- falloff distance, *see* light attenuation,
 - linear
- falloff map, 419
- falloff radius, *see* light attenuation, linear
- fanning of polygon, 338
- far clip plane, 364
- Feldman, Michael, 30
- Fermat, Pierre, 490
- Ferris Bueller's Day Off*, 537
- The Feynman Lectures on Physics*, 551
- Feynman, Richard, 551
- field of view, **365–368**, 374, *see also* zoom
 - orthographic projection, 368
- fighter pilot, 201
- filter, 581
- first law of computer graphics, 5
- first law of video game physics, 565
- first-order control system (lag), 580
- fixed-axis rotations, **233**, 276, 287
- fixed-function pipeline, 414, 416, 422, 450
- “fixin’”, 201
- flat shading, 411

- float, 4
- floating point numbers, 4
- flux density, 355
- focal distance, *see* focal length
- focal length, 372
- footnotes, xvii, 486
- force, 554, *see also* Newton's laws
 - acts on two bodies, 560
 - acts over time, 556
 - and torque, 610
 - causes acceleration, 555
 - derivative of momentum, 583
 - friction, *see* friction
 - gravity, *see* gravity
 - impulsive, *see* impulse
 - spring, *see* spring
 - units, 556
- fortnight, 483
- forward rendering, 348, 456
- Foucault's pendulum, 560
- fractions, 196
- frame buffer, 345, 441, 444
- Fred Brooks, 621, 627
- free fall, 516, 527
- free-body diagram, 557
- frequency, 484
 - of harmonic oscillator, 574, 575
 - of light, 353
- Fresnel reflectance, 410
- friction, 567–571
 - common sense, 555
 - damping, 576
 - kinetic, 567, 570
 - static, 567
- front buffer, 445
- frustum, *see* view frustum
- fun vs. realism, 566
- function, 494
- functional form (curve), 647
- fundamental theorem of calculus, 536–540
- furlong, 491

- G (gravitational constant), 564
- G-buffer, 348
- Galapagos Islands, 589
- Galen, 41
- Galileo, 43
- game loop, 628
- Gauss, Karl Friedrich, 29
- Gaussian elimination, 170, 660
- geocentric universe, 80
- geometric continuity, 700–701
- geometric optics, 346
- Gimbal lock, 206, 208, **238**, 241, 247, 280

- global illumination, 361
- global parameter (curve), 692
- global space, *see* world space
- global support, 680, 691
- gloss map, 401
- glossiness, *see* specular exponent
- GLSL, 457
- gobo, 381, 401, **416**, 419
- goniophotometer, 353
- Gouraud shading, 387, **411–413**, 451
 - Blinn-Phong, 412
 - HLSL example, 466
- Gram-Schmidt orthogonalization, 175, *see* orthogonalizing a matrix
- graphics pipeline, *see* real-time rendering pipeline
- gravitational constant, 564
- gravity, 484, 516, 527, 546, 563–567
 - fiddling with, 565
 - on Earth, 564
 - universal, 563
 - video game, 564
- Greenwich, England, 82
- grid lines, 11, 193, 215
- guard band, 452

- h** vector (lighting), *see* halfway vector
- half Lambert, 408
- half-open intervals, *see* interval notation
- halfway vector, 403, 450
- Hamilton product, 252
- Hamilton, William, 267
- Hamlet*, 828
- handedness, 15–18
 - axis of rotation, 139, 547, 604
 - cross product, 69
 - polar coordinates, 204, 229
- happiness vs. salary, 497
- hare, *see* tortoise and hare
- harmonic oscillator, 573, *see also* spring
 - damped, *see* damped oscillation
 - frequency, 574, 575
 - kinematics equations, 575
- Havok, 621
- head of vector, 35
- heading, **207**, 229
 - vs. yaw, 234
- heading-pitch-bank, 229
- Hedberg, Mitch, 294
- height map, 431
- height of triangle, 318
- Heisenberg, 482
- heliocentric universe, 80
- Helmholtz reciprocity, 352

- Hermite basis, 668
- Hermite curve, 665–670
 - and Bézier curve, 683
- Hermite spline, 694–697
- Hermite, Charles, 665
- Heron's formula, 318
- herring sandwich, xiii, 86, 425, 558
 - microwavable, 88
 - projectile, 711
- Hertz (Hz), 485
- hierarchy of coordinate spaces, 106–108
- hinge joint, 626
- Hitchhiker's Guide to the Galaxy*, xiii
- hither clip plane, *see* near clip plane
- HLSL, 343
 - examples, 457–474
 - vs. Cg and GLSL, 457
- hole (polygon), 333
- Holmes, Oliver Wendell, 136, 161
- home pose, 428
- homogenous coordinates, 176–183
 - used by clip matrix, 371
- Hooke's law, 571
- Horatio, 828
- hotspot (specular), 400
- hotspot falloff (spot light), 418
- human vs. mathematician, 21
- Hutchins, Robert Maynard, 343
- hypersphere, 260
- hypotenuse, 23

- id Tech 4*, 418
- id Tech 5*, 432
- ideal gas law, 496
- identities
 - trigonometry, *see* trigonometry, identities
 - vector algebra, 70
- identity matrix, 116
- identity quaternion, 249
- ignorance, of authors, *see* authors, ignorance
- ill conditioned matrix, 169
- ill-formed matrix, 227, 278
- imaginary number, *see* complex number
- implicit form, 295
 - 2D line, 300
 - circle and sphere, 303
 - curve, 647
 - plane, *see* plane equation
- impulse, 502, 590
 - angular, *see* angular impulse
 - in collision response, 595
- impulsive force, *see* impulse
- impulsive torque, *see* angular impulse
- incenter of triangle, 330
- indefinite integral
 - as antiderivative, 539
 - vs. definite integral, 539
- indexed triangle mesh, 382–386, *see also* triangle mesh
- inelastic collision, 591–593
- inertia, 484, 554
- inertia tensor, **616–618**, *see also* moment of inertia
 - of dynamics body, 622
- inertial reference frame, 558
- inertial space, 86
- infinitesimal, 498
- infinitesimal rotation, 246
- infinity norm, 74
- inner product, *see* dot product
- instantaneous velocity, 490–503
 - approximating, 491
 - definition, 494
 - tangent line, 492
- int**, 4
- integers, 3
- integral, 530–540
 - and area, **518**, 530, 534
 - antiderivative, 535
 - definite, *see* definite integral
 - definite vs. indefinite, 539
 - definition, 531
 - examples, 532
 - indefinite, *see* indefinite integral
- integral equation, 361
- integrand, 531
- integration
 - Euler, *see* Euler integration
 - numerical, *see* numerical integration
 - of rotation, 636
 - physics simulation, 632
- integration by parts, 535
- intensity of light, *see* radiometry
- interior angle
 - at polygon vertex, 335
 - at triangle vertex, 317
- International Space Station, 551, 640
- Internet, assumed availability of, 486, 551, 617
- interpolation
 - of Euler angles, 239–242
 - of exponential map, 245
 - of lighting values, 411
 - of quaternions, *see* slerp
 - of texture mapping coordinates, 394

- of vertex normals, *see* per-pixel shading
 - polynomial, *see* polynomial interpolation
 - rasterization, 456
 - using barycentric coordinates, 324
- intersection
 - of AABB and plane, 725
 - of AABB and sphere, 731
 - of plane and sphere, 732
 - of ray and plane, 724
 - of ray and sphere, 727
 - of ray and triangle, 734
 - of three planes, 726
 - of two 2D lines, 721
 - of two 3D rays, 722
 - of two spheres, 729
- intersection test, 717, 720–743
 - static vs. dynamic, 721
- interval notation, 20–21
- intrinsic rotations, 233
- inverse of matrix, 168–171, 226
 - definition and identities, 169–171
 - geometric interpretation, 171
- inverse of quaternion, 251
- inverse transpose of matrix, 392
- invertible matrix, 168
- invertible transformation, 156
- irradiance, 355
- isotropic reflection, 410

- Jacobian matrix, 631
- Jell-O, 194
- jerk, 516
- job interview
 - AABB intersection, 737
 - BRDF vectors, 399
 - projectile motion, 521
 - vector reflection, 400
- joint (physics), 622, 625–627
- jokes
 - in footnotes, xvii
 - take up space, 486
 - that aren't funny, xv
- joule (J), 354, 532
 - vs. Newton meter, 609
- jumping (game mechanic), 565

- Kelvin, 42
- key (spline), 693
- kinematically controlled object, 598, 623
- kinematics, 486–491, 513–530
 - circular motion, 542–549
 - of harmonic oscillator, 572–578
 - projectile motion, 516–530
 - rotational, 603–606
 - vs. dynamics, 483
- kinetic friction, *see* friction, kinetic
- knot, 693–694
 - vs. control point, 654, 670
- knot vector, **654**, 660, 662
- Knuth, Donald, 84
- Kochanek-Bartels spline, *see* TCB spline

- l vector (lighting), 399, 450
- La Grange* (song), 661
- La Grange, TX, 661
- lag (control system), 580
- Lagrange basis, 659–664, 670
- Lagrange's notation, 503
- Lagrange, Joseph Louis, 661
- Lagrangian dynamics, 480, 639
- Lambert factor, 386, 406
 - in rendering equation, 361
- Lambert's law, 356, 405
- Lao Tzu, 217
- latitude, 81, 205
- launch angle, 528
- launch speed, 528
- Laura Croft, 425
- law of cosines, 27, 318
- law of sines, 26, 318
- law of universal gravitation, 563
- LCD monitor, 346
- left hand rule, 15, *see also* handedness
- Leibniz notation, 498, 512
- Leibniz, Gottfried, 490, 531
- Lemony Snicket, 715
- length
 - fundamental quantity, 483
- lerp (linear interpolation), 239, 259
- level of detail, 440
- lever arm, 571, **608**, 615
- Lewin, Walter, 573, 639
- libido, 487
- Lie algebra, 244, 246
- lies
 - commision, 481
 - during introductions, 502
 - omission, 479
- light attenuation, 417–418
 - in rendering equation, 417
 - linear, 414, 418
 - realistic inverse-squared, 417
 - via falloff map, 422
- light diffuse color, 405
- light intensity, *see* radiometry
- light probes, 424

- light source, 414–424
 - attenuation, *see* light attenuation
 - Dirac delta, 358, 416
 - directional, *see* directional light
 - Doom*-style, *see* volumetric light
 - omni, *see* point light
 - point, *see* point light
 - spot, *see* spot light
 - volumetric, *see* volumetric light
- light specular color, 401
- lighting model, 396, *see also* BRDF
- lightmap, 423
- limit, 493
- limiting value, 493
- limits of integration, 531, 539
- line, 297–303, *see also* ray
 - closest point, 717
 - infinite 2D, 300–302
 - intersection in 2D, 721
- line segment, 297
- linear algebra, 104, 130
 - vs.* this book, 34, 659
- linear complimentary problem (LCP), 632
- linear curve, 650
- linear independence, 102
- linear interpolation, 653
 - in Aitken’s algorithm, 657
 - in the de Casteljau algorithm, 672
- linear operator, *see also* linear transformation
 - derivative is, 505–506
- linear transformation, 124, 137
 - definition, 155
 - doesn’t translate the origin, 156, 178
- linear velocity, *see* velocity
 - vs.* angular velocity, 548
- Linnaeus, Carolus, 41
- local parameter (curve), 692
- local space, *see* object space
- local support, 680, 691
- logarithm of quaternion, 256
- longitude, 81, 205
- Lord of the Rings*, 566
- loudness, 42
- LU decomposition, 660

- Maclaurin series, 509
- Madonna, 410
- Magliozzi, Tom and Ray, 83
- magnitude
 - of cross product, 67
 - of quaternion, 250
- Major-General Stanley, 716
- manifold, 247

- marching cubes algorithm, 296
- marginal utility, 497
- Mars Climate Orbiter, 194
- mass, 484
 - in Newton’s laws, 554
 - of dynamics body, 622
- mass element, 587, 613, 617
- material, 396, 439
 - ambient color, 406
 - diffuse color, *see* diffuse color
 - emissive color, 407
 - specular color, *see* specular color
- mathematician
 - vs.* engineer, 502
 - vs.* human, 21
- MathWorld, Wolfram, xvii
- Matisse, Henri, 713
- matrix
 - clip, *see* clip matrix
 - determinant, *see* determinant
 - diagonal, 115
 - inverse transpose, 392
 - multiplication, *see* matrix multiplication
 - multiplication by scalar, 117
 - notation, 114
 - projection, *see* clip matrix
 - rank, *see* basis vectors
 - span, *see* basis vectors
 - transpose, 116
 - The Matrix* (movie), 113
- matrix chain problem, 121
- matrix creep, 175, 227
- matrix form (orientation), 220–229
 - advantages, 225
 - code interface, 222
 - conventions, 220
 - converting to Euler angles, 278–281
 - converting to quaternion, 284–287
 - disadvantages, 226
 - from Euler angles, 275–278
 - from quaternion, 281–284
- matrix multiplication
 - geometric interpretation, 124
 - linear algebra rules, 118–123
- matrix notation for curve, 649, 667, 674, 676
- Maya*, 428
- mechanics
 - dynamics, *see* dynamics
 - kinematics, *see* kinematics
 - vs.* physics, 479
- median of triangle, 330
- MegaTexturing, 432

- Mencken, H. L., 799
- metaballs, 296, 381
- metalness, 409
- metamer, 353
- Mines of Moria, 566
- minor of matrix, 164
- mirror addressing mode, 395
- mirrored texture maps, 437
- mistakes, xx
- MIT OpenCourseWare
 - linear algebra, 132
 - physics, 573, 639
 - scientific computing, 640
- Miyamoto, Shigeru, 343
- model space, 370, 451, *see also* object space
- model transform, 153, 276, **370**, 451
- moment of inertia, 611, 613
 - 3D, *see* inertia tensor
- momentum, 581–585
 - angular, *see* angular momentum
 - conservation of, *see* conservation of momentum
 - definitions, 581
 - in collisions, *see* collision
 - integral of force, 583
 - linear vs. angular, 613
 - units, 581
- money can't buy happiness, 497
- Money for Nothing*, 425
- monitor, *see* display device
- monomial form (curve), 648
 - endpoints, 650
 - subdivision, 687
- Monte Carlo integration, *see* numerical integration
- Monty Python, 490
- moon, 589
- Moore's law, 88
- Morpheus, 113
- motor, 626, 627
- multiplicative identity
 - identity matrix, 116
 - identity quaternion, 249
- Mythbusters, 592

- n** vector (lighting), 399
- NASA, 194, 785
- natural numbers, *see* numbers, natural
- near clip plane, 364
 - reason for, 377
- negation
 - of quaternion, *see* quaternion, negation
 - of vector, *see* vector, negation
- Newton (N) (unit of force), 485, 532, 556
- Newton meter (unit of torque), 609
- Newton's collision law, **597**, 618, 630
- Newton's laws, **554–562**, *see also* force
 - and momentum, 584
 - conservation of momentum, 584
 - rotational analog, 613, 617
- Newton, Isaac, 482, 490, 504, 553, 554
 - degree of cleverness, 558
- Newtonian dynamics, *see also* Newton's laws
 - vs. Lagrangian, 480
- Nintendo Wii, *see* Wii
- nonuniform knot vector, 654
- norm (of vector), 74
- normal, *see also* unit vector
 - in triangle mesh, 386
 - is dual vector, 392
 - of plane, 312
 - of triangle, 317
 - surface, *see* surface normal
 - terminology, 53
 - transforming, 391, 427
- normal force, 563, 569, *see also* contact force
- normal map, 431
- normalization constraint
 - of barycentric coordinates, 321
 - of BRDF, 352
- normalized device coordinates, 378
- normalized quaternion, 250
- normalized vector, *see* unit vector
- North Pole, 589
- NTSC television standard, 484
- null space, 157
- numbers
 - computer representation, 4–5
 - floating point, *see* floating point numbers
 - integers, *see* integers
 - natural, 2
 - rational, 3
 - real, 3
- numerical differentiation, 498
- numerical integration, 416, 532, 557, 624, 633, *see also* Euler integration
 - in graphics, 357, 360
- nutration, 236

- O'Rourke, P. J., 805
- OBB (oriented bounding box), 304
- Obi-Wan Kenobi, 553
- object space, **83**, 218, 369

- odometer, 534, 537
- Old Man Murray, 622
- omni light, *see* point light
- opacity, 456, 458
- Open Dynamics Engine, 621, 627, 632, 639
- open intervals, *see* interval notation
- OpenCourseWare, *see* MIT
 - OpenCourseWare
- OpenGL, 83, 124, 343, 378, 396, 409, 414, 475
 - clip matrix, 376
 - screen space conventions, 378
 - UV conventions, 393
- opposite triangle leg, 23
- orbital angular momentum, *see* angular momentum
- orbital angular velocity, *see* angular velocity
- orbital motion, *see* circular motion
- orientation
 - in 3D, 217–291
 - vs. direction, rotation, angular displacement, 218
- origin, 7
- orthogonal basis vectors, 105
- orthogonal matrix, 158, **171–176**
 - geometric interpretation, 172
 - math definition, 171
- orthogonalizing a matrix, **175–176**, 227, 436
- orthographic projection, 144, 148–150
 - clip matrix, 374, 376
 - viewing in 3D, 368
 - vs. perspective projection, 368
 - zoom, 369
- orthonormal basis, **105**, 158, 174
- orthonormal basis vectors, 436
- orthonormal matrix, 392
- Orwell, George, 81
- oscillation, *see* harmonic oscillator
- overdamping, 578
- page flipping, 445
- parabolic motion, *see* projectile motion
- parallel axis theorem, 618
- parallel light, 416
- parallel projection, *see* orthographic projection
- parallel vector using dot product, 63
- parallelepiped, 168
- parallelogram, 318
 - area of, 67
- parameterization (curve), 652, 687, 692
- parametric continuity, 698–700
- parametric curve, 646–647
- parametric form, 296
 - ray, 299
- particle, 562
 - Particle Man*, 295
- Pascal (unit of pressure), 486, 549
- Pascal’s triangle, 678
- Pascal, Blaise, 490, 678
- passive transformation, **94**, 137
- PD controller, 579
- penalty method, 629
- per-face shading, 411
- per-pixel shading, 387, 411
 - HLSL example, 459
- per-vertex shading, *see* Gouraud shading
- perimeter of triangle, 318
- perpendicular bisector, 301
- perpendicular vector using dot product, 63
- perspective foreshortening, 185
- perspective projection, 183–189
 - clip matrix, 371, 375
 - vs. orthographic projection, 368
- petunias, xiii, 567, 569–571
- phantom point, 711
- phase offset, 575
- PhD adviser, 490, 661, 678
- philosophy, 1
- Phong exponent, *see* specular exponent
- Phong shading, *see* per-pixel shading
- Phong specular model, 399–404
- photometry, 356
- Photoshop*, 432, 491, 691, 695, 700
- physics
 - dynamics, *see* dynamics
 - kinematics, *see* kinematics
 - vs. mechanics, 479
 - what’s left out, 479
- physics engine, 621, 628, 639
- PhysX, 621
- Pi (π), 21, 198
 - continuous vs. discrete, 4
- pick-up line, cheesy, 564
- PID controller, 579
- pinhole camera, 185
- pipeline, *see* real-time rendering pipeline
- The Pirates of Penzance*, 716
- pitch, **207**, 229, 232
- pivoting, 165
- Pixar Animation Studios, 704
- pixel, 345
 - aspect ratio, 363–364, 367
 - coordinates of, 346

- not a rectangle of color, 346
 - square pixels, 363
 - pixel shader, 440, 442, 456
 - HLSL examples, 457–474
 - planar mapping, 393, 435
 - plane, 311–317
 - best fit, 314
 - closest point, 719
 - defined by three points, 313
 - distance to point, 316
 - front and back side, 313
 - implicit form, *see* plane equation
 - intersection in 3D, 726
 - intersection with AABB, 725
 - intersection with ray, 724
 - intersection with sphere, 732
 - normal, 312
 - plane equation, 312–313
 - backface culling, 455
 - from three points, 313
 - geometric interpretation, 312
 - PlayStation 2, 425, 443
 - point
 - locating in 2D, 10
 - locating in 3D, 14
 - vs. vector, 39–41
 - point at infinity, 177, 180
 - point light, 414
 - point of concavity, 334
 - point velocity, 548
 - point vs. vector, 177, 219
 - polar axis, 192
 - polar coordinates, 191–213
 - 2D, 192–201
 - 3D, 203–213
 - 3D cylindrical, *see* cylindrical coordinates
 - 3D spherical, *see* spherical coordinates
 - converting to/from Cartesian, 198–201
 - vector, 213
 - why bother using, 201
- pole, 192
- polygon, 332–339
 - convex vs. concave, 334–338
 - fanning, 338
 - hole, 333
 - self-intersecting, 334
 - simple vs. complex, 333–334
 - triangulation, 338
- polygon mesh, 381, *see also* triangle mesh
- polynomial curve, 647–649
- polynomial interpolation, 653–665
- position
 - of vector, 35
 - relative vs. absolute, 35, 82
- power, 354, 532
 - radiant, *see* radiant flux
- power form (curve), *see* monomial form (curve)
- power rule (differentiation), 507
- pre-lit vertices, 448
- precession, 236
- prerequisites, xviii
- presenting the back buffer, 445
- prime notation, 503
- Principia*, 553, 563
- prismatic joint, 626
- product notation, 20
- product rule, 535
- projected area, 356
- projected light map, 416
- projectile motion, 516, 520–530, 559
- projection
 - matrix, *see* clip matrix
 - orthographic, *see* orthographic projection
 - perspective, *see* perspective projection
 - to screen space, 83
 - using dot product, 58
- proofs, *see* stickler alert
- proper Euler angles, 235
- proper transformation, 158
- Pythagorean identities, 25
- Pythagorean theorem, 25, 199
-
- quadratic equation, xviii, 521, 551
- quantization, 273
- quantum mechanics, 554
- quaternion, 246–273
 - “difference”, 254
 - advantages, 263
 - aliasing, 249
 - as complex number, 264–271
 - conjugate, 250
 - converting to Euler angles, 288–291
 - converting to matrix, 281–284
 - derivative, 637
 - disadvantages, 263
 - dot product, 255
 - exponential function, 256
 - exponentiation, 257
 - from Euler angles, 287–288
 - from matrix, 284–287
 - geometric interpretation, 248–249

- identity, 249
 - interpolation, *see* slerp
 - inverse, 251
 - logarithm, 256
 - lore, 267
 - magnitude, 250
 - multiplication, 251
 - multiplication by scalar, 256
 - negation, 249
 - notation, 247–248
 - slerp, *see* slerp
- r** vector (lighting), 399
- radiance, 356
 - radians, 194, 545
 - converting to degrees, 22
 - radiant emittance, 355
 - radiant energy, 354
 - radiant exitance, 355
 - radiant flux, 354
 - radiant power, *see* radiant flux
 - radiometry, 354–358
 - radiosity (unit of flux density), 355
 - radiosity techniques, 423
 - radius vector of AABB, 306
 - rank
 - and barycentric coordinates, 322
 - of basis vectors, 102
 - rasterization, 347, 440, 455–456
 - rational curve, 648
 - rational numbers, *see* numbers, rational
 - ray, 297–303
 - 3D intersection, 722
 - as curve, 650
 - closest point, 718
 - intersection with plane, 724
 - intersection with sphere, 727
 - intersection with triangle, 734
 - parametric form, 299
 - raytracing, 346
 - real numbers, *see* numbers, real
 - Real-Time Rendering* (book), 438, 475, 717, 737
 - real-time rendering pipeline, 438–456
 - realism vs. fun, 566
 - rectangular spot light, 416
 - recurrence relation, 657, 673
 - reference frame, 558
 - reflectance model, *see* BRDF
 - reflection (transformation), 144, **151–152**
 - reflection vector, 399
 - reflex vertex, 335
 - regular partition, 531
 - relative displacement, 219
 - relative measurements, 41
 - relative position, 35, 39
 - relativity, 554
 - Renault, 670, 671
 - render context, 446
 - render target, 363
 - rendering algorithm, 346
 - rendering equation, 359–362
 - light attenuation, 417
 - shadows, 410
 - Renderman, 457
 - repeat addressing mode, 395
 - resolution
 - of display device, 363
 - of render window, 367
 - rest length of spring, 571
 - retroreflection, 410
 - RGB color space, 353–354, 398
 - Riemann integral, 519, 531
 - rigging, 425, 429
 - right hand rule, 16, *see also* handedness
 - rigid body, 562
 - rigid body transformation, 158
 - Rodrigues vector, 236
 - roll, 232
 - roll-pitch-yaw, 233
 - Ross, Diana, 160
 - rotation
 - about arbitrary axis, 141–144
 - about cardinal axis, 139–141
 - in 2D, 138
 - in 3D, 217–291
 - integration of, 636
 - vs. orientation, 218
 - rotation matrix, *see also* matrix form
 - converting to Euler angles, 278–281
 - converting to quaternion, 284–287
 - derivative, 637
 - from Euler angles, 275–278
 - from quaternion, 281–284
 - rotation vector, 246, *see also* exponential map
 - rotational inertia, *see* inertia tensor, moment of inertia
 - Runge phenomenon, 691
 - Runge-Kutta integration, 634
- Sand-Reckoner*, 81
- scalar vs. vector, 32
 - scale (transformation), 144–148
 - along cardinal axis, 144–146
 - arbitrary direction, 146–148
 - nonuniform, 144
 - scientific computing, 640

- scissoring, 452, 455
- scratch direction, 410
- screen space, 9, 83, 93, **378–379**, 440
- seam edge, 333
- Sears Tower, *see* Willis Tower
- secant, 23
- second-order system, *see* damped oscillation
- self-illuminated surface, *see* emissive surface
- self-intersecting polygon, 334
- semiperimeter, 319
- sequential impulse method, 630
- set point (control system), 579
- sewing machine, 533
- sexagesimal number system, 21
- shader constant, 446, 459
- shadows, 410, 424
- Shapes* (poem), 341
- shearing, 152–153, 179
- Sherlock Holmes, 1
- shininess, *see* specular exponent
- short, 4
- SI system, 354, 485, 532, 556, 609
- sigma notation, *see* summation notation
- signed area, 319, 328
- signed displacement, 36
- signed distance, 11, 192, 301, 316
- silliness of authors, xvii
- Silverstein, Shel, 341
- simple harmonic motion, *see* harmonic oscillator
- simple polygon, 333
- simulation, 621
- sine
 - definition using unit circle, 22
 - derivative, 510
 - Taylor series, 508
- singular matrix, 157, 168
- sinusoidal, 575
- size vector of AABB, 305
- skeletal animation, 424–431, 447
 - HLSL example, 472
 - joint, 626
 - vertex format, 449
- skew box, 127, 167
- skinning, 425, *see also* skeletal animation
- slerp, 255, 259–263
 - example code, 262
 - formal definition, 260
 - practical definition, 261
- slider joint, 626
- sliver triangle, 338
- slope and velocity, 488
- slope-intercept form, 300
- smoothstep, 669, 712
- $SO(3)$, 244
- solid angle, 355
- source fragment, 347
- Space Quest*, xv
- space station, *see* International Space Station
- span
 - of basis polynomials, 662
 - of basis vectors, 101
- specular color, 401
- specular exponent, 400
- specular map, 401
- specular reflection, 398–404
- speed, *see also* velocity
 - and average velocity, 486
 - is a scalar quantity, 35
 - vs. velocity, 35, 488
- speedometer, 533
- sphere, 303–304
 - intersection in 3D, 729
 - intersection with AABB, 731
 - intersection with plane, 732
 - intersection with ray, 727
- spherical coordinates, 204–213
 - and Euler angles, 232
 - converting to/from Cartesian, 211–213
 - traditional conventions, 204
 - video game conventions, 206–207
- spherical harmonics, 423
- spherical light, *see* point light
- spherical linear interpolation, *see* slerp
- spherical mapping, 393
- Spielberg, Steven, 478
- spin (angle), 236
- spin angular momentum, *see* angular momentum
- spin angular velocity, 549, *see also* angular momentum
- spline, 690–711
 - Bézier, 694–697
 - continuity, *see* continuity
 - Hermite, 694–697
 - knot, 693–694
 - notation, 692–693
- spot light, 415
- spring, 571–581, *see also* harmonic oscillator
 - penalty method, 629
 - restorative force, 571
- spring constant, 572
- spring-damper, *see* damped oscillation

- square matrix, 115
- square pixels, 363
- standard lighting model, *see* Blinn-Phong
- standard position (of angle), 22
- state variables (physics engine), 621–627
- static friction, *see* friction, static
- static intersection test, 721
- steradian (sr), 356
- stickler alert
 - 4×3 matrix, 181
 - derivative at discontinuity, 502
 - group theory, 38
 - integrability requirements, 519
 - limit, 494
 - limits and derivatives, 502
 - norms, 51
 - points vs. vectors, 40, 668
 - proofs omitted, xvii, 504
 - Riemann integral, 531
 - Taylor series, 509
- stiffness, spring, 572
- Strang, Gilbert, 132
- structure of arrays (SOA), 449
- styrofoam, 566
- subdivision (curve), 685–690
 - Bézier form, 688–690
 - monomial form, 687–688
- subsurface scattering, 352
- sum and difference (trig) identities, 26
- sum rule (differentiation), 505–506
- summation notation, 20
- Super WHY!*, 137
- SuperBall, 596
- support, 680, 691
- surface area of sphere, 304
- surface normal, 53, 386–393, 399, *see also* normal
 - in collision, 594
 - in rendering equation, 386
- surface-local space, *see* tangent space
- suspension (vehicle), 579, 580
- Sutherland-Hodgman algorithm, 451
- symmetric Euler angles, 235

- Taco Bell, 40
- tail of vector, 35
- Tait-Bryan angles, 235
- tangent
 - of curve, 652, 700, *see also* velocity, curve
 - of spline, 695
- tangent (trigonometric function), 23
- tangent basis, *see* tangent space
- tangent line and instantaneous velocity, 492
- tangent space, 100, 381, 432–435
- tangent vector (bump mapping), 100, 432
- Tarantino, Quentin, 75
- Taxicab norm, 74
- Taylor series, 508–511, 551, 634
 - exponential function, 510
 - sine and cosine, 508
- TCB spline, 705–710
- television, *see* display device
- temperature, 41
- tension (TCB spline), 705
- ternary operator, 259
- texel, 393
- texture map, 439
- texture mapping, 393–395
- texture-mapping coordinates, *see* UV coordinates
- The Print Shop*, 621
- They Might Be Giants, 295
- tilt, 232
- time, 483
- time-to-parameter function, 692, 697
- Titanic*, 659
- Tomb Raider*, 425
- torque, 549, 571, **609**, 613
 - 2D, 609
 - 3D, 615
 - and force, 610
 - impulsive, *see* angular impulse
- tortoise and hare, 486, 495
- transformation, 86–108
 - active vs. passive, 87–96, 137
 - computing using basis vectors, 97–106
 - model, *see* model transform
 - view, *see* view transform
- transforming normals, 391
- translation matrix, 178
- transposition, of matrix, 116
- triangle, 317–332
 - area, 318–321
 - barycentric space, 321–324
 - intersection with ray, 734
 - normal, 317
 - notation, 317
 - plane containing, 317
 - special points, 329–332
- triangle mesh, 381–386
 - indexed, 382
- triangle rule of vector addition, 49
- triangle soup, 625
- triangulation of polygon, 338

- trigonometry, 22–27
 - identities, 24–27
- trip odometer, 537
- triple product, 163
- truth, philosophy of, 1
- turning an edge, 391
- Twain, Mark, xvii
- twist, 218, 232
- typeface conventions, 33

- undamped angular frequency, 577
- underdamping, 577
- uniform circular motion, *see* circular motion
- uniform knot vector, 654
- unit circle, 22
- unit conversion, 486
- unit quaternion, 250
- unit vector, 53–55, *see also* normal
- United States, 81
- universal gravitation, 563
- universal joint, 626
- universal space, *see* world space
- Unreal* engine, 381
- upright space, 84–86, 218
 - defense of, 108–109
- Upside Down*, 160
- user constraint (physics), 625–627
- UV coordinates, **393**, 447

- v** vector (lighting), 399
- valence, 382, 385
- Vandermonde matrix, 660
- vector
 - addition, 47–50
 - and Cartesian Coordinates, 36
 - as matrix, 116
 - as sequence of displacements, 37, 49, 75
 - cross product, *see* cross product
 - dimension, 32
 - direction, 34
 - dot product, *see* dot product
 - examples, 36
 - geometric definition, 34
 - in polar form, 213
 - magnitude, 34, **51–53**, 74
 - mathematical definition, 32
 - multiplication by scalar, 45–47
 - negation, 43–45
 - normalized, *see* unit vector
 - notation, 32
 - row vs. column, 32, 116, 117, **123–124**
 - subtraction, *see* vector, addition
 - vs. point, 39–41
 - vs. scalar, 32
- Vector** (container class), 32
- velocity
 - angular, *see* angular velocity
 - angular vs. linear, 548
 - average, *see* average velocity
 - constant, 516
 - derivative, 513
 - derivative of position, 495
 - instantaneous, *see* instantaneous velocity
 - is a vector quantity, 35
 - of curve, 651–653, *see also* velocity, curve
 - of spline, 702–711
 - relative, 43
 - vs. speed, 35
- velocity-based simulation, 631
- vertex
 - common graphics formats, 448
 - of polygon, 332
 - of triangle, 317
 - of triangle mesh, 382
 - pre-lit, 448
 - rendering data, 446
 - skinned, 425, 447, 449
 - valence of, *see* valence
- vertex normal, 386, 447
 - calculating, 387
 - interpolating, *see* per-pixel shading
- vertex shader, 440, 442, 450–451
 - HLSL examples, 457–474
- vertex shading, *see* Gouraud shading
- view frustum, 364–365, 374
 - clip planes, 375
 - field of view, 367
- view space, *see* camera space
- view transform, 153, 276, **370**, 451
- visible surface determination, 346
- volume (loudness), 42
- volume of sphere, 304
- volumetric light, 418–422, 451
- vomit comet, 785
- von Braun, Werner, 601

- w*-buffering, 379
- Walt Disney Animation Studios, 704
- Waring, Edward, 661
- watt (W), 354, 532
- Watterson, Bill, xxi
- wavelength of light, 353
- weight, 484

- West, Mae, 645
- Whaddya know?*, 30
- widescreen monitors, 363
- wiggles, 648, 691
- Wii, 374, 387, 397, 412, 414, 422, 476
- Wikipedia, xvii, 232, 551, 578, 617, 790
- Willis Tower, 514, 516, 521
- Willy Wonka, xi
- window, rendering, 362
 - aspect ratio, 367
 - resolution, 367
- winged-edge model, 386
- Wolfram MathWorld, xvii
- work (physical quantity), 480
- world space, 81–82, 451
- wrap addressing mode, 395
- wrapPi, 241
- “y’all”, 201
- y -intercept, 300
- yaw, 232
 - vs. heading, 234
- yaw-pitch-roll, 232, 233
- yellow fever, 31
- Yoda, 479, 560
- yon clip plane, *see* far clip plane
- z -axis, 13
- Z-fold paper, 621
- zenith, 205
- zero gravity, 640, 785
- zero vector, 38
- zoom, 365, 374, *see also* field of view
 - orthographic projection, 369
- ZZ Top, 661

*What is it ye would see?
If aught of woe or wonder, cease your search.
— Horatio in Hamlet, Act V, scene II*