

Index

- absolute
 - elsewhere, 12
 - future, 12
 - past, 12
- accelerated particle, 41, 114–115, 171–172, 206–207
- acceleration, 2–3, 46, 114–115, 171–172, 436–438, 440–442
 - absolute, 2
- accretion disk, 336
- active gravitational mass, 196, 200
- adiabatic process, 102
- affine parameter, 155, 164, 174
- Albert Einstein Institute, 396
- angular diameter distance, 433
- angular momentum, 179, 298, 302, 325–326, 328–330
- angular velocity, 179, 247–248, 329
- Assumption of Mediocrity, 423
- background Lorentz transformations, 188, 189, 243
- background Minkowski spacetime, 205
- bar detectors, 214–220, 224, 239, 252–254
- baryons, 99, 372, 449–451, 454
- basis one-forms, polar coordinates, 121, 129, 133, 135
- basis vectors, 36, 45, 50, 58–62, 65–67, 73, 76–124, 126–130, 134–138, 149, 373–374, 469
 - derivatives of, 61, 65, 76, 122, 124, 126–130, 135, 138, 142, 150
 - inverse transformations, 38, 59
 - orthonormal, 45, 135–138, 469
 - polar coordinates, 121, 126–136, 142
 - transformation of, 36–40, 59, 61, 72, 122, 128, 134, 137
- Bayesian statistics, 383, 387
- beam detectors, 215, 219–226
- Bell, Jocelyn, 286, 287
- Bianchi identities, 162–164, 187
- Big Bang, 369, 415, 438–443, 455–462
- Big Crunch, 441
- binary pulsars, 287–289, 307, 364–367, 381–383
- binary star system, 235, 250–251, 290–291, 338, 362–367, 381–383, 398–400, 402–405, 434–435
 - EMRI biunaries, 366
- binary stars
 - Hulse–Taylor, 245–247
 - realistic, 247–249
 - scaling relations, 249–250
- Birkhoff’s theorem, 274
- black holes, 27, 226–230, 250, 269, 288–310, 315–316, 322–328, 333–345, 348–350, 363–367, 396–400, 403–405, 452
 - degrees of freedom, 337
 - formation of, 280, 289–291, 297, 322, 326, 338, 342, 350, 365, 403, 452–453
 - in Newtonian gravity, 230, 296, 307–309, 405
 - Kerr, 325–328, 334–337, 343, 345, 348, 350, 366
 - metric, 269, 280, 296, 307–309, 316, 325–326, 328, 337, 343, 348, 350
 - of stellar mass, 280, 290–291, 304, 338, 348, 405
 - real, 202–203, 322, 328, 337, 350, 363
 - Schwarzschild, 280–297, 322, 325–326, 328, 349–350
- branes, 461
- Buchdahl’s theorem, 280
- burst signals, 395
- catalogs, 405–406
- center of momentum, 43
- Chandrasekhar limit, 281
- Chandrasekhar, S., 286
- Christoffel symbols, 126–134, 137, 150, 155, 157–158, 161, 173, 177, 207
 - and the metric, 130, 132, 137, 173, 208
 - calculation from the metric, 130
- clusters, 312–314, 340–342, 366–417, 453–454
- coherent detection, 388–390
- cold electron gas, 282–285
- column vectors, 70
- conservation
 - of energy, 42–43, 98, 112, 177–178, 237–239, 243–244, 345, 347
 - of energy–momentum, 98
 - of entropy, 95, 99, 102, 173
 - of particles, 42–43, 84, 99–100, 172–175, 177–179, 345
 - of quantities, 179, 296, 298
- conservation laws, 43, 98–102, 173–174
- constants, in SI and geometrized units, 4–186
- contraction, 23, 59, 85–88, 162
- coordinate systems, 3–4, 25–26, 117–119, 127–129, 131–134, 136–148, 158–160, 176–179, 187, 206–207, 216–217, 267–269

- coordinates, Kruskal–Szekeres, 319
- Copernican Principle, 419, 423
- cosmic censorship conjecture, 327
- Cosmic Explorer, 228
- cosmic microwave background (CMB), 215, 369, 371–372, 417, 433, 448
- cosmography, 431
- cosmological constant, 186, 420–421, 427–429, 438–443, 445–447, 458–462
- cosmological distance ladder, 431, 434–435
- cosmological principle, 419–420, 422
- cosmological singularity, 442
- cosmology, 415–416
 - metrics, 418–425, 427
- covariant derivative, 127, 129, 132, 149, 158–160, 162, 164
- covariant differentiation, 130
- curvature, 141, 143–144, 152–153, 157–160
 - intrinsic and extrinsic, 152
 - of a sphere, 117, 143–153, 268
 - role of, 116
- curvature singularity, 317
- curved spacetime
 - two-spheres in, 267
 - waves in, 212
- curves
 - and vectors, 62–63, 73–75, 120, 121, 124, 142, 154–157
 - cylinder, intrinsic geometry of, 152
 - definition, 103–121, 152, 155–156, 171
- dark energy, 417, 438, 440–443, 445–448
- dark energy density, 438, 440–443, 445–448
- dark matter, 314, 417, 440–443, 445, 447–454, 457–459
- dark pressure, 416–442
- derivatives
 - covariant, 127, 130, 132, 149–150, 158–160, 165
 - notation for, 64, 65, 75–76, 126–127, 160
 - of basis vectors, 61, 65, 76, 122, 124, 126–130, 135, 137, 142, 150
 - of general vectors, 61, 123–126, 128, 137, 149–150
 - of one-forms, 61, 65, 75–76, 119–120, 129–179
 - of tensors, 75–76, 119–120, 127–130, 132, 142, 149, 157–160, 162–165, 173–174
 - vector field, 61, 119–120, 123–124, 127–129, 142, 149
- differentiable manifolds, 141, 170–171
- differential structure, 75–143, 274–275
- displacement vector, 33, 46, 122–124
- divergence, 128–129, 151–152, 317
- Doppler-shift formula for photons, 49
- dot product, 57
- dragging of inertial frames, 329
- dual vector space, 58, 69–70
- dummy index, 35
- dust, 85, 91–93, 100–101, 456
 - stress–energy tensor, 91
- Earth, mass of, 113–114
- Einstein equations
 - for weak gravitational fields, 115, 187, 188, 192–195, 203, 307–309
 - in vacuum, 203, 272
 - integration of, 195, 274, 442
- Einstein equivalence principle, 115, 171–174
- Einstein summation convention, 34
- Einstein Telescope, 228
- Einstein tensor, 162–165, 173–174, 183–184, 188–191, 271, 424, 438–442
- electromagnetic spectrum, 213, 215
- electromagnetic waves, 209–213, 229–230, 360, 368–369, 455
- electrons, 281–285, 449
- element of a continuum, 84
- elsewhere, absolute, 12
- energy
 - at infinity, 177, 270, 334–337, 346–348
 - density of, 84, 88, 90–95, 97–98, 183, 280–281, 283–285, 297, 393–394, 417, 448, 451, 457, 460
 - lost by a radiating system, 244
- energy flux, 90–95, 98, 239–245, 281, 431–432
 - gravitational wave, 218
 - gravitational waves, 239–245, 251, 360
- entropy, 94, 95, 102, 271, 326
 - law of conservation of, 95, 100, 102, 173
- equation of geodesic deviation, 162, 182
- equations of state, neutron stars, 285–288, 339, 366
- equivalence, principle of, 115, 171–174
- ergoregion, 331–337, 348
- ergosphere, 331
- ergotoroids, 331
- Euclidean space, 5, 117, 141, 155, 170–171, 426–427
- event horizon, 318–325, 346
- events, 3–21, 26, 170–171, 318–325, 396–402
- exact plane wave, 210
- extremal length, 155
- extreme mass-ratio inspiral (EMRI) binaries, 366
- extrinsic curvature, 152
- Fermi particles, 285
- flat manifold, 143–145, 154–159
- flat space, spherical coordinates, 268–269

- fluid, 84–174, 180, 271–272, 438–440
- fluid element, 84–85, 94–99, 101–104, 439
 - four-velocity, 91, 94
- flux, across a surface, 88–92, 105
- four-momentum
 - conservation of, 42–43, 174
 - of a particle, 42–43, 47–49, 176–177
- four-velocity, 41–42, 45, 47–48
 - of fluid element, 90, 94
- Fourier transforms, 367, 382
- free index, 35
- freely falling frame, 115–172
- freely falling particles, 115, 171–172, 178, 298
- Friedmann–Robertson–Walker metric
 - closed, 425
 - flat, 425
 - hyperbolic, 418
 - open, 418
 - spherical, 425
- function, 56–69, 73, 75, 189–191, 276–279
- future, absolute, 12
- galaxies, 312–314, 338–342, 365–367, 400–402,
415–420, 427–430, 433–436, 444–454
- Galilean law of addition of velocities, 2
- gamma-ray bursts, 401
- gauge transformations, 188, 190–192
- Gauss’ law, 90, 146–152
- general horizon, 322, 325–327
- general relativity, 3, 178–179, 190–194, 307–309,
327, 399, 415, 416
 - curved spacetime of, 75, 170–172, 174, 179
- general vector, 35, 73, 123–126, 136–138, 149–150
- GEO600, 225, 396
- geodesic, 153–156, 160–162, 171–172, 206–208
 - extremal length, 155
- geodesic deviation, 207
- geometer, 73
- Giacconi, Ricardo, 364
- GPS navigation system, 113
- gradient, 69, 75, 90, 103, 129
- gravitational fields, 3–4, 111–117, 170–172, 178–196,
207, 210–212, 214, 229–230, 237–239, 307–309,
343–344, 393–395, 455–456
- gravitational lensing, 212, 314
- gravitational potential energy, 174–178
- gravitational radiation, 194, 202–203, 213–215,
228–231, 234–237, 239–242, 244–250, 252–372,
402–405, 455–456
- gravitational redshift experiment, 113–115
- gravitational self-energy, 177
- gravitational spacetime, 170–172, 188–190, 210–212,
321–325, 343–344
- gravitational wave, 113–114, 192–194, 196, 202–290,
336–344, 360–364, 366–377, 386–407, 444–457
 - amplitude of, 213–214, 218–220, 222–223,
225–226, 229–230, 234–237, 239, 243, 247–248,
250–253, 361–362, 367–369, 374–377, 388–389,
392–394, 398
 - burst signals, 395
 - catalogs, 405–406
 - coherent detection, 388–390
 - detection thresholds, 386–388
 - detections of, 397–402
 - distance measurement using, 250–253
 - energy flux, 218, 239–245, 251, 361
 - filtering, 378–383
 - from binary systems, 362–367
 - generation of, 230–237
 - information extraction, 383–386
 - polarization of, 210, 215, 220, 223, 226, 228, 231,
234–235, 250, 368, 372–374, 383, 388–390, 395,
399, 405–456
 - pulsars, 390–392
 - stochastic backgrounds, 369–372
- gravitational wave bursts, 368
- gravitational wave detectors, 202, 207, 216–220,
222–230, 237–364, 367–370, 372–377, 381–383,
386–396, 399–400, 454
- gravitomagnetism, 330
- gravitons, 49, 350
- gravity, 111–117, 164–172, 175–177, 183–187,
192–195, 307–310, 344, 461–462
 - deflection of light by, 309
 - Newtonian, 170–172, 175–176, 192–214, 276,
307–310, 416
- GW150914, 397–399
- GW170814, 399
- GW170817, 399
- GW190425, 403
- GW190521, 404
- GW190814, 405
- harmonic oscillator, 217
- Hawking radiation, 345–350
- heat conduction, 100
- Hewish, Antony, 286
- Higgs boson, 458
- Hilbert space, 70
- homogeneity, 192–193, 416–428, 438–439, 447–448,
460
- horizon, 315–328, 331–334, 336–338, 346–348,
350–423
 - Kerr, 325–328, 331–332, 350
 - particle, 316, 318–319, 331, 334, 346, 363–423
- horizontally, direction that hyperbolae run, 321
- Hubble constant, 418
- Hubble parameter, 418
- Hubble–Lemaître flow, 418
- Hulse–Taylor binary pulsar, 245–247

- hyperbola, 13–16
 - tangent to, 17
- hypersurface, 43, 104, 420–423, 426–429
- index, 33–36, 39–41, 59–60, 73–75, 190
 - dummy, 35, 37
 - free, 35
 - Greek, 6
 - Latin, 6, 35
 - raising and lowering of, 74, 130
- inertial frames, 26, 43, 111–117, 149, 170–174, 176, 207–208
 - dragging of, 329
 - freely falling, 115–117, 171–172, 178, 209
 - nonexistence at rest on Earth, 112
- inertial observers, 2–145, 170–171, 173–174, 270
- inertial reference frame, 4
- inflation, 459
- inner product, 69–72, 468
- interferometers, 214, 220, 223–226, 228, 373
 - gravitational wave response, 373–377
 - networks of, 226–228
 - observations, 214, 224, 228
- intermediate-mass black holes, 290, 452
- interval
 - invariance of, 9, 12, 13, 21
 - spacelike, 12, 13, 111
- intrinsic curvature, 152, 156
- inverse transformations, 39
- isotropic coordinates, 308, 308, 426–427
- Jacobian, 146
- Keplerian motion of the planets, 176
- Kerr black hole, 325–366
- Kerr horizon, 325–328, 331–332, 350
- Kerr metric, 325–326, 328–332, 337, 343
- Kerr solution, 325, 331
- Kronecker delta, 10, 74, 470
- Large Hadron Collider, 458
- laser interferometer gravitational wave detector, 223–225
- law of conservation of entropy, 173
- Lense–Thirring effect, 330
- light cones, 12–13, 239–321
- LIGO, 387
- LIGO detectors, 224–227, 251–254, 360–362, 369–370, 372–373, 375–378, 381–383, 394–396, 398–400, 406
 - advanced upgrade, 396
 - detections, 397–402
- LIGO–Virgo collaboration, 387, 395, 398
- line element, 123, 267–268, 307–309, 317, 423–425
 - of flat spacetime, 145, 211, 268
- linear algebra, 468
- linear function of M one-forms and N vectors
 - into real numbers, 73
- linear function of M one-forms into real numbers 72
 - reduced quadrupole moment, 233
 - Riemannian, 138, 159, 165
 - symmetric, 67
 - trace-free moment, 233
- LISA, 228–229, 363–364, 366–367, 407, 445, 452
 - Pathfinder mission, 229
- local flatness, 117–145, 149, 172–173
- local inertial frames, 115–117, 143–145, 149, 170–173, 207–209, 346–348
- locally trapped surfaces, 325
- loop quantum gravity, 461, 463
- Lorentz contraction, 1, 18, 23, 85
- Lorentz gauge, 188–192, 204–206
- Lorentz transformation, 21–23, 119, 144–146, 189
 - inverse, 39
- luminosity distance, 244–245, 251, 431
- magnetism, 286–287, 289–290, 328–330
- magnification, 313
- main sequence stars, 280
- manifolds
 - coordinates, 144–148, 150, 164–188
 - differentiable, 170–171
 - flat, 144–145, 150, 152, 159
 - Riemannian, 143–149
- mass, of a relativistic body, 195, 196, 296
- mass density, 103–104, 183, 280–285
- mass function, 272
- matrices, 119–120
 - inverse, 73, 470
 - multiplication, 469
- matter energy density, 439–443, 445–448
- metric, 45, 56–59, 61, 64, 65, 67–75, 111, 123, 130, 132, 137, 142–149, 158, 163, 170, 172, 174–176, 178–185, 187–189, 193, 196, 200, 203, 208, 212, 220–222, 244, 268–271, 273–274, 276, 278–279, 304, 307–309, 316, 319–326, 328–332, 348, 350–425
 - and local flatness, 117–145, 147, 149, 159, 193, 274, 325, 346, 348, 416, 424, 427
 - antisymmetric, 67, 74
 - as a mapping of vectors into one-forms, 62, 64, 68–71, 74–75
 - black hole, 280, 325–326, 328, 343
 - calculation of Christoffel symbols from, 130
 - Christoffel symbols and, 130, 132, 137, 173, 180, 208
 - components of, 45, 56–59, 62, 68–72, 74–75, 111, 123, 130, 132, 137, 142–144, 146, 148, 159, 174, 177, 179, 183–184, 187–189, 208, 216, 244, 269–271, 298, 329, 374

- metric (cont.)
 - cosmological, 416, 418, 423–425, 428, 430, 459–460
 - inverse, 59, 68–428
 - Minkowski, 147, 170, 175, 188
 - of waves, 193, 196, 203, 208, 212, 214, 216, 221, 222, 244, 274, 337, 343, 374
 - signature of, 144, 164
 - static spherically symmetric spacetimes, 269–322
- Michelson–Morley experiment, 2
- microlensing, 314
- Minkowski metric, 176
- Minkowski space, 117, 147, 267, 427
- momentarily comoving reference frame (MCRF), 41, 47–49, 84–85, 90–103, 173, 183
- momentum density, 91–93, 95, 98, 282–285
- momentum, flux of, 91–93, 98–99
- motion
 - equation of, 174–176, 187, 209, 271, 307–309
 - of a freely falling particle, 115, 171, 174, 176, 209
- multimessenger astronomy, 361
- naked singularities, 327
- neutrinos, 289–314, 369
- neutron stars, 194, 202, 214, 236, 250–251, 277, 280–281, 284–339, 343–344, 360–364, 366–368, 378–379, 398–400, 402–405, 415–416, 434–435
 - forces which support, 282
 - gravitational waves from, 390–392
- neutrons, 99, 280–282, 284–339, 360–364, 366–368, 398–400, 402–405
- Newtonian dark star, 297
- Newtonian gravitational fields, 170–172, 192–196, 307–309
- Newtonian gravity, 170–172, 176, 192–195, 307–310, 416
- Newtonian limit, 176, 187, 276, 308
- Newtonian potential, 174, 194, 237, 307–308
- Newtonian stars
 - equation of hydrostatic equilibrium, 276
 - structure of, 274–276, 284, 415
- Newtonian tidal gravitational force, 237
- normal one-forms, 71, 80
- normal vectors, 65, 71
- notation for derivatives, 75
- notation, for derivatives, 76, 126–127
- null rays, 323
- null vector, 44, 204–205
- number density, 84–95, 282–285, 457–458
- observations, 1–4, 17–21, 170–171, 226–229, 237, 250–253, 285–288, 311–316, 321–322, 338–346, 360–368, 370–372, 389–391, 398–407, 419, 421–423, 427–429, 431–436, 452–462
- Olbers’ Paradox, 417
- one-forms, 58–72, 88–92, 118–124, 129–133
- order-of-magnitude estimates, 237
- orthogonality, 268–269, 321
- orthonormality, 135–138
- outer product sign, 66
- paradoxes, 23–24
- parallel transport, 154, 156, 160, 164
- parallelism, 117, 152–154, 159–160
- particle horizon, 318–319, 346, 363–423
- past, the, 421–423, 429–430
- path, 113–121, 152–154, 156–158, 321–322
- Pathfinder, 229
- Penrose process, 335, 348
- perfect fluids, 84–96
- periastron shift, 307
- pericenter shift, 307
- photons
 - potential, 300–302, 333–334
 - zero rest-mass, 48–62
- Planck mass, 349
- plane wave, 204, 206, 210–212, 240–243, 373–375, 383–384
 - exact, 210, 211
- plane-fronted waves with parallel rays, 212
- polar coordinate basis vectors, 121–124, 126–136
- polar coordinates
 - tensor algebra in, 117, 118, 123, 142
 - tensor calculus in, 124, 127
- polarization, of gravitational waves, 210–211, 228, 234–235, 372–374, 388–390, 404–456
- polytrope, 278
- post-Newtonian effects, 194, 252, 307–309
- post-Newtonian gravity, 307–309
- Pound–Rebka–Snider experiment, 114
- precession, 303, 330
- pressures, 84, 100, 103, 277–278, 281–285, 440–442
- principle of equivalence, 19–115, 171–174
- principle of relativity, 1, 11, 19, 171–172
- proof masses, 229, 325–327
- proper distance, 12, 206, 208, 220–222, 427–433
- proper volume element, 147
- protons, 99, 281, 284–285, 457
- pulsar, 214–215, 236, 286–289, 364–368, 381–383, 390–391
- pulsar timing, 213–215, 286–287, 364–368, 390–391, 393–394
- r-mode instability, 367
- radar, 186–222
- red giant, 281
- redshift, 111–115, 252, 307, 427–438, 445–448
 - cosmological, 252, 418, 427–430, 434–448
 - gravitational, 111–115, 252, 309, 445

- redshift (cont.)
 - of photons, 111–112, 115, 269, 427–430, 432–434, 447–448
- relativity, principle of, 171–172
- rest mass, 42, 43, 49, 111–114, 298
- Ricci scalar, 162, 164
- Ricci scalar curvature, 424
- Ricci tensor, 162, 164, 184
- Riemann tensor, 138, 160, 162–164, 173, 208
- Riemannian manifolds, 143, 164
- Riemannian spaces, 117
- scalar product, 44–45, 56, 59, 61, 71–72
- Schwarzschild geometry, 296, 317–319, 322
- Schwarzschild horizon, 318, 322, 323, 325–327, 331–332, 350
- Schwarzschild metric, 273–274, 280, 304–309, 325–326, 346
- second law of thermodynamics, 95
- shot noise, 225, 375
- SI units, 4–5, 185, 186, 246
- signature of the metric, 144
- simultaneity, 8, 16–17, 20, 171
- singularity
 - cosmological, 441–442
 - curvature, 317, 327
 - naked, 327
- slow-motion assumption, 231
- sound, cosmic, 229–230
- spacelike interval, 111
- spacetime, 1, 5–6, 27–174, 188–190, 267–270, 318–326, 343–346, 422–427
 - asymptotically flat, 194, 269
 - curvature, 117, 152, 170, 172–174, 327
 - metric of, 74, 111, 144–146, 170, 172, 174, 188–189, 268–270, 423–425
 - slightly curved, 174
 - static spherically symmetric, 269
- spacetime diagrams, 5–16
 - construction of coordinates, 6, 8, 11
- spatial momentum, 48
- special relativity
 - Lorentz transformation, 1, 39, 188
 - metric of, 111, 179, 222
 - perfect fluids in, 84–96, 100
- specific entropy of the Universe, 447
- speed of light, 1
- sphere, curvature, 143–153
- spinor space, 75
- Square Kilometer Array (SKA) radio telescope, 215
- standard candle, 251, 431
- stars
 - composition of, 281, 284, 290, 296
 - exact interior solutions, 276, 278, 337
 - exterior geometry, 273, 274
 - interior structure, 275, 280, 322
 - mass of, 104, 236–237, 247, 274–297, 307, 312–314, 322, 337–344, 360–364, 366–368, 381–383, 398, 400–401, 403–405, 415–416, 434–435, 450, 452–453
 - surface of, 275, 280–281, 286, 296–297, 314, 318, 322, 331
- static limit, 331
- static spacetimes
 - definition, 269, 322
- stationary horizons, 325, 331–332
- stellar mass black holes, 290–317
- stochastic background, 392–394
- stress–energy tensor, 164, 439
- string theory, 461
- supernova, 288–364, 368, 434
- supernova explosions, 212, 288–290, 369, 434–435
- surface element, 90, 95–96
- surfaces, one-forms and, 61, 62–99, 122
- tension of dark energy, 441
- tensor, 56–59, 65–68, 71–76, 91–92, 123–124, 127–132, 134, 141, 142–143, 157–160, 162–165, 173–184, 189–191
 - antisymmetric, 67, 71
 - components of, 56–59, 66–68, 71–76, 91–92, 123–124, 127–132, 134, 142–143, 157–160, 165, 183–184, 189–190, 208
 - definition, 45–57, 91–92, 149–150
 - differentiation of, 74, 130, 142–143, 160, 165, 184
 - field, 127–129, 134, 142, 143, 183–184, 189
 - general stress–energy, 92, 95
- tensor algebra
 - in polar coordinates, 117, 118, 123, 142
 - review of, 142
- tensor analysis, 58–59, 75–76
- thermodynamics
 - first law of, 94, 349
 - second law of, 84, 95
- Thorne–Zytkow object, 365
- three-dimensional wave equation, 203
- tidal forces, 117, 207–209, 327
- time-delay interferometry (TDI), 229
- timelike interval, 13, 111
- Tolman–Oppenheimer–Volkov equation, integration of, 274
- transponders, 222

- twin paradox, 23–25
- two-spheres
 - in a curved spacetime, 267
 - meshing into a three-space, 268
- uncertainty principle of quantum mechanics, 327
- units, 4, 84–88, 91–92, 135–136, 185–186, 240–241, 243–246
 - geometrized, 4–5, 185, 186, 245–246
 - SI, 4, 184–186, 246
- universality of the speed of light, 1, 2, 4, 9–10, 21
- Universe
 - acceleration of, 417, 434, 436–441
 - closed, 364, 369–370, 417, 441, 444
 - evolution of, 364, 418, 421, 430, 436–445, 447–462
 - expansion of, 417–419, 421, 428–430, 433, 436–444, 447–448, 457
 - flat, 416, 427, 441, 444
 - Friedmann–Robertson–Walker, 438
 - history of, 418, 422–423, 430, 441, 443, 447
 - homogeneity of, 416–424, 428, 439, 447–448, 458–459
 - hyperbolic, 441
 - isotropic, 417, 418, 420, 431, 441
 - measures of distance in, 170–171, 251, 312, 401, 421, 427–431, 433–434, 436–437, 445–454
 - models of, 372, 416, 422, 436–438, 442–445, 449, 458–462
 - radiation-dominated, 441–442, 448, 457
 - re-collapsing, 441
 - scale factor, 429, 433–434, 438, 441, 447–448
 - specific entropy, 457
- vector
 - as a function of one-forms, 58, 62–65, 68–73, 75–76, 90, 120, 142
 - basis, 36–42, 44–45, 58–62, 65–67, 73, 76–124, 126–130, 134–138, 142, 150, 373–374, 469
 - column, 469
 - curves and, 63, 74–75, 120, 121, 124, 142, 154–157
 - definition, 33, 36–37, 40–42, 44, 56–57, 59, 71, 118–121, 149–150
 - derivatives of general, 61, 123–126, 128, 138, 149–150
 - displacement, 33, 46, 73, 123
 - gradient, 62–65, 69, 73, 75–76, 123–124
 - linearity, 33–34, 36–37, 56–57, 59–60, 68, 73, 142
 - linearly independent, 57, 59–60, 468
 - magnitude, 43, 61, 71, 74
 - vector algebra, 33–34, 40, 70, 73–75, 118–120
 - vector analysis, 33–60, 75
 - vector space, 58–63, 69–71, 74–75, 80, 149–150, 153–154, 468, 469
 - velocity-addition law, 23
 - vibrations, interferometers and, 219–226
 - Virgo detector, 377, 381, 400
 - viscosity, 100
 - visual observation, 4
 - volume element, 84–85, 90, 147, 275
- wave function, 70
- weak equivalence principle, 296
- weak gravitational fields, 171–172, 188, 192–196, 307–309
- Weber, Joseph, 368
- white dwarf, 282, 285, 434–435
- zero-angular-momentum observer (ZAMO), 335
- zero rest-mass particles, 49–62