

Index

- 3-velocity, 88
- 4-vector, 85
- 4-velocity, 25, 119, 142

- A Large Hadron Collider Experiment, 169
- ALICE, *see* A Large Hadron Collider Experiment
- Alice, 8, 22, 23, 49, 50
see also A Large Hadron Collider Experiment
- Apollo 15, *see* Galileo Galilei
- auto-parallel curve, 102

- BAO, *see* baryon acoustic oscillations
- Barish, Barry C., 129
- baryon, 152, 160
see also matter, baryonic
- baryon acoustic oscillations, 160
- baryon-to-photon ratio, 159
- baryonic
 matter, 161
- bending of light, *see* light deflection
- Bianchi identity, 116
 first, 113, 183
 second, 183
- Big Bang, 58, 139, 153, 160
- binary pulsar, *see* pulsar, binary
- black hole, 39, 42, 73, 75, 166
see also event horizon
- black-body spectrum, 139
- Bob, 8, 22, 23, 49, 50

- Bolyai, Janós, 27
- Bondi, Herman, 129

- causal structure, 26
- Cepheid variable, 33
- CERN (European centre for nuclear research), 169
- Christoffel symbols, 105
- CMB, *see* cosmic microwave background
- commutator
 covariant, 179
 Lie, 180
- comoving coordinates, *see* coordinates, Lagrangian
- connection, 99
 coefficients, 100, 111
 Levi-Civita, 105, 112, 116
 metric compatible, 99, 106
see also auto-parallel curve
- coordinate transformation
 active, 91
 passive, 91
- coordinates
 Eddington–Finkelstein, 73
 Eulerian, 91, 141
 Lagrangian, 91, 141
 space-like, 72
 time-like, 72
- Copernican principle, 139
- Coriolis force, 52
- cosmic microwave background, 139, 155, 157

- see also* surface of last scattering
- cosmological
 - constant, 122, 145, 146, 150, 152
 - fluid, 141
- Coulomb, Charles-Augustin de, 1
- covariant derivative, *see* derivative, covariant
- curvature, 112
 - spacial, 124
 - see also* tensor, Riemann
- dark energy, 152
 - see also* cosmological constant
- dark matter, *see* matter, dark
- deceleration parameter, 149
- deflection, *see* light deflection
- derivative
 - covariant, 96, 100–102
 - exterior, 97, 102
 - Lie, 90, 96, 99, 102, 180
- deuterium, *see* hydrogen, heavy
- diffeomorphism, 91
- distance, 151, 170
- Donne, John, 42
- dot product, *see* inner product
- Drever, Ron, 129
- Dyson, Frank Watson, *see* light deflection, solar eclipse 1919
- eclipse, solar, *see* light deflection, solar eclipse 1919
- Eddington, Arthur, *see* coordinates, Eddington–Finkelstein
 - see also* light deflection, solar eclipse 1919
- EHT, *see* Event Horizon Telescope
- Einstein, 2
 - equations, 3, 119, 122
 - summation convention, 15
 - tensor, 114
- electromagnetism, 1–3
 - electrostatic force, 3
 - Coulomb's law, 1, 3
 - electric permittivity of the vacuum, 1
 - electromagnetic wave, 3
 - electrostatic force, 2
 - electrostatic potential, 3
 - Gauss' law, 3
 - Maxwell's equations, 2, 97, 129
 - radio waves, 3
- electroweak unification
 - weak force, 166
- ellipse, 11, 61
- energy
 - conservation of, 59, 60
 - density, 119, 121, 124, 139, 157
 - relativistic particle, 88
 - see also* radiation, thermal
- energy-momentum conservation, 144
- energy-momentum tensor, 119, 142
 - fluid at rest, 144
 - relativistic fluid, 119
- equation of state, 148
 - dust, 148
 - ideal gas, 148
 - see also* radiation, thermal
- equivalence principle, 8–10, 25, 123
- Euclid, *see* Euclidean, postulates
- Euclid's fifth postulate, *see* Euclidean postulates
- Euclidean
 - postulates, 94
 - space, 14
- event horizon, 38, 73
- Event Horizon Telescope, 75
- Far Infrared Absolute Spectrophotometer, 139
- Faraday, Michael, 3
- Fermat
 - principle of least time, 9
- Feynman, Richard P., 3, 123
- Finkelstein, David, *see* coordinates, Eddington–Finkelstein
- FIRAS, *see* Far Infrared Absolute Spectrophotometer
- flat space-time, *see* Minkowski, space-time
- freely falling observer, *see* inertial, observer
- Friedmann equation, 145, 146, 153, 157, 171
- galaxies, distribution of, 139
- galaxy clusters, 143, 147
- Galileo Galilei
 - Apollo 15, 6
 - leaning tower of Pisa, 6
- Gargantua, *see* Interstellar, 2014 movie
- gauge conditions, 132
- Gauss'
 - Theorema Egregium*, 116

- land survey, 9
- law, 3, 123
- Gauss, Carl Friedrich, 9
 - see also* Gauss' and hyperbolic plane
- geodesic, 16, 29, 44, 45, 47, 55, 56, 58, 64, 78, 85, 103–105, 109, 121
- Global Positioning System, 36
- GPS, *see* global positioning system
- gravitational
 - acceleration (Newtonian), 4, 6
 - constant, *see* Newton, universal, constant of gravitation
 - field (Newtonian), 2, 4
 - lensing, 76
 - potential energy (Newtonian), 4
 - radiation, 129
 - red-shift, *see* red-shift, gravitational
 - waves, 78, 129
- gravity, 1–4, 6
 - Einstein's equations, *see* Einstein, equations
 - Newton's universal law of gravitation, *see* Newton, universal, law of gravitation
 - probe A, 39
 - waves, 78
- great circle, 10

- Hafele, Joseph C., *see* time dilation, Hafele–Keating experiment
- heat death, 58
- helium, 5, 163
 - ionised, 5, 159
 - primordial, 164, 165
 - production in the early Universe, 164
- Hertz, Heinrich Rudolf, 3
- Higgs boson, 166
- holonomy, 112
- homogeneity, 139
- Hooke, Robert, 1
- horizon problem, 170
- Hubble
 - constant, 32, 147, 161
 - diagram, 34
 - expansion, 31
 - relation, 33, 151
- Hubble, Edwin Powell, 31
- Hulse, Alan R., *see* pulsar, binary
- Humason, Milton La Salle, 33
- hydrogen, 33
 - heavy, 163
 - ionisation, 159
 - primordial, 164
- hyperbolic plane, 26, 27, 145

- ideal gas, *see* equation of state, ideal gas
- inertial
 - coordinates, 22, 41, 123
 - coordinates, local, 108
 - mass, *see* mass, inertial
 - observer, 108, 124
 - reference frame, 21, 49, 53
- inflation, *see* horizon problem
- inflaton, 172
- inner product, 86
- Interstellar, 2014 movie, 39
- inverse square law, 4
- ionised gas clouds, 143
- isotropy, 139

- Jacobi identity, 183

- Keating, Richard E., *see* time dilation, Hafele–Keating experiment
- Kepler's laws, 147
 - 1st law, 61
 - 2nd law, 59
 - 3rd law, 40, 155
- Kepler, Johannes, *see* Kepler's laws

- Laser Interferometer and Gravitational-Wave Observatory, 80
- Leavitt, Henrietta Swan, 33
- Lehrer, Tom, 27
- leptons, 174
- Levi–Civita connection, *see* connection, Levi–Civita
- Lewis, Clive Staples, *see* Narnia
- Lie
 - transport, 91
 - see also* derivative, Lie
- Lie, Sophus, 90
- light cone, 25
 - future, 26
 - past, 26
- light deflection, 64
 - solar eclipse 1919, 67
 - see also* gravitational, lensing
- light-like, 21
- LIGO, *see* Laser Interferometer and Gravitational-Wave Observatory

- line element, 15
 - see also* metric
- lithium, 163
- Lobachevsky plane, *see* hyperbolic plane, 28
- Lobachevsky, Nicolai Ivanovich, 27

- M87, 75
- map maker's problem, 18
- mass
 - density, 140
 - gravitational, 4
 - inertial, 4
- matter
 - anti-matter asymmetry, 173
 - baryonic, 152, 158, 164, 165
 - dark, 77, 152, 164
 - density of the Universe, 147, 152
 - ionised, 159
 - luminous, 147, 152
 - non-baryonic, 152
- Maxwell, *see* electromagnetism, Maxwell's equations
- Maxwell–Boltzmann distribution, 163
- Mercury, *see* precession, perihelion of Mercury
- metric, 14
 - Euclidean, 14
 - Lobachevsky plane, 28
 - 2-sphere, 19
 - see also* space-time
- microwave background, *see* cosmic microwave background
- Milne, Robert E., *see* space-time, Milne universe
- Minkowski, Hermann
 - space-time, 21
- momentum, 119
 - angular, 58, 59, 82
 - relativistic, 88

- Narnia, 73
- neutrinos, 162
- Newton, 1, 4, 6
 - 1st law, 46
 - 2nd law, 4
 - universal
 - constant of gravitation, 2
 - see also* Schiehallion
 - law of gravitation, 1, 4, 6, 55
- Nobel Prize, 3, 78, 129, 166

- nucleosynthesis, 163, 170
 - see also* Big Bang

- orbit equation (relativistic), 61
- orthonormal basis, *see* vector, orthonormal basis

- parallel, 94
 - transport, 99, 109
- parsec, 33
- perihelion, *see* precession, perihelion of Mercury
- photon gas, *see* radiation, thermal
- Planck, Max
 - satellite, 10
- plasma, 159
- Poisson's equation, 4, 124
- positrons, 164, 173
- Pound, Robert, *see* red-shift, Pound–Rebka experiment
- precession
 - perihelion of Mercury, 64
- pressure, 140
 - see also* tensor, pressure
- Principe, Island of, *see* light deflection, solar eclipse 1919
- proper time, 9, 22–25, 48, 85
- pulsar, binary, 129
- Pythagoras' theorem, 14

- quarks, 173, 174

- radiation
 - electromagnetic, 67
 - gravitational, 129
 - thermal, 125, 139, 143, 155–157
- Rebka, Glen A. Jr., *see* red-shift, Pound–Rebka experiment
- red-shift, 32, 150
 - distance relation, 33, 147, 151
 - galactic, 33
 - gravitational, 36, 38, 41, 55, 59
 - Pound–Rebka experiment, 39
- Ricci tensor, *see* tensor, Ricci
- Ricci, scalar, 112
- Riemann tensor, *see* tensor, Riemann
- Rolax watch, 22, 23, 37–39

- Sakharov, Andrei Dmitrievich, *see* matter, anti-matter asymmetry

- Schiehallion, (*Gaelic: fairy hill of Caledonia*), 38
- Schwarzschild
 line element, 37
 radius, 37, 60
 radius of the Earth, 38
 radius of the Sun, 64
see also space-time
- Schwarzschild, Karl, 37
- Schwinger, Julian, 3
- Scott, David (Apollo 15 commander), 6
- Shapiro time delay, 67
- solar eclipse 1919, *see* light deflection
- space-like
 coordinate, 72
 separation, 21, 72
- space-time
 expanding, 30
 Milne universe, 35, 153
 Minkowski, 11, 78, 130
 Robertson–Walker, 143
 Schwarzschild, 37, 126
- sphere
 2-dimensional, 18, 20
 3-dimensional, 144
- Stefan–Boltzmann constant, *see* energy, thermal radiation
- surface of last scattering, 160, 169
- Taylor, Joseph H., *see* pulsar, binary
- tensor, 89
 contravariant, 177
 covariant, 177
 Einstein, 114, 116
 energy-momentum, *see*
 energy-momentum tensor
 polarisation, 133
 pressure, 119
 Ricci, 112, 116, 130
 Riemann, 109, 116, 130, 180, 181
 thermal history of the Universe, *see*
 Universe, thermal history
 thermal radiation, *see* radiation,
 thermal
- Thorne, Kip S., 39, 129
- tides, 8, 41
- time dilation, 23, 38
 Hafele–Keating experiment, 41
see also gravitational, red-shift
- time-like
 coordinate, 72
 curve, 24
 4-velocity, 25
 separation, 21, 72
 trajectory, 23
- Tomonaga, Sin-Itiro, 3
- torsion, 105, 117, 181
- Universe
 early, 143, 158, 162, 169
 expanding, 146
 matter density, 147, 152
 matter-dominated, 155, 158
 radiation-dominated, 157, 158
 thermal history, 158
- vector, 92
 orthonormal basis, 93
- waves
 electromagnetic, 67
 gravitational, 129
 radio, 75
- weak force, 166
- Weber, Joseph, 129
- weight, 6
see also mass
- Weiss, Rainer, 129
- Wilkinson microwave anisotropy probe,
 165
- WMAP, *see* Wilkinson microwave
 anisotropy probe
- world line, 25, 41, 47, 124
see also time-like, curve
- X-rays, 143