

Index

- 4-flux, in a dust cloud, 45
- 4-momentum, 33
- abstract index tensor notation, 181
- action
 - as integral of Lagrangian, 55
 - definition, 53
- AdS/CFT correspondence, 189
- affine connection, 69
- affine parameters, 65
- angular diameter distance, 180
- antisymmetric tensor, 39
- arrow, of vector, 32
- atomic structure, and smoothness, 2
- azimuth, in spherical coordinates, 40
- basis vector
 - cartesian, 20
 - expression for, 22
 - operator form for, 184
 - plane polar coordinates, 22
 - unit, 41
- bending of light in a gravitational field, 18, 124
- Bianchi identities, 95
- Breit frame, 64
- calculus of variations, 53
- chain rule, of partial derivatives, 40
- Christoffel symbols, 69
- colatitude, in spherical coordinates, 40
- conformal field theory – anti-de Sitter space
 - correspondence, 189
- connection coefficients, 69
- conserved quantities, 66
- contraction, of tensors, 35
- contravariant tensor, 180
- coordinate system, definition, 19
- coordinate transformation, 5
 - space-time, 31
- coordinates
 - plane hyperbolic, 39
 - spherical polar, 40
 - spherical shell, 40
- cosine rule, spherical trigonometry, 17
- cosmological constant, in FRW cosmology, 147
- cosmological principle, 131
- cosmological redshift, 132, 133
- cosmology, further reading, 190
- covariant derivative, 71
- covariant tensor, 180
- curvilinear coordinates, 19, 20
- cyclic coordinates, 66
- delta, Kronecker, 37
- derivative
 - definition of, 2
 - of metric coefficients, 75
- diagnostic quiz, 16
- differentiable curves, 1
- differentiation, of tensor components, 67
- divergence, of stress–energy tensor, 51
- divergence-free tensors, 51
- dust, 43
 - 4-flux of, 45
 - energy and momentum of, 46
 - stress–energy tensor of, 46
- East Coast, metric convention, 180
- Eddington–Finkelstein coordinates, 124
- Einstein summation convention, 15, 20
- Einstein telescope, 188
- Einstein tensor, for FRW cosmology, 141
- Einstein’s equations, 143
 - up to a constant, 97
- elastic band, stretched, 8, 20, 53
- elevator in free fall, 13, 18
- emergent theory of gravity, 4
- energy conservation, and the stress–energy tensor, 50
- energy–momentum–mass relation, 34
- energy–momentum–stress tensor
 - of dust, 46
 - physical meaning of components, 50
- equation of motion, deduction from conserved
 - quantities and invariants, 67
- equivalence, principle of, 13

- Euler–Lagrange equations, 53, 55, 59
 - in classical mechanics, 59
- exact solutions, of Einstein’s equations, 188
- expansion, Taylor, 5
- experiments in gravitation, 188
- four momentum, 33
- Friedmann equation, 143
- Friedmann–Lemaître–Robertson–Walker metric, *see* FRW cosmology, 131
- FRW cosmology
 - acceleration equation, 146
 - Christoffel symbols, 137
 - comoving and lab coordinates, 144
 - comparison with related Newtonian problem, 142
 - Einstein tensor, 143
 - fluid equation, 146
 - Friedmann equation, 146
 - Lagrangian for, 135
 - Ricci scalar, 140
 - Ricci tensor coefficients, 140
 - Riemann tensor coefficients, 138
- gauge, transverse traceless, 155
- geodesic, 4, 8, 53
- geodesic equations, derivation, 76
- gravitational wave
 - action on single interferometer arm, 162
 - analysis of $\times$ polarisation, 176
 - cavity pole, 173
 - cavity storage time, 173
 - Christoffel symbols, linearised, 153
 - detectors, 187
 - directions of accelerations, 159
 - distortion of ring of test masses, 162
 - Einstein’s equations for, 152
 - equation, 154
 - laboratory coordinate manifestation, 158
 - Michelson interferometer, 166
 - nuisance paramters, 163
 - offset locking of interferometer, 168
 - optical storage cavities, 170
 - orthogonal $+$ and $\times$ polarisations, 161
 - polarisation rotation in racetrack detector, 177
 - polarisations of, 160
 - radiation pressure noise, 178
 - response of Michelson interferometer, 167
 - round-trip travel time down one interferometer arm, 164
 - simplified Einstein’s equations for, 153
 - simplified interferometer layout, 162
 - technical noise in interferometers, 165
 - transverse traceless gauge, 157
 - transverse traceless metric coefficients for, 155
- Gravity Probe B, 187
- Higgs boson, and massive particles, 3
- homogeneity, isotropy of FRW space-time, 131
- hyperbolic coordinates, plane, 39
- index-free tensor notation, 181
- inertial observer, 13, 19
- integration by parts, in derivation of Euler–Lagrange equations, 57
- interval, Lorentz invariant, 11
- invariants, use to find equations of motion, 67
- inverse, metric, 37
- Kerr metric, 123
- Killing vectors, 67
- Kronecker delta, 37, 41
- Kruskal–Szekeres coordinates, for the Schwarzschild geometry, 116
- Lagrangian
 - differential with respect to parameter on curve, 60
 - for geodesic world lines in space-time, 63
 - for photons and other massless particles, 64
 - mechanics, 53
 - tensor expression for, 62
- latitude, line of constant, 18
- Levi-Civita tensor, 42
- lift, free fall, 13, 18
- light beam, Lagrangian for, 64
- longitude, in spherical coordinates, 40
- Lorentz boost, of the stress–energy tensor in cosmology, 51
- Lorentz contraction, relative to dust reference frame, 44
- Lorentz invariant interval, 11
- Lorentz transformation, 10, 30
 - of 4-momentum components, 33
- lowering, raising tensor indices, 36
- luminosity distance, 180
- metric
 - η_{ij} coefficients in flat space, 9
 - derivative of coefficients of the metric tensor, 75
 - inverse, 37
 - sign convention for components of, 180
- metric coefficients, 8
 - as dot products of basis vectors, 22
 - East Coast convention, 180
 - in space, 10
 - West Coast convention, 180
- metric components, transformation law for, 27
- mixed tensor, 180
- monotonically increasing parameter, on curve, 61
- numerical relativity, 189
- one-form, 182
- operator form for basis vectors, 184
- order, of indices, 38
- parabolic trajectory, 2, 18
- parallel transport, geometrical meaning of, 83
- parity, 42
- phase shift, invariant, 34
- photon
 - ds^2 for, 65
 - Lagrangian for, 64

- pigeon coordinates, 10, 12, 14, 88
- plane polar coordinates, 20
- pole, cavity pole in gravitational wave interferometry, 173
- polynomial, derivative of, 17
- principle of equivalence, 13
- probe, of gravity at small distance scales, 4
- pseudo-tensor, 42
- pseudoforces
 - and gravity, 14
 - in rotating frames, 3, 14
- Pythagoras' theorem, 7
- quantum computing, and quantum gravity, 189
- quantum field theory, and differential geometry, 189
- quantum limit, standard, for LIGO, 168
- quiz, diagnostic, 16
- raising, lowering tensor indices, 36
- Raychaudhuri equation, 146
- rectilinear coordinates, 20
- Reissner–Nordstrom metric, 122
- research literature in gravitation, 187
- Ricci scalar, for FRW cosmology, 140
- Ricci tensor, 94
- Riemann coefficients, independent non-zero subset, 91, 94
- Riemann curvature tensor, definition, 87
- Riemann curvature, in terms of Christoffel symbols, 88
- Riemann tensor coefficients, symmetries, 88, 90
- saddle, 53, 134
- Schwarzschild geometry
 - Christoffel symbols for, 104
 - correspondence with Newtonian gravity, 112
 - Einstein tensor, 110
 - event horizon for, 114
 - Lagrangian for, 101
 - Ricci scalar, 110
 - Ricci tensor coefficients, 107
- Schwarzschild metric
 - in Kruskal–Szekeres coordinates, 119
 - result, 114
- shot noise, in gravitational wave detectors, 168
- smooth curves, and nature, 1
- space-time geometry, 10
- space-time, contents of, 43
- spherical polar coordinates, 40
- spherical shell, 40
- spherical triangle, 17
- straight line, shortest distance between two points,
 - proof, 59
- stress–energy tensor
 - of dust, 46
 - physical meaning of components, 50
- summation convention, Einstein's, 15
- Sun, Schwarzschild radius of, 115
- supersymmetry, for unifying gravity and quantum mechanics, 188
- surface term, 58
- symmetric tensor, 39
- symmetries, of Riemann curvature coefficients, 88, 90
- symmetrisation and antisymmetrisation, 39
- tangent plane, 7
- tangent, to curve, 4
- Taylor expansion, 5
- tensor
 - antisymmetric, 39
 - differentiation of, 67
 - higher ranks, 74
 - in plane polar coordinates, 26
 - in space-time, 30
 - Kronecker delta, 41
 - Levi-Civita, 42
 - pseudo, 42
 - rank $\begin{smallmatrix} 0 \\ 1 \end{smallmatrix}$, 32, 35, 72
 - rank $\begin{smallmatrix} 0 \\ 2 \end{smallmatrix}$, 27, 73
 - rank $\begin{smallmatrix} 1 \\ 0 \end{smallmatrix}$, 32, 71
 - rules for manipulating tensor components, 35
 - swapping summed indices, 38
 - symmetric, 39
 - transformation laws for components of tensors of arbitrary rank, 27
- tensor analysis, principle of, 30
- tensor components, order of indices, 38
- tensor methods, in classical physics, 189
- tolerance, engineering, 2
- transformation, coordinate, 5
- triangle, spherical, 17
- unification of gravity and quantum mechanics, 4, 188
- unit vector, 41
- Universe, constituent components, 43
- vector, components, 20
- West Coast, metric convention, 180
- Wheeler, quotation, 3
- world lines, 63
 - of photons in the Kruskal geometry, 120
- wormholes, 121
- zero-gravity simulator, 18