

Index

- Λ CDM models, 444
- absolute derivatives, 58, 61
- accretion
 - and binary spinup, 205
 - as energy storage reservoir, 281
 - disk, 264, 276, 281, 283, 285, 293, 297–299, 302, 313, 315, 317
 - on black holes, 276, 277, 280, 281, 283, 295
 - on compact companion, 262
 - on neutron stars, 205
 - Roche lobe overflow, 532
- acoustic scale, *see* cosmic microwave background (CMB)
- action, 98
- active galactic nuclei (AGN), 292
- addition theorem (spherical harmonics), 429
- ADS astronomy abstract service, 571
- AdS/CFT correspondence, 240, 556, 558
- aether, 6
- affine parameters, 98
- afterglows, *see* gamma-ray bursts, afterglows
- AGN, *see* active galactic nuclei
- angular size distance, 433, 434
- anholonomic basis, *see* non-coordinate basis
- anti-de Sitter space, 558
- area theorem, *see* Hawking area theorem
- arXiv preprint server, 571
- asymptotically flat solutions
 - and local energy conservation, 132
 - Kerr spacetime, 244
 - Schwarzschild spacetime, 159
- AT 2017gfo, 522
- atlas, 33
- BAO, *see* baryon acoustic oscillations (BAO)
- baryogenesis
 - and absence of antimatter in Universe, 453
 - and excess of photons over baryons, 453
 - baryon non-conservation, 457
 - conditions for baryon asymmetry, 457
 - leptogenesis, 459
 - origin of baryons, 457
 - problem in big bang, 453
- baryon acoustic oscillations (BAO), 408, 438, 439
- baryon number, 239, 457, 458
- baryon to photon ratio η , 426
- baryonic mass, 199
- baryonic matter, 355
 - and baryon number, 457, 458
 - as “ordinary matter“, 329
 - as dark matter, 356
 - density constrained by big bang, 425
- basis
 - and directional derivatives, 37–39
 - anholonomic, 37–39
 - coordinate, 27, 37–39, 67, 126
 - dual, 18
 - for a vector space, 42
 - holonomic, 37–39
 - Lie bracket of basis vectors, 67
 - non-coordinate, 37–39, 67
 - orthonormal, 18, 36
 - tangent, 16
 - transformation of basis vectors, 68
- Bianchi identity, 150
- big bang, 412
 - and inflation, 444, 453
 - anisotropies in CMB, 429
 - baryogenesis problem, 453
 - baryon to photon ratio η , 413, 426
 - beyond standard big bang, 448
 - cast of characters, 419
 - conditions for baryon asymmetry, 457
 - cosmic microwave background (CMB), 426
 - cosmic neutrino background, 427
 - dark ages, 422, 423
 - decoupling from equilibrium, 417
 - decoupling of photons, 422, 423, 427, 429
 - decoupling of weak interactions, 418
 - deuterium bottleneck, 421
 - equilibrium in expanding Universe, 416
 - evolution of early Universe, 414
 - evolution of scale factor, 412
 - flatness problem and fine tuning, 451
 - history of Universe, 419
 - horizon problem and causality, 449
 - hot, dense initial state, 329
 - incomplete explanations, 449
 - mass-5 and mass-8 bottleneck, 421
 - matter and radiation density, 413
 - matter-dominated evolution, 412
 - modification by inflation, 457

- big bang (cont.)
 - modifying the first second, 453
 - monopole problem, 451
 - neutron to proton ratio, 424
 - no carbon production by triple- α , 421
 - nucleosynthesis, 420, 421
 - nucleosynthesis constraints on baryon density, 425
 - origin of the baryons, 457
 - production of ^4He , 424
 - production of the light elements, 420
 - radiation-dominated evolution, 412
 - recombination transition, 422
 - reionization transition, 422, 423
 - singularity, 258
 - structure and smoothness dichotomy, 452
 - successes, 448
 - thermodynamics, 414
 - unexplained initial conditions, 449
 - vacuum energy problem, 452
- Binary Pulsar, 200
 - emission of gravitational waves, 202, 497
 - merger timescale, 204
 - orbital properties, 201
 - origin and fate, 203
 - precession of periastron, 172, 202
 - precision test of general relativity, 202, 544
 - time dilation, 202
- binary star systems
 - circularization of orbits by tidal interactions, 262
 - contact binary, 491
 - high-mass X-ray binaries (HMXB), 262
 - mass function, 262, 263, 265–267
 - mass of, 262, 263, 265–267
 - radial velocity curve, 262
 - spectroscopic, 262, 263, 265–267
 - X-ray binaries, 257, 262
- Birkhoff's theorem, 226
- BL Lac objects, 295
 - blazars, 295
 - emission of high-energy photons, 302
 - inverse Compton scattering, 303
 - Markarian 421, 302
 - variable brightness, 295
- BL Lacertae objects, *see* BL Lac objects
- black hole central engines, 280
 - accretion, 280, 281, 283
 - accretion efficiencies, 283
 - accretion on supermassive black holes, 295
 - active galactic nuclei, 292
 - BL Lac objects, 295
 - Blandford–Znajek mechanism, 280
 - causality and source size, 291
 - Centaurus A, 301
 - gamma-ray bursts, 304
 - limits on accretion rates (Eddington limit), 282
 - magnetic fields, 280
 - quasars, 285, 290
 - radio galaxies, 292
 - Seyfert galaxies, 293
 - unified model, 295
- black hole laser, 235
- black holes
 - accretion, 280, 281
 - analog, 235
 - and asymmetric gravitational collapse, 259, 260
 - and charge, 225, 246
 - and gravitational waves, 532
 - and information, 239
 - and Penrose processes, 253
 - and stationary observers, 251
 - and the holographic principle, 240
 - apparent horizons, 260
 - area of event horizon, 247
 - as central engines, 280, 281
 - as endpoint of stellar evolution, 532
 - at center of Milky Way (Sgr A*), 268, 532, 544
 - Birkhoff's theorem, 226
 - candidates in X-ray binaries, 266
 - cosmic censorship, 224
 - Cygnus X-1, 267
 - energy sources, 280
 - entropy, 236, 237
 - evaporation of quantum black holes, 231, 559
 - event horizons, 213, 215, 260
 - evidence for stellar-mass black holes, 262
 - extraction of rotational energy, 253
 - extremal Kerr, 245
 - feeding, 301
 - four laws of black hole dynamics, 237
 - frame dragging for rotating, 249
 - from direct stellar collapse, 531, 533
 - generalized second law of thermodynamics, 236
 - gravitational waves from binary merger, 510
 - Hawking, 229, 230, 234, 559
 - imaging event horizons, 276
 - in the early Universe, 274
 - in X-ray binaries, 262
 - intermediate-mass, 272
 - Kerr, 243
 - Kerr–Newman, 225, 245, 246
 - known masses of, 532
 - miniature, 234
 - natal kick, 531
 - no-hair theorem, 225
 - observational evidence for, 257, 261, 275
 - origin of name, 214
 - prediction of, 214
 - quantum, 229
 - Reissner–Nordström, 225, 246
 - rotating, 243
 - Schwarzschild, 213
 - singularity theorems, 224, 258–260

- skepticism by Einstein and Eddington, 257
- sonic, 235
- spherical, 213
- static limit, 251
- supermassive in the cores of galaxies, 266, 275
- theorems and conjectures, 224
- thermodynamics, 236, 258
- water masers of NGC 4258, 270, 271, 532
- Blandford–Znajek mechanism, 280
- blazars, 295, 302
- boost transformations, 75
- Bose–Einstein statistics, 548
- boson condensation, 548
- branes, *see* superstrings and branes
- Brans–Dicke (scalar–tensor) theory of gravity, 541
- Bullet Cluster, 354

- cartesian product, 36, 45
- Casimir effect, 550
- causal structure of spacetime, 79, 80, 120
- causality and source size, 291, 311
- CDM (cold dark matter), *see* dark matter
- central engines, *see* black hole central engines
- Chandra deep field, 274
- Chandrasekhar limiting mass, 115, 193
- charge conjugation symmetry C , 457, 458
- Christoffel symbols, 58
 - are not tensors, 58, 59, 65
 - equivalence with connection coefficients, 135, 136
 - of the first kind, 59
 - of the second kind, 59
 - transformation law, 58
- Christoffel, Erwin, 136
- closed timelike loops, 81
- closure, 42
- CMB, *see* cosmic microwave background (CMB)
- collapsar model of gamma-ray bursts, 315
 - and long-period bursts, 315
 - and metallicity, 313
 - and Wolf–Rayet stars, 315
 - jets, 315
- common envelope evolution, 531, 532
- commutator, 39, 67
- comoving coordinates, 371
- comoving frame, *see* comoving observer
- comoving observer, 367, 371, 378
- compactification, *see* superstrings and branes
- concordance model, 406
- confinement of quarks and gluons, 419
- conformal factor, 376
- conformal time, 376, 377
- conformal transformation, 376, 385
- conformally flat spaces, 377
- congruence, 62, 63
- connection coefficients
 - and differential geometry, 140
 - and preservation of scalar product under parallel transport, 140
 - and tangent spaces, 135
 - compatibility demands, 140
 - determination from metric tensor, 140
 - equivalence with Christoffel symbols, 135, 136
 - for Friedmann cosmologies, 379
 - for Friedmann cosmologies (table), 380
 - interpretation of indices, 135
 - static solutions, 381
 - the affine connection, 135
 - uniqueness of the affine connection, 140
- contracted Bianchi identity, 150
- contravariant vectors, *see* vectors
- coordinate basis, 37–39
- coordinate curve, 37–39
- coordinate patches, 33
- coordinate systems, 14
 - basis vectors, 15
 - Boyer–Lindquist, 245
 - dual basis, 18
 - Eddington–Finkelstein, 218
 - euclidean, 14
 - Kruskal–Szekeres, 221
 - non-orthogonal, 18
 - orthogonal, 18
 - parameterizing, 14
 - spacelike components, 32
 - tangent basis, 16
 - timelike components, 32
- correlation function, 429
- cosmic censorship, 224
 - and extremal Kerr black holes, 246
 - and naked singularities, 224, 246, 259
- cosmic inflation, *see* inflation
- cosmic microwave background (CMB), 426
 - acoustic oscillations, 435, 436
 - acoustic scale, 436
 - adiabatic fluctuations, 437
 - and baryon acoustic oscillations, 438
 - and cosmological parameters, 405
 - anisotropies, 330, 373, 429
 - blackbody spectrum, 427
 - cause of temperature fluctuations, 433
 - COBE, 429
 - correlation function, 429
 - cosmological parameters (table), 441
 - decoupling time for photons, 427, 429
 - dipole component, 373
 - discovery, 427
 - fluctuations, 330, 405, 448
 - interpretation, 427
 - last scattering surface, 427, 429, 433
 - Planck satellite, 429
 - power spectrum, 432
 - precise measurement of cosmology parameters, 439

- cosmic microwave background (CMB) (cont.)
 - preferred angular scale, 437
 - preferred distance scale, 437
 - Sachs–Wolfe effect, 433, 435
 - seeds for structure formation, 441
 - sound horizon, 436
 - spectrum, 427
 - spherical harmonic expansion, 429
 - temperature, 330, 373, 427, 448
 - WMAP, 429
- cosmic time, 366, 367, 370
- cosmological constant, *see* dark energy; Friedmann cosmologies
- Cosmological Principle, 327, 448
- cosmological proper time, *see* cosmic time
- cosmology
 - and elementary particle physics, 329
 - closed universe, 343
 - concordance model, 406
 - Cosmological Principle, 327, 365
 - cosmological redshift, 327
 - critical density, 342
 - dark energy, 329, 382
 - dark matter, 329, 348
 - deceleration and density parameters, 361
 - deceleration parameter, 359
 - density parameters, 358
 - density parameters (table), 359
 - dominance of dark energy and dark matter, 444
 - energy densities (current), 398
 - energy densities and changes in scale, 389
 - evolution of scale factor with time, 344
 - expanding balloon analogy, 372
 - expansion governed by general relativity, 328
 - expansion interpretation of redshifts, 332
 - flat universe, 343
 - Friedmann cosmologies, 365
 - Hubble law, 327, 331
 - Hubble parameter, 327, 331, 337
 - Hubble radius, 376
 - Hubble time, 335
 - in Newtonian picture, 337, 341, 361, 383
 - inflationary, 453
 - lookback times, 346
 - most matter is not baryonic, 329
 - open universe, 343
 - possible expansion histories for dust model, 344
 - precision measurements of parameters, 439
 - the big bang, 329
 - the Universe is expanding, 327
 - the Universe is observed to be flat, 442
 - Type Ia supernovae and the accelerating Universe, 404
 - what is expanding?, 328
- cotangent bundle, *see* fiber bundle, cotangent bundle
- cotangent space, 36
- covariance, 32
 - manifest, 87
 - of Maxwell equations, 87
 - principle of general covariance, 106, 125
- covariant derivative, 26, 56, 58
 - and Christoffel symbols, 58
 - and connection coefficients, 135
 - and parallel transport, 61, 132, 134, 135
 - and vacuum energy, 61
 - implications, 61
 - is non-commuting operation, 60, 65
 - Leibniz rule for derivative of product, 60, 67
 - of metric tensor vanishes, 61
 - rules for, 60
- covariant vectors, *see* dual vectors (one-forms)
- covectors, *see* dual vectors (one-forms)
- CP symmetry, 457, 458
- CPT symmetry, 457, 458
- critical density, 342
- curvature
 - and dimensionality of spacetime, 149
 - and general covariance, 125
 - and tangent spaces, 35
 - density, 359, 390
 - distance intervals in curved spacetime, 129
 - Gaussian, 117, 126, 128
 - intrinsic and extrinsic, 117, 126, 149
 - of spacetime, 11, 126
 - radius of curvature, 126
 - Ricci flat spaces, 151
 - Ricci scalar, 150
 - Ricci tensor, 150
 - Riemannian curvature tensor, 148
 - vectors in curved space, 35
- curvature density Ω_k , 359, 390
- cyclic identity, 149
- Cygnus X-1, 267
- d'Alembertian operator
 - for electromagnetic waves, 87
 - for gravitational waves, 470
- dark ages, 422, 423
- dark energy
 - a property of space itself, 550
 - and acceleration of the scale factor, 358
 - and cosmological constant, 381
 - and evolution of the Universe, 329
 - and supersymmetry, 552
 - and the cosmic scale factor, 343
 - as vacuum energy, 382, 452, 549
 - equation of state, 358, 388, 550
 - summary, 442
 - vacuum energy for bosonic fields, 550
 - vacuum energy for fermionic fields, 552
- dark matter
 - and baryonic matter, 355

- and formation of structure, 442
- as remnant of big bang, 426
- baryonic matter, 356
- bulk of matter in Universe, 329
- can't be primarily baryonic matter, 356
- cold dark matter, 357
- cold dark matter and bottom-up structure, 442
- Coma Cluster, 350
- evidence for, 348
- galaxy rotation curves, 348
- gravitational lensing, 350
- hot dark matter, 357
- hot dark matter and top-down structure, 442
- hot gas in clusters of galaxies, 350
- in the Bullet Cluster, 354
- masses of large galaxy clusters, 349
- nonbaryonic candidates, 356
- summary, 442
- supersymmetry, 547
- WIMPS, 357
- de Sitter curvature precession,
 - see* geodetic precession
- de Sitter space, 392
- deconfinement of quarks and gluons, 419
- deflection of light in gravitational field
 - and equivalence, 110
 - elevator experiment, 110
 - gravitational curvature radius, 111
- density parameters Ω , 358
 - baryonic Ω_b , 355, 356, 441
 - cold dark matter Ω_{CDM} , 441
 - curvature Ω_k , 358, 359, 390
 - massive neutrino Ω_ν , 441
 - matter Ω_m , 358, 359, 390
 - radiation Ω_r , 358, 359, 390
 - vacuum energy Ω_Λ , 358, 359, 390, 441
- derivative, *see* differentiation
- differentiation
 - absolute, 58, 61
 - covariant, 58
 - in spaces with position-dependent metrics, 26
 - Lie, 62
 - of tensors, 49, 56
 - partial, 49, 57
- Dirac notation (quantum mechanics), 46
- direct product, *see* tensors, tensor product
- directional derivatives, 37–39
- Double Pulsar
 - as test of general relativity, 204
 - merger timescale, 204
 - orbit of, 204
 - origin of, 205
 - precession of periastron, 204
 - properties of, 204
- dragging of inertial frames, *see* frame dragging
- Dragonfly 44, 354
- dual vectors (one-forms), 49
 - and Dirac bra, 46
 - and row vectors, 43
 - as maps to real numbers, 21, 42
 - co-varying quantities, 50
 - defining in curved space, 21, 35
 - duality with vectors, 21, 42, 43, 51
- Eddington, Arthur, 115, 257, 381, 469
- Eddington–Finkelstein coordinates, 218
- Einstein equations
 - alternative form, 151
 - definition, 150, 151
 - finding solutions, 154
 - for general spherical metric, 569
 - in vacuum, 151
 - numerical solutions, 156
 - sign conventions, 154
 - solutions with high symmetry, 155
 - weak-field limit, 145, 155
- Einstein ring, *see* gravitational lensing
- Einstein summation convention, 20, 34
- Einstein tensor, 150
- Einstein–de Sitter universe, 348
- Einstein–Rosen bridge, 222, 223
- embedding
 - diagram, Schwarzschild metric, 164
 - not required to compute curvature, 130
- energy conditions in general relativity, 131
- energy–momentum tensor, *see* stress–energy tensor
- equation of state for universe, 387, 441
- equivalence principle, 10, 106
 - alternative statements, 109
 - and acceleration of Earth–Moon system by Sun, 107, 543
 - and Einstein's remarkable intuition, 11, 109
 - and event horizons, 230
 - and gravitational constant, 543
 - and lunar rangefinding, 107, 543
 - and Nordtvedt effect, 543
 - and Riemannian geometry, 117
 - and the path to general relativity, 110, 121
 - and weak-field solutions, 155
- deflection of light in gravitational field, 110
- Eötvös experiment, 107
- Eötvös parameter, 107
- elevator experiments, 108
- gravitational redshift, 112
- inertial and gravitational mass, 107
- local inertial frames, 118
- locality and tidal forces, 119
- principle of strong equivalence, 108, 109, 207
- strong equivalence and weak equivalence, 108
- ergosphere, 251
 - and Penrose processes, 253
 - motion of photons, 251

- ergosphere (cont.)
 - no stationary observers, 251
 - relation to horizon, 251
 - stationarity condition, 251
- Euler–Lagrange equation, 97, 98
- event horizons
 - and equivalence principle, 230
 - and lightcones, 216
 - area of, 247
 - cosmic censorship conjecture, 224
 - cosmological, 375, 376
 - for black holes, 213, 218, 245
 - in Eddington–Finkelstein coordinates, 220
 - in Kruskal–Szekeres coordinates, 223
 - Kerr spacetime, 245, 247
 - Schwarzschild spacetime, 213
- failed supernovae, 531, 533
- Fermi–Dirac statistics, 548
- Feynman diagrams, 418
- fiber bundle
 - and local gauge invariance, 35
 - as local product space, 36
 - base space, 36
 - cotangent bundle, 35, 36, 42
 - example of non-metric space, 26
 - fiber space, 36
 - for S^1 , 36, 37
 - tangent bundle, 35–37, 42
 - trivial and nontrivial, 36
- fluence, 306
- foliation of spacetime, 367
- formation of structure
 - cold dark matter and bottom-up formation, 442
 - hot dark matter and top-down formation, 442
 - inflationary explanation, 456
 - role of dark matter, 442
 - scale-invariant density fluctuation spectrum, 456
 - seeds from CMB fluctuations, 441
 - summary, 442
 - timescales, 442
- frame dragging
 - and impossibility of stationary observers, 251
 - and Lense–Thirring effect, 184, 186, 249
 - angular velocity of zero angular momentum particle, 250
 - in Kerr spacetime, 249
 - in Schwarzschild spacetime, 183, 186
 - measured by Gravity Probe B, 184
- Friedmann cosmologies, 365
 - a standard model, 390
 - calculation of observables, 392
 - calculations with benchmark parameters, 409
 - comoving observers, 378
 - concordance model, 406
 - conformal time and horizons, 376, 377
 - connection coefficients, 379
 - connection coefficients (table), 380
 - constant negative curvature, 369
 - constant positive curvature, 368
 - cosmological constant, 381
 - cosmological principle, 365
 - dark energy, 381, 382
 - de Sitter solution, 392
 - density parameters, 358, 359, 390, 441
 - Einstein equations for the RW metric, 378, 380
 - energy densities (current), 398
 - energy densities and scale factor, 389
 - equation of state, 387, 388
 - evolution of density components, 389
 - evolution of early Universe, 414
 - evolution of scale factor, 412
 - evolution of Universe, 386, 410
 - flat universes with radiation or matter, 396
 - flat, single-component universes, 391
 - fluid equation, 387
 - Friedmann (Einstein) equations, 380, 386, 389, 397
 - general solutions, 394
 - history of, 381
 - homogeneous, isotropic spaces, 366, 368
 - horizons, 396, 397
 - Hubble constant, 398, 402
 - matter energy density, 404, 413
 - matter-dominated equation of state, 412
 - numerical solution, 397
 - parameters of minimal model, 398, 402, 408
 - particle and event horizons, 374
 - proper distance, 373
 - pure matter universes, 399
 - pure radiation universes, 400
 - pure vacuum energy universes, 400
 - pure vacuum energy with curvature, 392
 - radiation energy density, 404, 413
 - radiation-dominated equation of state, 412
 - resolving Newtonian difficulties, 383
 - Ricci scalar, 380
 - Ricci tensor, 380
 - Robertson–Walker metric, 369, 370
 - single component with curvature, 399
 - single-component solution observables (table), 394
 - solution dominated by vacuum energy, 392
 - solution of evolution equations, 391
 - solution of minimal standard model, 397
 - solutions with multiple density components, 401
 - stress–energy tensor, 378
 - the universe is observed to be flat, 442
 - thermodynamics, 414
 - vacuum energy, 382
 - vacuum energy density, 404
 - variation of energy densities with scale, 389
 - visible Universe, 396
 - zero curvature, 369

- Friedmann, Alexander, 370, 381
 Friedmann–Lemaître–Robertson–Walker (FLRW) metric, *see* Robertson–Walker metric
 Friedmann–Robertson–Walker (FRW) metric, *see* Robertson–Walker metric
 functional, 98
 fundamental observer, *see* comoving observer
- gamma-ray bursts, 304
 afterglows, 308, 314, 522, 528
 and energy conservation, 311
 and gravitational waves, 204, 522
 and Kerr black holes, 281
 and multimessenger astronomy, 522
 and star-forming regions, 312
 association with core collapse supernovae, 312, 315
 association with galaxies, 312
 association with neutron star mergers, 315, 317, 522
 beamed emission, 311, 522, 528
 breaks in lightcurve, 311
 causality and source size, 311
 central engine, 315
 characteristics, 314
 collapsar model, 313
 cosmological origin, 314
 discovery, 304
 duration, 314
 fireball model, 308, 314
 fluence, 306
 isotropic distribution on sky, 314
 localization, 307, 522
 long-period, 281, 306, 314, 315
 long-period bursts and Wolf–Rayet stars, 312
 Lorentz γ -factor, 315
 nomenclature, 314
 nonthermal emission, 314
 off-axis emission, 528
 optical depth, 308
 power-law spectrum, 309
 short-period, 306, 314, 315, 522
 the gamma-ray sky, 304
- gauge transformations, 86
 choice of gauge in general relativity, 471
 comparison of electromagnetism and gravity, 472
 gauge-fixing constraint, 86
 in electromagnetism, 86
 in general relativity, 471
- gauge/gravity duality, *see* AdS/CFT correspondence
 Gauss, Karl Friedrich, 117
 Gaussian curvature, 128
 and circumference of circles, 128
 and the *Theorema Egregium*, 117
 generalization to Riemann curvature, 148
 intrinsic determination, 130
 intrinsic property of the space, 130
 gaussian fluctuations, 429, 456
- general relativity
 alternative theories of gravity, 541
 and Binary Pulsar, 200, 202
 and energy conservation, 132, 133
 and Newtonian gravity, 133, 145
 and PSR J0337+1715, 207
 and PSR J0348+0432, 205
 and spacetime symmetries, 132
 and the Double Pulsar, 204
 Bianchi identity, 150
 classical tests, 539
 deflection of light in gravitational field, 178, 539
 Einstein equations, 150, 151, 569
 Einstein equations for general spherical metric, 569
 Einstein tensor, 150
 gauge transformations, 471
 gravitational waves, 202, 465
 incompatibility with quantum mechanics, 554
 limiting cases of the Einstein tensor, 154
 linearized Einstein equations, 468
 modern tests, 540
 neutron stars, 193
 nonlinearity of gravity, 152, 466
 numerical relativity, 156
 parameterized post-Newtonian (PPN) method, 540, 542
 precession of orbits, 172, 174
 precession of perihelion for Mercury, 174, 539
 pulsar tests of, 200, 202, 204
 recipe for constructing, 147
 redshift of light in gravitational field, 113, 115, 539
 Ricci flat spaces, 151
 Ricci scalar, 150
 Ricci tensor, 150
 Riemannian curvature tensor, 148
 role of pressure, 133
 Schwarzschild solution, 159
 Shapiro time delay, 179, 352, 353
 sign conventions, 154
 solving the Einstein equations, 154
 stress–energy tensor, 129, 194
 summary of tests, 539
 systematically stronger than Newtonian gravity, 198
 testing in the strong-gravity limit, 466, 520, 544
 weak-field limit, 145, 155
 what couples to gravity?, 133
 wormholes, 161, 162
- geodesic equation, 138
 geodesic incompleteness, 258
 geodesics, 95
 and Killing vectors, 103
 and quantum uncertainty, 229
 euclidean space, 95
 Euler–Lagrange equation, 97
 geodesic equation, 138, 180

- geodesics (cont.)
 - incompleteness, 258
 - Minkowski space, 95
 - photons and massless particles, 98
 - principle of extremal proper time, 96
 - quantities conserved along, 103
- geodetic precession
 - and de Sitter curvature precession, 180–182, 184
 - measured by Gravity Probe B, 182–184
 - of Earth–Moon “gyroscope”, 181
 - of gyroscopes in orbit, 180
 - tested by lunar ranging, 181
- geometrical object, 15, 44
- geometrized units, 92, 565, 566
- geometry
 - and metric tensor, 26
 - euclidean, 14
 - non-euclidean, 27
- global positioning system, *see* GPS and relativity
- global topological techniques, 258, 259
- GP-B, *see* Gravity Probe B
- GPS and relativity, 122
- Grand Unified Theories (GUTS)
 - and baryogenesis, 459
 - baryon nonconserving reactions, 459
- gravitational charge, 185
- gravitational curvature radius
 - and deflection of light, 111
 - and strength of gravity, 111, 122
- gravitational lensing, 350
 - and dark matter, 350, 354
 - by black holes, 513
 - Einstein cross, 351, 352
 - Einstein ring, 277, 513
 - in the Bullet Cluster, 354
 - microlensing, 351
- gravitational mass, 199
- gravitational redshift
 - and energy conservation, 122
 - as a time dilation, 115
 - weak-field limit, 112
- gravitational time dilation
 - and GPS, 122
 - weak-field limit, 115
- gravitational waves, 465
 - a new window on the Universe, 521
 - amplitudes, 491
 - amplitudes and event rates, 492
 - and asymmetric gravitational collapse, 259
 - and gamma-ray bursts, 204
 - and late stellar evolution, 531
 - and mass of graviton, 521
 - approximate energy densities, 489
 - as a test of general relativity, 466, 544
 - as probe of dark events, 467
 - as standard sirens, 512, 527
 - as test of strong gravity, 205, 520
 - coherence, 477
 - comparison with electromagnetic polarization, 475
 - comparison with electromagnetic waves, 476
 - detection technology, 468
 - emission from pulsar–white dwarf binary PSR J0348+0432, 205
 - frequency, 484
 - from Binary Pulsar, 202, 497
 - from binary system, 494
 - from contact binary, 491
 - from core collapse supernovae, 503
 - from merger of black hole binaries, 502, 506, 510, 532
 - from merger of black-hole, neutron star binary, 503
 - from merger of supermassive black holes, 504
 - from neutron star mergers, 318, 500, 522
 - from weak sources, 489
 - GW150914, 465, 506, 521, 532, 544
 - GW150914 source location, 508
 - GW150914 waveform, 506
 - GW151226, 514, 521
 - GW170104, 519, 521
 - GW170814, 519–521
 - helicity components, 474
 - history of idea, 469
 - influence on binary orbit, 496
 - laser interferometer detectors, 480
 - LIGO, 480
 - linearized Einstein equations, 468
 - linearized Einstein equations with sources, 490
 - luminosity from binary systems, 494
 - matched filter technique, 477, 506, 515, 518
 - multimessenger astronomy, 483, 522
 - multipolarity of, 490
 - no monopole or dipole, 490
 - polarization tensor, 473
 - power, 493
 - pulsar timing arrays, 484
 - quadrupole formula for power, 493
 - ranges of detectable strains and frequencies, 483
 - ratio of wavelength to source size, 476
 - reduced quadrupole tensor, 493
 - response of test masses, 477, 479
 - significance, 465
 - spectrum, 465, 466
 - states of polarization, 473, 480
 - strain, 477, 479, 484, 493, 505–507
 - strong-field sources, 500
 - template waveforms, 504
 - testing nonlinearity of general relativity, 466
 - the deepest probe, 467
 - trace-reversed amplitude, 472
 - transverse–traceless (TT) gauge, 473
 - weak-field, 473
 - weak-field solution in TT gauge, 474
- gravitomagnetic effects, 185
- graviton, 152, 383, 475, 477, 521, 554

- Gravity Probe B
 and frame dragging, 183, 184
 and geodetic precession, 182–184
- GRB, *see* gamma-ray bursts
- Grossmann, Marcel, 118
- GUTS, *see* Grand Unified Theories (GUTS)
- GW150914, 506
 properties of (table), 511
 source location, 508
 test of strong-gravity general relativity, 520
 waveform, 506
- GW170817, 522
- gyroscopes
 and gravitomagnetic effects, 180
 and rotating spacetime, 183
 gyroscopic equation, 180
- Harrison–Zel’dovich spectrum, 456
- Hawking area theorem, 224, 247, 258
- Hawking black holes, 229, 235
 and information, 239
 and quantum fluctuations, 231
 blackbody temperature, 232
 endpoint of evaporation, 239
 entropy, 236
 generalization of area theorem, 236
 generalized second law of thermodynamics, 236
 mass emission rates, 232
 surface gravity, 232
 temperature, 236
 thermodynamics, 236
- Hawking radiation, 230, 235
- Heisenberg uncertainty principle, 456, 554, 559
- Hertzprung gap, 532
- Hilbert space, 46
- Hilbert, David, 11, 109
- HMXB, *see* binary star systems - high-mass X-ray binaries (HMXB)
- holographic principle
 and black holes, 240
 and information, 240
 and the Universe, 240
- holonomic basis, *see* coordinate basis
- horizons
 analog, 235
 apparent, 260
 event horizons, 375, 376
 horizon problem in big bang, 449
 particle horizons, 375
 relationship of particle and event horizons in cosmology, 378
- Hubble expansion, 327
- Hubble law, 331
 and expansion interpretation of redshifts, 332, 448
 and Friedmann cosmology, 409
 and scale factor, 331
 deviations from, 409
 Hubble parameter, 331, 337, 402, 528
 Hubble radius, 376
 Hubble time, 335
 Hubble, Edwin, 381
 Hulse–Taylor binary, *see* Binary Pulsar
 hypersurface, 33
- indefinite metric, 69
- inflation, 453
 and density fluctuations, 442, 456
 and elementary particle physics, 454
 and flatness of the Universe, 444
 and flatness problem of big bang, 451
 and formation of structure, 452, 456
 and gaussian fluctuations, 456
 and horizon problem of big bang, 449
 and monopole problem of big bang, 451
 consequences of, 454
 expansion in de Sitter phase, 453
 exponential growth of scale factor, 453
 gaussian fluctuations, 429
 modifies but does not replace big bang, 457
 scale-invariant density fluctuation spectrum, 456
 solution of the flatness problem, 455
 solution of the horizon problem, 455
 solution of the monopole problem, 456
 versions of, 454
- inflationary cosmology, *see* inflation
- information
 and black holes, 239
 and entropy, 239
 and the holographic principle, 240
- inhomogeneous Lorentz transformations, *see* Poincaré transformations
- innermost stable circular orbit (ISCO)
 binding energy, 283
 Kerr solution, 283
 Schwarzschild solution, 172
- integration
 area of 2-sphere by invariant integration, 57
 covariant volume element, 56
 invariant, 26, 56
 of tensors, 56
- intrinsic derivative, *see* absolute derivatives
- inverse Compton scattering, 303
- ISCO, *see* innermost stable circular orbit (ISCO)
- isometries
 Kerr metric, 244
 Killing vectors, 64, 100, 166
 quantities conserved along geodesic, 103
 Schwarzschild metric, 166
- Jacobian determinant, 56
- Jacobian matrix, 51
- jets
 and rotating magnetic fields, 285
 apparent superluminal motion, 285

- jets (cont.)
 collapsar model, 315
 counterjets, 285
 from AGN, 292
 from quasars, 290
 Lorentz γ -factor, 315
 radio jets from Centaurus A, 302
 radio jets from NGC 4258, 270
 relativistic beaming, 285
- Kerr black holes
 accretion, 283
 and gamma-ray bursts, 304
 and Penrose processes, 253
 area of event horizon, 247
 as central engines, 280
 extremal, 245
 extremal and cosmic censorship, 246
 observational evidence for extremal, 246
 source of quasar power, 290
- Kerr spacetime, 243
 asymptotically flat solutions, 244
 Boyer–Lindquist coordinates, 245
 ergosphere, 251
 event horizons, 247
 frame dragging, 249
 interpretation of parameters, 244
 metric, 243
 motion of light in, 248
 motion of particles in, 248
 reduction to Schwarzschild solution, 244
 singularity and horizon structure, 245
 solutions of, 243
 symmetries and Killing vectors, 244
 vacuum solutions, 244
- Killing vectors, 101
 and isometries, 100
 and Lie derivatives, 64, 101
 and spacetime symmetries, 244
 for the Kerr metric, 244, 248
 for the Schwarzschild metric, 166, 230
 spacelike or timelike character, 230, 254
- kilonova, 526, 528, 529
 Kretschmann scalar, 227
 Kronecker delta, 22, 23, 41, 43, 51
 Kronecker product *see* tensors, tensor product
 Kruskal diagrams, 221
 Kruskal–Szekeres coordinates, 221
- Lagrangian, 98
 lanthanides and opacity, 528
 last scattering surface, *see* cosmic microwave background (CMB)
 Lemaître, Georges, 370, 381
 Lense–Thirring effect, *see* frame dragging
 leptogenesis, 459
- Levi-Civita connection, *see* connection coefficients
 Levi-Civita symbol, *see* completely antisymmetric 4th-rank tensor
 Levi-Civita, Tullio, 136
 Lie bracket, 39, 67
 Lie derivative, 62
 and covariant differentiation, 58
 and Killing vectors, 64, 101
 contrasted with covariant derivative, 58, 63
 explicit expressions, 63
 isometries, 64
 Lie transport, 64
 more primitive than covariant derivative, 64
 switching partial and covariant derivatives, 64, 68, 101
- Lie dragging, 63
 Lie transport, 64
 LIF, *see* local inertial frame (LIF)
 lightcone, 77
 and causality, 79, 80, 120, 216
 and simultaneity, 78
 and the constant speed of light, 79
 for black hole spacetimes, 216
 global organization of lightcones, 120
 in Eddington–Finkelstein coordinates, 219
 in general relativity, 120
 in Kruskal–Szekeres coordinates, 223
 invariance of, 216
 lightlike intervals, 84
 null intervals, 84
 spacelike intervals, 84
 lightlike intervals, *see* lightcone, null intervals
 LIGO, 480, 482
 line element, 24
 euclidean, 25
 for plane polar coordinates, 25
 in curved space, 129
- local inertial frame (LIF), 109, 118–121, 138
 lookback times, 346
 Lorentz covariance
 and special relativity, 69
 of Maxwell equations, 84
 Lorentz factor
 for gamma-ray bursts, 311
 in special relativity, 77
 Lorentz transformations, 7, 73
 and spacetime diagrams, 80
 as rotations in Minkowski space, 74
 boosts between inertial systems, 74, 75, 77, 82
 Lorentz group, 125, 127
 spatial rotations, 74
 Lorentzian manifold, 71
 LS (last scattering), *see* cosmic microwave background (CMB), last scattering surface
 LSS (last scattering surface), *see* cosmic microwave background (CMB), last scattering surface

- luminosity distance, 406, 433, 434
 lunar rangefinding, 107, 543
- macronova, *see* kilonova
- magnetic fields
 and jets, 285
 and rotating black holes, 285
 Blandford–Znajek mechanism, 280
- magnetic monopoles
 and inflation, 451
 and magnetic charge for black holes, 225
- manifold, 33
 atlas, 33
 charts, 33
 coordinate patches, 33
 differential, 33
 geodesically complete, 222, 259
 maximal, 222
 Riemannian, 33, 116
 spacetime, 32
- mapping, 21
- mass
 as gravitational charge, 185
 equivalence of active and passive, 124
 equivalence of gravitational and inertial, 107, 123
- mass function, 262, 263, 265–267
- matched filtering, 506, *see* gravitational waves
- Maxwell equations, 84
 and aether, 6
 and Galilean invariance, 6
 covariance, 87
 gauge transformations, 86
 in Heaviside–Lorentz units, 84
 Lorentz covariance, 84
 scalar and vector potentials, 85
- Mercator projection, 83, 304, 376
- metallicity
 and formation of massive binaries, 530, 531
 and gamma-ray bursts, 312
 and photon opacity, 312, 531
- metric
 indefinite, 71, 76
 Kerr, 243
 pseudo-Riemannian, 116
 Riemannian, 116
 Robertson–Walker, 369, 370
 Schwarzschild, 159
 signature, 9, 119
 slowly-rotating, 183
 static, 160, 244
 stationary, 160, 244
 symmetries of (isometries), 64, 100
- metric space, 26
- metric tensor, 53, 54
 and geometry of space, 26
 and line element, 24, 53
 and scalar products, 70
 as gravitational potential, 139
 as source of gravitational field, 139
 connection coefficients computed from, 140
 contravariant components, 23
 covariant components, 23
 covariant derivative vanishes, 61
 for Schwarzschild spacetime, 159
 in euclidean space, 23
 in Minkowski space, 70
 indefinite metric, 69
 Kerr, 243
 properties, 23
 quantum fluctuations of, 556
 signature, 71
 singularities, 160
 used to raise and lower indices, 53, 54, 71
- Michelson–Morley experiment, 7
- Minkowski space, 69
 4-velocity and 4-momentum, 94
 and causality, 79
 and spacetime, 8
 event, 71
 geodesics, 95
 indefinite metric, 69
 invariance of spacetime interval, 71
 lightcone structure, 77
 lightlike intervals, 84
 line element, 8, 70
 Lorentz transformations, 73
 Lorentz-invariant dynamics, 95
 metric signature, 9, 71
 metric tensor, 8, 70
 null (lightlike) intervals, 78, 84
 observers, 99
 rotations, 76
 scalar product, 70
 spacelike intervals, 78, 84
 tensors, 72
 timelike intervals, 78
 worldline, 71, 94
- Minkowski, Hermann, 8, 118
- Mollweide projection, 304
- multimessenger astronomy, 483, 522
- naked singularities, *see* cosmic censorship
- natural units, *see* geometrized units
- neutrinos
 cosmic neutrino background, 427
 decoupling scale, 418
 leptogenesis, 459
- neutron stars, 193
 equation of state from gravitational waves, 522
 formation of binary neutron stars, 203
 gravitational mass and baryonic mass, 199

- neutron stars (cont.)
 - interpretation of mass parameter, 198, 199
 - mass and density, 193
 - Oppenheimer–Volkov equations, 196
 - pulsars, 200
 - simple estimates, 193
 - size, 193
 - solution of Einstein equations, 194–196
 - stress–energy tensor, 194
- NGC 4258, 270, 532
- no-hair theorem, 225
- Nobel Prizes for relativity, 203
- Noether’s theorem, 102
- non-coordinate basis, 37–39
- nonthermal emission, 287
 - from AGN, 292
 - from gamma-ray bursts, 308, 314
 - from quasars, 288
 - implications of, 287
 - polarization, 287
 - requires optically-thin medium, 309
 - synchrotron radiation, 287
- Nordtved effect, 543
- null energy condition, 131
- numerical relativity, 12, 156
 - 3+1 formalism, 156
 - and apparent horizons, 260
 - and initial data, 156
 - and strong gravity, 156
 - matched filter waveforms, 517
 - plagued initially by instabilities, 534
 - simulation of GW150914, 506, 507, 512
 - simulation of GW151226, 515
- observers, 99
 - comoving, 367, 371
 - inertial observers, 118
 - no stationary in ergosphere, 251
- one-forms, *see* dual vectors (one-forms)
- Oppenheimer–Volkov equations, 196
 - differences from Newtonian hydrostatics, 197
 - interpretation, 197
- optical depth
 - altered by relativity, 311
 - and opacity, 310
 - definition, 310
 - in gamma-ray burst, 308, 309
- parallel transport, 134
 - and absolute derivative, 136
 - and connection coefficients, 135
 - and covariant derivative, 135
 - dependence on path, 134
- parameterization
 - of curves, 15
 - of surfaces, 15
- parameterized post-Newtonian (PPN) formalism, 515, 540, 542
- parity symmetry P, 457, 458
- Pauli exclusion principle, 548
- Penrose processes, 237, 253
- perfect cosmological principle, 327
- periapsis, 268
- Planck scale, 238
 - and initial singularity, 258
 - breakdown of current physical laws?, 338, 558
 - Planck era, 338, 553
 - Planck scale parameters (table), 554
 - quantum gravity, 238, 338, 553
- Poincaré transformations, 125, 127, 139
- Poisson equation, 145
- Pop III stars, 423, 531, 534
- Pound and Rebka experiment, *see* redshift, gravitational for Earth
- PPN, *see* parameterized post-Newtonian (PPN) formalism
- preferred frames of reference, 373
- principle of extremal proper time, 96
- principle of general covariance, 106
- principle of relativity, 5, 10, 32
- principle of strong equivalence, 109
- proper time, 70
- pseudo-euclidean manifold, *see* Lorentzian manifold
- pulsars, 200
 - as test of general relativity, 200, 202
 - Binary Pulsar, 200, 202
 - discovery, 257
 - nomenclature, 200
 - pulsar–WD–WD triplet PSR J0337+1715, 207
 - pulsar–white dwarf binary PSR J0348+0432, 205
 - the Double Pulsar, 204
- QSOs, *see* quasars
- quantum gravity, 238, 553
 - and renormalization, 554
 - and superstrings, 554
 - and the Planck scale, 553
 - inconsistency of quantum mechanics and general relativity, 554
 - quantum fluctuations of the metric, 556
 - superstrings and branes, 556
 - the Universe as a quantum fluctuation of the spacetime metric, 557
- quantum mechanics
 - and black holes, 229, 258
 - and dark energy, 549
 - and geodesics, 229
 - and gravity, 238
 - and Hawking radiation, 230
 - fermions and bosons, 548
 - Feynman diagrams, 418
 - incompatibility with general relativity, 554

- quantum gravity, 553
- quantum vacuum fluctuations in inflation, 456
- renormalization of quantum field theory, 554
- vacuum fluctuations, 231, 549, 557
- zero-point energy, 550, 551
- quasars, 285
 - black hole central engines, 257, 290
 - characteristics, 288
 - discovery and interpretation, 288
 - energy source, 295
 - evolution of density with time, 289, 301
 - jets, 290, 315
 - Lorentz factors of, 315
- quasistellar objects, *see* quasars
- quasistellar radio sources, *see* quasars
- quotient theorem, 66, 67
- r-process
 - heavy r-process nuclei, 528, 529
 - in neutron star mergers, 528, 529
 - kilonova, 528, 529
 - light r-process nuclei, 528, 529
- radio galaxies, 292
- recombination transition, 422
- redshift
 - and deceleration of Universe, 359
 - as a time dilation, 115
 - cosmological, 327, 331
 - expansion interpretation, 332
 - for Schwarzschild solution, 165
 - gravitational, 112, 113, 115
 - gravitational for Earth, 114, 123
 - gravitational for Sirius B, 114, 115
 - measuring for white dwarf, 115
 - near a black hole, 218
 - weak-field limit, 167
- reionization transition, 422, 423
- relativity principle, *see* principle of relativity
- repeated indices, *see* Einstein summation convention
- Ricci flat space, 151
- Ricci scalar, 150
- Ricci tensor, 150
- Riemann zeta function, 415
- Riemann, Bernhard, 117
- Riemannian curvature tensor, 148
 - and Gaussian curvature, 149
 - as commutator of covariant derivative, 157
 - dependence on dimensionality, 149
 - symmetries, 148
- Riemannian manifold, 116
 - and the equivalence principle, 117
 - locally euclidean, 116
- Robertson, Howard, 370
- Robertson–Walker metric
 - a consequence only of geometry, 371
 - and cosmological principle, 370
 - and event horizons, 376
 - and Hubble law, 371, 374
 - and line element for homogeneous, isotropic spacetime, 369, 370
 - and particle horizons, 375
 - comoving coordinates, 371
- RW metric, *see* Robertson–Walker metric
- S0-102, *see* Sgr A*
- S0-2, *see* Sgr A*
- Sachs–Wolfe effect, *see* cosmic microwave background (CMB)
- Sakharov conditions for baryon asymmetry, 457
- scale factor of Universe, 331–333, 335, 370–372, 412
- scale-invariant density fluctuations, 456
- Schwarzschild black hole, 213
 - area of event horizon, 247
 - event horizon, 213, 215
 - lightcone diagrams, 216
- Schwarzschild metric, *see* Schwarzschild spacetime
- Schwarzschild spacetime, 159
 - asymptotically flat solutions, 159
 - classes of orbits, 169
 - conserved quantities, 167
 - coordinate distance, 163
 - coordinate time, 164
 - deflection of light by gravity, 178
 - Eddington–Finkelstein coordinates, 218
 - embedding diagrams, 164
 - escape velocity, 174
 - form of metric, 159
 - gravitational redshift, 165
 - innermost stable circular orbit, 172
 - interpretation of radial coordinate, 160, 161
 - isometries, 166
 - Killing vectors, 167
 - Kruskal diagrams, 221
 - Kruskal–Szekeres coordinates, 221
 - lightcones, 216
 - orbits for light rays, 177
 - particle orbits, 167–169
 - physical distance and time, 162
 - precession of orbits, 172, 174
 - proper distance, 163
 - proper time, 164
 - radial fall of test particle, 175
 - Shapiro time delay, 179
 - singularities of the metric, 160, 176
 - solution, 159
 - vacuum solutions, 159
- seeds for structure formation in early Universe, 441
- Seyfert galaxies, 293
 - brightness variability, 294
 - Seyfert 1 galaxies, 294
 - Seyfert 2 galaxies, 294

- Sgr A*
 - and the star S0-102, 269
 - and the star S0-2, 268, 532, 544
 - evidence for a supermassive black hole, 268
 - testing general relativity, 544
 - testing the no-hair theorem, 269
- Shapiro time delay, 179, 352, 353
- singularities
 - and cosmic censorship, 246
 - and Eddington–Finkelstein coordinates, 218
 - and global topological techniques, 258, 259
 - and Kruskal–Szekeres coordinates, 221
 - coordinate, 162
 - initial cosmological, 329
 - naked, 246
 - of Kerr spacetime, 245
 - of Schwarzschild metric, 160, 176, 218, 221
 - physical, 162
 - theorems, 224, 258, 259, 261
- singularity theorems, 224, 258, 259, 261
- Slipher, Vesto, 381
- Sloan Digital Sky Survey (SDSS), 408, 438
- sonic black holes, 235
- sound horizon, *see* cosmic microwave background (CMB)
- space
 - anti-de Sitter, 558
 - de Sitter, 392, 453
 - dimensionality and curvature, 149
 - metric, 26
 - Minkowski, 8, 69
 - non-metric, 26
 - Ricci flat, 151
 - Riemannian, 116
 - spacetime foam, 556
 - with wormholes, 556
- spacelike surface, 78, 258
- spacetime foam, 556
- special relativity
 - and Lorentz covariance, 69
 - event, 71
 - Lorentz γ -factor, 315
 - Lorentz transformations, 73
 - proper time, 70
 - relativity of simultaneity, 78, 82
 - space contraction, 82
 - time dilation, 72, 82
 - twin paradox, 82
 - worldline, 71
- spectral index, 308
- standard and standardizable candles
 - Cepheid variables, 404
 - Type Ia supernovae, 404
- standard candle, 434
- standard cosmological model, 327
- Standard Model of elementary particle physics
 - GUT extension, 459
 - magnetic monopoles, 451
 - particles important for big bang, 419
 - particles of (table), 417
 - role in cosmology, 329
- standard ruler, 434
- standard sirens, 512, 527
- stress–energy tensor, 129
 - energy conditions, 131
 - for comoving Robertson–Walker observer, 378
 - perfect fluid, 143, 194
- strong energy condition, 131
- structure formation, *see* formation of structure
- summation convention, *see* Einstein summation convention
- superluminal motion (apparent), 90, 285
- supermassive black holes
 - energy source for quasars and AGN, 290
 - evidence for, 266, 268–270, 272, 273, 275
 - heavy seeds model of formation, 274, 534
 - light seeds model of formation, 274, 534
 - relationship with stellar black holes, 534
- supernovae
 - as standard candles, 405
 - association with gamma-ray bursts, 312
 - lightcurves, 317
 - Type Ia, 405
 - Type Ib, 312
 - Type Ic, 312
- superstrings and branes, 554
 - brane theory, 555
 - compactification, 559
 - experimental tests of, 557
 - number of spacetime dimensions, 556, 559
 - quantum gravity, 556
 - superstrings, 555
- supersymmetric particles, 549
- supersymmetry
 - and dark matter, 547
 - and new particles, 549
 - broken, 549
 - no experimental evidence for, 549
 - symmetry uniting fermions and bosons, 549
- surface gravity, 232
- symmetries
 - group theory, 127
 - isometries, 100
 - isotopic spin, 548
 - Killing vectors, 100, 101, 166
 - Lorentz group, 125, 127
 - Noether’s theorem, 102
 - non-supersymmetric, 548
 - of the metric, 100, 166
 - Poincaré group, 125, 127
 - solution of the Einstein equations for high symmetry, 155

- spontaneously broken or hidden symmetry, 550
 supersymmetry, 547
- tangent bundle, *see* fiber bundle, tangent bundle
 tangent space, 35–37
 and parallel transport, 35, 134
 and vectors in curved space, 35
- tensor density, 52
- tensors
 and covariance, 32
 and form invariance of equations, 64
 antisymmetric (skew symmetric), 54
 antisymmetrizing operation, 54
 as linear maps, 41, 42, 45, 46
 as operators, 41
 calculus, 56
 completely antisymmetric 4th-rank tensor, 52
 contravariant, 41
 covariant, 41
 defined by their transformation law, 41, 48, 52
 differentiation, 56
 dual vectors (one-forms), 49
 Einstein summation convention, 20, 34
 Einstein tensor, 150
 higher-rank, 52
 horizontal placement of indices, 53
 in linear algebra, 43
 in Minkowski space, 72
 in quantum mechanics, 43, 46
 index-free formalism, 41, 42, 45, 46
 integration, 56
 Kronecker delta, 41
 metric tensor, 53, 54
 mixed, 41
 rank, 40
 rank-2, 52
 Riemann curvature, 52
 scalars, 48
 symmetric, 54
 symmetrizing operation, 54
 tensor density, 52
 tensor product, 45
 torsion, 140
 transformation laws (table), 52
 type, 40, 45, 67
 vectors, 48, 49
 vertical placement of indices, 18, 20, 32, 34
Theorema Egregium, 117
 tidal forces, 119, 120
 time machines, *see* time travel
 time travel, 80, 81, 162, 346, 552
 Tolman–Oppenheimer–Volkov equations, *see*
 Oppenheimer–Volkov equations
 topological defects and magnetic monopoles, 452
 torsion, 140
 TOV equations, *see* Oppenheimer–Volkov equations
- trace-reversed amplitude, 472
- transformations, 14
 active, 63
 between coordinate systems, 28
 between inertial systems, 5
 boosts, 75
 Galilean, 5, 29
 gauge in electromagnetism, 86
 Lie dragging, 63
 Lorentz, 7, 30
 of derivatives, 40
 of fields, 40
 of integrals, 40
 of scalars, 48
 of vectors, 49
 passive, 34
 Poincaré, 125, 127
 rotations, 29
 rotations in euclidean space, 73
 rotations in Minkowski space, 74
 spacetime, 34
 vectors, 49
- transverse–traceless gauge, 473
- trapped surfaces, 258–260
- TT gauge, *see* transverse–traceless gauge
- twin paradox, 82
- Type Ia supernovae
 and the accelerating Universe, 404
 as standardizable candles, 404
 lightcurves, 405
 measuring large distances with, 404
- UDG, *see* ultra-diffuse galaxies (UDG)
- ultimate free lunch, 557
- ultra-diffuse galaxies (UDG), 354
- unified model of AGN and quasars, 295
 accretion disk and dusty torus, 299
 anisotropic ionization cones, 298
 black hole central engine, 297, 299
 effect of orientation, 300
 high-velocity clouds and broad emission lines, 299
 low-velocity clouds and narrow emission lines, 299
 relativistic jet outflow, 299
- vacuum energy, *see* dark energy
- vacuum solutions
 gravitational waves, 468
 Kerr spacetime, 244
 Schwarzschild spacetime, 159
- vector space, 21, 42
- vectors, 49
 and column vectors, 43
 and Dirac ket, 46
 and tangent spaces, 35
 angle between two vectors, 385
 as geometrical objects, 15

- vectors (cont.)
 - as maps to real numbers, 21, 42
 - contra-varying quantities, 50
 - defining in curved space, 21, 35
 - dual vector spaces, 21, 42, 43
 - dual vectors, 49
 - duality with dual vectors, 21, 42, 43, 51
 - expansion in basis, 20
 - scalar product, 20, 51
 - vector space, 21, 42
- vertical position of indices, *see* Einstein summation convention
- virial theorem
 - and weak gravitational waves, 492
 - applied to galaxies, 272
 - evidence for supermassive black holes, 273
 - for a set of stars, 270
 - mass of large galaxy clusters, 349
 - virial masses, 274
- visible Universe, 396
- VLBA, 276
- Walker, Arthur, 370
- warp drives, 552
- weak energy condition, 131
- white holes, 222, 235
- Wolf–Rayet star, 312–315, 317
- wormholes, 161, 162, 222, 223, 552, 556
- Yukawa potential, 544
- zero age main sequence (ZAMS), 532