

# INDEX

- Abbott, James, 135 (Exercise 4-1)
- aberration of starlight, 81 (Exercise 3-9)
- absolute elsewhere, 181
- “absolute” space and time (Newton), 160, 284
- abuse of the concept of mass, 244–251 (Section 8.8)
- acceleration, relative, as witness to gravity, 30–36 (Sections 2.3, 2.4), 280–287 (Sections 9.4, 9.5, 9.6)
- acceleration-proof clocks, 152
- active future, 182
- addition of velocities, 82–84 (Exercise 3-11), 103–110 (Section L.7)
- Aging, Principle of Maximal, 150
- Akihito, Emperor of Japan, 138
- American Civil War, 25
- Andromeda galaxy
  - Enterprise in, 106–107 (Box L-2)
  - trip to by rocket, 22–23 (Exercise 1-9)
  - trip to by Transporter, 23 (Exercise 1-10)
- angles, transformation of, 114–115 (Exercise L-6)
- annihilation, positron–electron, 237–238, 242–243 (Sample Problem 8-4), 260 (Exercises 8-14, 8-15)
- appearance, visual, of relativistic objects, 64, 92–93 (Exercise 3-17)
- Arecibo radio antenna (Puerto Rico), 291
- arrow of momenergy, 191–195 (Section 7.2)
- autobiography of a photon, 184–185 (Exercise 6-4)
- available interaction energy, 261 (Exercise 8-17)
- backyard zoo of particles, 235 (Box 8-1)
- bad clock, 112–113 (Exercise L-2)
- barn and pole paradox, 166 (Exercise 5-4)
- Bartlett, Steven, 19
- Bay of Fundy, tides in, 32–33 (Box 2-1)
- Berman, Eric, 254 (Exercise 8-1)
- beta (Greek  $\beta$ ), symbol for speed, 41, 253
- Betrayal, Great, 108–109 (Box L-1)
- black hole, 289 (Box 9-2), 292–295 (Section 9.8)
  - as source of neutrinos, 80 (Exercise 3-8)
- bomb
  - fission, 249
  - hydrogen (fusion), 248–249
  - Super, 108–109 (Box L-1)
- bounce, free-float, 45 (Exercise 2-2)
- Braginsky, Vladimir, 36, 223
- broadening of spectral lines, Doppler, 264 (Exercise 8-25)
- bulb
  - flickering, paradox of, 186–187 (Exercise 6-7)
  - speeding, 264 (Exercise 8-21)
- $c$  (speed of light), *see* light speed
- Caesar, Julius, 106–107 (Sample Problem L-2)
- cannonball, human, 45 (Exercise 2-1)
- Canopus, trip to, 121–134 (Chapter 4)
- cat, Cheshire, 292
- causality, light speed limit on, 171 (Section 6.1), 180–183
- center of momentum frame, 246–251
- Čerenkov radiation, 80–81 (Exercise 3-8)
- Chandrasekhar, S., 288
- Chandrasekhar limit, 288–289 (Box 9-2)
- chemistry, relativistic, 254 (Exercise 8-2)
- Civil War, American, 25
- Cleopatra, 228
- clock
  - acceleration-proof, 152
  - atomic, test of twin effect, 131
  - bad, 112–113 (Exercise L-2)
  - construction of, 78 (Exercise 3-3)
  - light-flash, 12
  - reference, 37
- clock paradox, *see* Twin Paradox
- clocks
  - latticework of, 37–39 (Section 2.6), 45–46 (Exercises 2-3, 2-4)
  - plane of agreement of, 120 (Exercise L-15)
  - run at different rates in gravitational field, 118 (Exercise L-13)
  - “run slow?”, 76–77 (Box 3-4)
- collapse, gravitational, 288, 292–295 (Section 9.8)
- colliders, 261–262 (Exercise 8-17)
- collision, 221–252 (Chapter 8)
  - analyzing, 239 (Box 8-2)
  - elastic, 222, 240–241 (Sample Problem 8-3)
  - inelastic, 222–223
  - solving problems, 239 (Box 8-2)
- comet, 35
- communication, time delay in, 39–40
- communications storm, 48 (Exercise 2-11)
- compact stellar objects, 288–289 (Box 9-2)
- components of momenergy, 195–199 (Section 7.3)
  - energy, 201–206 (Section 7.5)
  - momentum, 199–200 (Section 7.4)
- Compton, Arthur Holly, 229
- Compton scattering, 229, 231, 267–268 (Exercise 8-29)
  - examples of, 268 (Exercise 8-30)
  - inverse, 269–270 (Exercise 8-32)
- computer size, 22 (Exercise 1-8)
- cone, light, partition in spacetime, 177–183 (Section 6.3)
- conscience-guided satellite, 277–279
- conservation laws, *see* energy; momentum; momenergy
- conserved, defined, 208–209 (Box 7-3)
- constant, defined, 208–209 (Box 7-3)

- contracting train paradox, 187–188 (Exercise 6-8)
- contraction, Lorentz, 63–65 (Section 3.5), 126–127 (Section 4.7)
- for cosmic rays, 215–216 (Exercise 7-7)
  - described by stretch factor, 157
  - how it occurs, 119–120 (Exercise L-14)
  - or rotation?, 92–93 (Exercise 3-17)
- conversion factors
- for energy, 203, 250
  - miles to meters, 2, 16, 58–59 (Box 3-2)
  - for momentum, 200
  - seconds to meters, 6, 12, 16, 58–59 (Box 3-2)
- conversion of mass to energy, 237–244 (Section 8.7), 254 (Exercise 8.1)
- cosmic rays, 160, 215–216 (Exercise 7-7)
- cosmos, 296–297 (Section 9.9)
- creation of proton–antiproton pair by an electron, 261 (Exercise 8-16)
- curvature
- of Earth, 281–283 (Section 9.5)
  - equation, Einstein's, 286
  - of spacetime, 280–287 (Sections 9.4, 9.5, 9.6)
- Daytime surveyor, 1–4 (Section 1.1), 16–17 (Box 1-1)
- decay
- mu meson, 23–24 (Exercise 1-11)
  - pi-naught meson, 267 (Exercise 8-28)
  - pi-plus meson, 24 (Exercise 1-12)
  - positronium, 260 (Exercise 8-13)
- deflection of starlight by Sun, 50–51 (Exercise 2-13)
- density of companion of Sirius, 258–259 (Exercise 8-7)
- detonator paradox, 185–186 (Exercise 6-5)
- deuterium, combined with helium, 237
- Dicke experiment, 36, 48–50 (Exercise 2-12)
- dimension, transverse, invariance of, 65–67 (Section 3.6)
- distance
- invariance of, 4, 17
  - proper, 174
- dog and passenger paradox, 25–26
- Dog Star (Sirius), 135 (Exercise 4-1), 258–259 (Exercise 8-7)
- Doppler shift
- along  $x$ -direction, 114 (Exercise L-5), 263 (Exercise 8-18)
  - at limb of Sun, 264 (Exercise 8-22)
  - $E = mc^2$  from, 264–265 (Exercise 8-26)
  - equations, 263 (Exercise 8-19)
  - line broadening, 264 (Exercise 8-25)
  - measurement of by resonant scattering, 271–272 (Exercise 8-36)
  - Twin Paradox using, 264 (Exercise 8-24)
- down with relativity!, 79 (Exercise 3-6)
- DUMAND experiment, 80 (Exercise 3-8)
- dwarf, white, 258–259 (Exercise 8-7), 288 (Box 9-2)
- $E = mc^2$ , 203, 206, 250
- from Doppler shift, 264–265 (Exercise 8-26)
- Earth
- curved, 281–283 (Section 9.5)
  - mass in units of meters, 258
  - surface of as a free-float frame, 46 (Exercise 2-5)
- Eigenzeit*, 11; *see also* proper time
- Einstein, Albert
- admiration for Newton, 284, 295
  - curvature equation, 286
  - eliminate gravity, 28
  - epigram, iii
  - equivalence of energy and mass, 250, 254–258 (Exercise 8-5)
  - and Galileo and Newton, 275–276 (Section 9.2)
  - and gravity, 275–298 (Chapter 9)
  - happiest thought of life, 25, 44
  - picture and quotes, 295
  - special relativity, 5
  - Train Paradox, 62–63
- Einstein puzzler, 78 (Exercise 3-2)
- elastic collision, 222, 240–241 (Sample Problem 8-3)
- electrodynamics, quantum, 185 (Exercise 6-4)
- electron, 235 (Box 8-1)
- creation of proton–antiproton pair by, 261 (Exercise 8-16)
- electron–positron annihilation, 237–238, 242–243 (Sample Problem 8-4), 260 (Exercises 8-14, 8-15)
- electron–positron pair production, *see* photon
- electrons, fast, 215 (Exercise 7-6)
- elsewhere, absolute, 181
- Emperor Akihito, 138
- Emperor Hirohito, 137
- emptiness of spacetime, 56–57 (Box 3-1)
- encounter, particle, 239 (Box 8-2)
- energy, 196, 213 (Table 7.1)
- conserved in a collision, 189–190 (Section 7.1), 207, 222–223 (Section 8.2), 239 (Box 8.2)
  - conversion of mass to, 237–244, (Section 8.7), 254 (Exercise 8-1)
  - interaction, 261 (Exercise 8-17)
  - kinetic, 201, 203, 206
  - Newtonian, low-velocity limit, 190, 203, 205 (Box 7-2)
  - and mass, 201, 203, 206, 250–251, 254–258 (Exercise 8-5)
  - production of, in Sun, 242–245 (Sample Problem 8-5)
  - quantities related to, 213 (Table 7-1)
  - rest, 201, 203, 250
  - shift of, due to recoil of emitter, 270 (Exercise 8-33)
  - threshold, 236, 259 (Exercise 8-12), 261 (Exercise 8-16)
  - as “time” part of momenergy, 201–206 (Section 7.5)

- transformation of, 215 (Exercise 7-5)
- in unit of mass, 190, 203
- without mass (photon), 228–233 (Section 8.4), 273–274 (Exercise 8-40)
- energy of light, 230
- energy of photon and frequency of light, 268–269 (Exercise 8-31)
- Engelsberg, Stanley, 45–46 (Exercise 2-4)
- Enterprise, Starship, 106–107
- Eötvös, Baron Roland von, 36
- equivalence of energy and mass, 250, 254–258 (Exercise 8-5)
- ether theory of light propagation, 84, 88
- Euclidean 3-vector, 192 (Box 7-1)
- Euclidean geometry, 8, 11, 126, 143, 151, 172, 177, 192 (Box 7-1), 198, 279
- event, 10, 16
  - and interval, 9–11 (Section 1.3)
  - locating, with latticework of clocks, 37–39 (Section 2.6)
  - not owned by any frame, 43
  - reference, 38
- events
  - relation between, 11, 172–177 (Section 6.2)
  - time of, 38, 137–139 (Section 5-1)
- evidence, experimental, for Twin Paradox 131–134 (Section 4.10)
- expanding universe, 82 (Exercise 3-10), 264 (Exercise 8-23), 296–297 (Section 9.9)
- experimental evidence for Twin Paradox, 131–134 (Section 4.10), 272–273 (Exercise 8-39)
- fast electrons, 215 (Exercise 7-6)
- fast protons, 214–215 (Exercise 7-4)
- faster than light?, *see* light, faster than?
- Federation, 108–109 (Box L-1)
- Feynman, Richard, 1
- firing meson, 110 (Sample Problem L-3)
- fission, 237–238
  - bomb, 249
- Fizeau experiment, 120 (Exercise L-16)
- flash, reference, 38
- flickering bulb paradox, 186–187 (Exercise 6-7)
- floating to Moon, 25–26 (Section 2.1)
- force of gravity, eliminate, 26–29 (Section 2.2)
- four times light speed, 89 (Exercise 3-15)
- four-vector, momenergy as, 191–195 (Section 7.2)
- frame
  - center of momentum, 246–251
  - Earth, 46 (Exercise 2-5)
  - free-float, *see* free-float frame
  - inertial, *see* free-float frame
  - laboratory, 5, 41
  - local, *see* free-float frame
  - Lorentz, *see* free-float frame
  - reference, 5; *see also* free-float frame
  - rocket, 41–43 (Section 2.9)
  - super-rocket, 69, 71, 140–142
- free float, 25–45 (Chapter 2)
- free-float bounce, 45 (Exercise 2-2)
- free-float (inertial) frame, 26–29 (Section 2.2)
  - defined, 31
  - Earth surface as, 46 (Exercise 2-5)
  - extent of, near Earth, 30–34 (Section 2.3), 46 (Exercise 2-6), 47 (Exercise 2-8), 285
  - extent of, near Moon, 46–47 (Exercise 2-7)
  - local, 30–34 (Section 2.3), 284
  - rocket, 41–43 (Section 2.9)
  - stripped down, 121–122 (Section 4.2)
  - super-rocket, 69, 71, 140–142
  - and test of twin effect, 133
  - touring spacetime without, 160–162 (Section 5.9)
  - verifying, 41, 279
  - what is same in different, 60–62 (Section 3.3)
  - what is not same in different, 56–60 (Section 3.2)
- frequency of light and energy of a photon, 268–269 (Exercise 8-31)
- Fundy, Bay of, 32–33 (Box 2-1)
- fusion, 237–238
- fusion bomb, 248–249
- future, active, 182
- Galilean principle of relativity, 53–55
- Galilean transformation, 113 (Exercise L-3)
- Galilei, Galileo
  - and gravitational acceleration, 36
  - and Newton and Einstein, 275–276 (Section 9.2)
  - picture and quotes, 54
  - and Leaning Tower of Pisa, 36
  - and Principle of Relativity, 53–55
  - and tides, 32
- gamma (Greek  $\gamma$ ), stretch factor, 99, 155–160 (Section 5.8)
- gamma rays, 237; *see also* photon
- General Conference on Weights and Measures, 12, 58
- general relativity, 275–298 (Chapter 9)
  - needed for Twin Paradox?, 132 (Box 4-1)
  - when required, 34, 35, 133, 276, 281
- geometry
  - Euclidean, 8, 11, 126, 143, 151, 172, 177, 192 (Box 7-1), 198, 279
  - curved space, 280–281 (Section 9.4),
  - curved spacetime 284–287 (Section 9.6)
  - Lorentz, 8, 11, 126, 143, 151, 172, 177, 192 (Box 7-1), 198, 284
- gigaflop, 22 (Exercise 1-8)
- gravitation
  - effect of on clocks, 118 (Exercise L-13)

- as curvature of spacetime, 284–287 (Section 9.6)
  - tutorial in Newtonian, 258 (Exercise 8-6)
- gravitational attraction of system containing photons, 257
- gravitational collapse, 288, 292–295 (Section 9.8)
- gravitational radiation, 288–292 (Section 9.7)
- gravitational red shift, 258 (Exercise 8-6)
  - test of, 272 (Exercises 8-37, 8-38)
- graviton, 153, 176
- gravity
  - as curved spacetime, 284–287 (Section 9.6)
  - in brief, 275 (Section 9.1)
  - eliminate, 28–29 (Section 2.2)
  - radiation, 288–292 (Section 9.7)
  - relative acceleration as witness to, 30–36 (Sections 2.3, 2.4), 280–287 (Sections 9.4, 9.5, 9.6)
  - waves, 288–292 (Section 9.7)
- Great Betrayal, 108–109 (Box L-1)
- Great Pyramid, 209
- grid, paradox of skateboard and, 116–117 (Exercise L-12)
- $h$ , Planck's constant, 265, 268–269 (Exercise 8-31)
- handle showing invariant magnitude of momenergy vector, 198
- headlight effect, 115 (Exercise L-9)
- heat
  - as system property, 224
  - weighing, 223
- helium in Sun, 242–245 (Sample Problem 8-5)
- Himalaya Mountains, 48–49
- Hirohito, Emperor of Japan, 137
- hole, black, 289 (Box 9-2), 292–295 (Section 9.8)
  - as source of neutrinos, 80 (Exercise 3-8)
- Horwitz, Paul, 186 (Exercise 6-6)
- Hubble, Edwin, 264
- Hubble constant, 264
- Hubble time, 264
- Hull, Penny, 19, 264, 272
- Hulse, Russell A., 291
- human cannonball, 45 (Exercise 2-1)
- hydrogen bomb, 248–249
- hydrogen burning in Sun, 242–245 (Sample Problem 8-5)
- hydrogen molecule ion, 233
- hyperbola
  - invariant, 143 (Section 5.3), 173–174
  - momenergy, 198
- identically accelerated twins paradox, 117–118 (Exercise L-13)
  - L-13)
- index of refraction and speed of light, 185 (Exercise 6-4)
- inelastic collision, 222–223
- inertia, 31, 189
- inertial frame, *see* free-float frame
- integrity of photon, 259 (Exercise 8-11)
- interaction energy, available, 261 (Exercise 8-17)
- interferometer
  - Fizeau, 120 (Exercise L-16)
  - Kennedy–Thorndike, 86–88 (Exercise 3-13)
  - Michelson–Morley, 84–86 (Exercise 3-12)
  - verifying free-float frame using, 46 (Exercise 2-5)
- interstellar travel, 274 (Exercise 8-41)
- interval, 6
  - and event, 9–11 (Section 1.3)
  - invariance of, *see* invariance of interval
  - as lightlike relation between events, 175–177
  - as spacelike relation between events, 11, 173–174
  - as timelike relation between events, 11, 172–173
- invariance of distance, 4, 17
- invariance of interval, 6–7, 17, 18
  - for all free-float frames, 71–73 (Section 3.8)
  - preserves cause and effect, 180–183
  - proved, 67–70 (Section 3.7)
  - and spacetime hyperbola, 143 (Section 5.3), 173, 174
  - and spacetime map, 143 (Section 5.3)
  - used in derivation of the Lorentz transformation, 102
- invariance of mass, 197, 246
- invariance of momenergy, 194, 198, 210
- invariance of speed of light, 60; 86–88 (Exercise 3-13)
- invariance of transverse dimension, 65–67 (Section 3.6)
- invariant, defined, 208–209 (Box 7-3)
- invariant hyperbola, 143 (Section 5.3), 173, 174
- inverse Compton scattering, 269–270 (Exercise 8-32)
- inverse Lorentz transformation, 102–103 (Section L.6)
- Japan, 27, 96–97, 161
- Japan Microgravity Center (JAMIC), 27 (Figure 2-3)
- Julius Caesar, 106–107 (Sample Problem L-2)
- $K^+$ -meson, 72 (Sample Problem 3-2)
- Kamisunagawa, 27
- Kennedy–Thorndike experiment, 86–88 (Exercise 3-13)
- Kepler, Johannes, 32
- kinetic energy, 201, 203, 206
- kinked worldline, 152–155 (Section 5.7)
- Klingons, 108–109 (Box L-1)
- Krotkov, Robert V., 36
- laboratory frame, 5, 41
- lattice clocks, synchronizing, 37–38, 45–46, (Exercises 2-3, 2-4)
- latticework of clocks, 37–39 (Section 2.6)
- Law of Addition of Velocities, 82–84 (Exercise 3-11), 103–110 (Section L.7)
- laws, conservation, *see* energy; momentum; momenergy
- Laws, Kenneth L., 77
- Leaning Tower of Pisa, 36
- length
  - mass in units of, 258 (Exercise 8-6)
  - time in units of, 11–13 (Section 1.4)
- length along a path, 147–148 (Section 5.5)
- length contraction, *see* Lorentz contraction
- less is more, 154–155 (Sample Problem 5-1), 163–164 (Exercise 5-1)

- light
- deflection of by Sun, 50–51 (Exercise 2-13)
  - frequency of and energy of a photon, 268–269 (Exercise 8-31)
  - gravitational red shift of, 258–259 (Exercises 8-6, 8-7)
  - pressure of, 254 (Exercise 8-3), 255
  - rocket propelled by, 274 (Exercise 8-41)
  - speed of, *see* light speed
  - See also* photon
- light, faster than?, 74–75 (Box 3-3), 96–99 (Section L.2), 108–109 (Box L-1), 122–123 (Section 4.3)
- four times the speed of light?, 89–90 (Exercise 3-15)
  - superluminal expansion of quasar 3C273?, 90–92 (Exercise 3-16)
  - things that move faster than light, 88–89 (Exercise 3-14)
- light bulb
- flickering, 186–187 (Exercise 6-7)
  - speeding, 264 (Exercise 8-21)
- light cone as partition in spacetime, 177–183 (Section 6.3)
- light-flash clock, 12
- lightlike relation between events, 172–177 (Section 6.2)
- light propagation, ether theory of, 84, 88
- light speed
- as conversion factor, 6, 12, 16, 58–59 (Box 3-2), 200, 203, 250
  - index of refraction and, 185 (Exercise 6-4)
  - invariant magnitude of, 60 (Kennedy–Thorndike experiment), 86–88 (Exercise 3-13)
  - isotropic (Michelson–Morley experiment), 84–86 (Exercise 3-12)
  - as limit on causality, 171 (Section 6.1), 180–183
  - as limit on observation, 39–40
  - See also* light, faster than?
- light-second, 11–13 (Section 1.4)
- light-year, 12
- limb of Sun, Doppler shift at, 264 (Exercise 8-22)
- limits of Newtonian mechanics, 34, 113–114 (Exercise L-4), 217 (Exercise 7-11)
- line, world, *see* worldline
- line broadening, Doppler, 264 (Exercise 8-25)
- linear accelerator, Stanford, 215 (Exercise 7-6)
- local inertial frame, *see* free-float frame
- local moving orders for mass, 277–280 (Section 9.3)
- local time, *see* proper time; interval
- locating events with latticework, 37–39 (Section 2.6)
- Lorentz, Hendrik, 5
- Lorentz contraction, 63–65 (Section 3.5), 126–127 (Section 4.7)
- for cosmic rays, 216 (Exercise 7-7)
  - described by stretch factor, 157
  - how it occurs, 119–120 (Exercise L-14)
  - or rotation, 92–93 (Exercise 3-17)
- Lorentz frame, *see* free-float frame
- Lorentz-FitzGerald contraction hypothesis, 88
- Lorentz geometry, 8, 11, 126, 143, 151, 172, 177, 192 (Box 7-1), 198, 284
- Lorentz interval, 6; *see also* interval; invariance of interval
- Lorentz transformation, 95–111 (Special Topic)
- equations, 102
  - form of, 100 (Section L.4)
  - inverse equations, 102–103 (Section L.6)
  - for momenergy components, 215 (Exercise 7-5)
  - usefulness of, 95 (Section L.1)
- manhole, paradox of rising, 116 (Exercise L-11)
- map, spacetime, *see* spacetime map
- mapmaking
- in space, 10, 21–22 (Exercise 1-6)
  - in spacetime, 164–166 (Exercise 5-3)
- mass
- abuse of the concept of, 244–251 (Section 8.8)
  - change in nuclear, 237–238
  - conversion of to energy, 237–244 (Section 8.7), 254 (Exercise 8-1)
  - created by material particle, 234–236 (Section 8.6)
  - created by photon, 233–234 (Section 8.5)
  - and energy, 201, 203, 206, 250–251, 254–258 (Exercise 8-5)
  - energy in unit of, 190, 203
  - energy without (photon), 228–233 (Section 8.4)
  - invariance of, 197, 246
  - local moving orders for, 277–280 (Section 9.3)
  - loss by Sun of, 242–245 (Sample Problem 8-5)
  - as magnitude of momenergy 4-vector, 195, 197
  - momentum in unit of, 190, 200
  - momentum without?, 273–274 (Exercise 8-40)
  - photon used to create, 233–234 (Section 8.5)
  - proof, 277, 279
  - “relativistic,” 250–251
  - “rest,” 251
  - as unit of length, 258 (Exercise 8-6)
  - use and abuse of the concept of, 244–251 (Section 8.8)
- mass of photon, 230
- mass of system of particles, 214 (Exercise 7-2), 224–228 (Section 8.3), 247
- Maximal Aging, Principle of, 150
- maximum speed of walking, 186 (Exercise 6-6)
- mechanics
- Newtonian, 113–114 (Exercise L-4), 192 (Box 7-1), 217 (Exercise 7-11)
  - relativistic, 192 (Box 7-1)
- megaflop, 22 (Exercise 1-8)
- meson
- decay of pi-naught, 267 (Exercise 8-28)
  - firing, 110 (Sample Problem L-3)
  - time stretching with, 23–24 (Exercise 1-11), 24 (Exercise 1-12), 72–73 (Sample Problem 3-2)

- meter  
 defined, 58–59 (Box 3-2)  
 of time, 11–13 (Section 1.4)  
 as unit of mass, 258 (Exercise 8-6)
- meter stick, tilted, 115–116 (Exercise L-10)
- Michelson–Morley experiment, 84–86 (Exercise 3-12)
- microgravity, 27 (Figure 2-3), 277 (Figure 9-2)
- Minkowski, Hermann, 15
- mile  
 defined, 58–59 (Box 3-2)  
 as sacred unit, 1–4
- minus sign, 6–8, 26, 190, 197
- minute, unit of distance and time, 11–13 (Section 1.4)
- momenergy  
 as 4-vector, 191, 192 (Box 7-1)  
 analogy of to tree, 210  
 arrow, 191–195 (Section 7.2)  
 components of, 195–199 (Section 7.3), 204  
 (Sample Problem 7-3)  
 conservation of, 189–190 (Section 7.1), 207–210  
 (Section 7.6), 247  
 defined, 191–195 (Section 7.2)  
 energy as “time” part of, 201–206 (Section 7.5)  
 handle showing invariant magnitude, 198  
 invariance of, 194, 198, 210  
 magnitude of is mass, 195, 197  
 momentum as “space” part of, 199–200 (Section 7.4)  
 quantities related to, 213 (Table 7-1)  
 tree, analogy of, 210  
 transformation of components of, 215 (Exercise 7-5)  
 units of, 194, 195, 200, 203
- momentum, 196, 213 (Table 7.1)  
 components of, 196  
 conserved in a collision, 189–190 (Section 7.1),  
 207, 222–223 (Section 8.2), 239 (Box 8.2)  
 derived from conservation law, 217–219 (Exercise  
 7-12)  
 of light, 230  
 Newtonian expression for, 190, 200  
 as “space” part of momenergy, 199–200 (Section  
 7.4)  
 transformation of, 215 (Exercise 7-5)  
 in unit of mass, 190, 200  
 without mass?, 273–274 (Exercise 8-40)
- momentum–energy 4-vector, *see* momenergy
- Moon, 25–26 (Section 2.1), 32–33 (Box 2-1)
- Moral Principle, Wheeler’s First, 20
- Mössbauer effect, 270
- Minkowski, Hermann, 15
- more is less, 154–155 (Sample Problem 5-1), 163–164  
 (Exercise 5-1)
- moving orders for mass, local, 277–280 (Section 9.3)
- muons, time stretching with, 23 (Exercise 1–11)
- nanosecond, 5
- Neptune, images from, 20 (Exercise 1-2)
- neutral or unreachable region, 182
- neutrino  
 described, 235 (Box 8-1)  
 detection of, 80 (Exercise 3-8)
- neutron, described, 235 (Box 8-1)
- neutron star, 288–289 (Box 9-2)  
 and gravity waves, 290–291
- Newton, Isaac, 275–280  
 absolute space and time, 160, 284  
 Einstein’s admiration for, 284, 295  
 First Law of Motion, 31  
 and Galileo and Einstein, 275–276 (Section 9.2)  
 picture and quotes, 278
- Newtonian mechanics, 192 (Box 7-1)  
 First Law of Motion, 31  
 gravitational theory, tutorial, 258 (Exercise 8-6)  
 limits of, 34, 113–114 (Exercise L-4), 217 (Exer-  
 cise 7-11)
- Nighttime surveyor, 1–4 (Section 1.1), 16–17 (Box 1-1)
- nuclear excitation, 259 (Exercise 8-8)
- observer, 39–40 (Section 2.7)
- oozing!, 12
- oscillator, relativistic, 135–136 (Exercise 4-3)
- oscilloscope writing speed, 89 (Exercise 3-14)
- pair production by photon(s), 233–234 (Section 8.5),  
 259 (Exercises 8-11, 8-12)
- Parable of the Surveyors, 1–4 (Section 1.1), 16–17  
 (Box 1-1)
- Parable of the Two Travelers, 281–283 (Section 9.5)
- paradoxes  
 contracting train, 187–188 (Exercise 6-8)  
 detonator, 185–186 (Exercise 6-5)  
 Einstein’s train, 62–63  
 flickering bulb, 186–187 (Exercise 6-7)  
 four times light speed, 89 (Exercise 3-15)  
 identically accelerated twins, 117–118 (Exercise  
 L-13)  
 passenger and dog, 25–26  
 pole and barn, 166 (Exercise 5-4)  
 rising manhole, 116 (Exercise L-11)  
 runner on the train, 168 (Exercise 5-7)  
 scissors, 88 (Exercise 3-14)  
 skateboard and grid, 116–117 (Exercise L-12)  
 space war, 79–80 (Exercise 3-7)  
 tilted meter stick, 115–116 (Exercise L-10)  
*See also* Twin Paradox
- particle, test, 36 (Section 2.5), 47–48 (Exercise 2-10)
- particles  
 backyard zoo of, 235 (Box 8-1)  
 creation of, 234–236 (Section 8.6), 261–262 (Ex-  
 ercises 8-16, 8-17)

- creation of by photons, 233–234 (Section 8.5), 259–260 (Exercises 8-11 and 8-12)
- encounter, 239 (Box 8-2)
- measuring speed of, 40–41 (Section 2.8)
- system of, 214 (Exercise 7-2), 221 (Section 8.1), 224–228 (Section 8.3), 244–251 (Section 8-8)
- timelike worldline of, 172
- used to create mass, 234–236 (Section 8.6)
- virtual, 56–57
- worldline of, 143–147 (Section 5.4)
- partition in spacetime, light cone as, 177–183 (Section 6.3)
- passenger and dog paradox, 25–26
- passive past, 182
- path, length along, 147–148 (Section 5.5)
- Peace Treaty of Shalimar, 108–109 (Box L-1)
- Philoponus, John, of Alexandria, 36
- photon, 228–233 (Section 8.4), 246
  - from annihilation, 237–238 (Section 8.7)
  - autobiography of, 184–185 (Exercise 6-4)
  - braking, 259 (Exercise 8-9)
  - Compton scattering of, 229, 231, 267–270 (Exercises 8-29, 8-30, 8-32)
  - creation of particle–antiparticle pair using, 233–234 (Section 8.5)
  - energy of, 228–233 (Section 8.4), 268–269 (Exercise 8-31)
  - energy measurement of, 254 (Exercise 8-4)
  - energy shift of due to recoil of emitter, 270 (Exercise 8-33)
  - gravitational red shift of, 258–259 (Exercises 8-6 and 8-7)
  - integrity of, 259 (Exercise 8-11)
  - mass of, 228–231 (Section 8.4)
  - momentum of, 230
  - pair production by, 233–234 (Section 8.5), 259–260 (Exercises 8-11, 8-12)
  - resonant scattering of, 271–272 (Exercises 8-35, 8-36)
  - rocket and interstellar travel, 274 (Exercise 8-41)
  - used to create mass, 233–234 (Section 8.5)
- physicist and the traffic light, 263–264 (Exercise 8-20)
- pi-naught meson, decay of, 267 (Exercise 8-28)
- pipes, speeding (thought experiment), 66
- pi-plus mesons, time stretching with, 24 (Exercise 1-12)
- Pisa, Leaning Tower of, 36
- place, fundamental to surveying, 9, 16
- plane of agreement of clocks, 120 (Exercise L-15)
- Planck, Max, 229
- Planck’s constant, 265, 268–269 (Exercise 8-31)
- plumb bob, deflection of by Himalaya Mountains, 48–49
- Poincaré, Henri, 5–6
- pole and barn paradox, 166 (Exercise 5-4)
- polyelectron, 233
- positron, 233–235
  - positron–electron annihilation, 237–238, 242–243 (Sample Problem 8-4), 260 (Exercises 8-14, 8-15)
  - positron–electron pair production, 233–234 (Section 8.5), 259 (Exercises 8-11, 8-12)
  - positronium, decay of, 260 (Exercise 8-13)
  - practical synchronization of clocks, 45–46 (Exercises 2-3, 2-4)
  - pressure of light, 254 (Exercise 8-3), 255
  - principle of invariance of distance, 4, 17
  - Principle of Maximal Aging, 150
  - Principle of Relativity, 53–60 (Sections 3.1, 3.2, 3.3)
    - examples of, 61–62 (Sample Problem 3-1), 78 (Exercise 3-4)
    - Galilean, 53–55
    - used in proof of invariance of interval, 73
  - proof mass (conscience), 277, 279
  - proper clock, 10
  - proper distance, 174, 184 (Exercise 6-3)
  - proper time, 10, 184 (Exercise 6-3)
    - along a worldline, 148–152 (Section 5.6)
    - tau as symbol of, 155
  - proton, described, 235 (Box 8-1)
  - proton–antiproton pair, creation of, 236
  - protons, fast, 214–215 (Exercise 7-4)
  - pulsar, 289
  - puppy, 224
  - puzzler, Einstein, 78 (Exercise 3-2)
  - Pyramid, Great, 209
  - Pythagorean theorem, 2, 7
  - quantum electrodynamics, 185 (Exercise 6-4)
  - quasar, 90–92 (Exercise 3-16), 114 (Exercise L-5), 294–295
  - radar speed trap, 166–168 (Exercise 5-5)
  - radiation, Čerenkov, 80–81 (Exercise 3-8)
  - radiation, gravitational, 288–292 (Section 9.7)
  - radius of a black hole, 292
  - railway coach
    - rising, 47 (Exercise 2-9)
    - and tidal accelerations, 30–34 (Section 2.3), 281
  - ray, gamma, *see* photon
  - ray, X-, *see* photon
  - rays, cosmic, 160, 215–216 (Exercise 7-7)
  - recoilless processes, 270–271 (Exercise 8-34)
  - recoil of emitter, energy shift due to, 270 (Exercise 8-33)
  - red shift, gravitational, 258 (Exercise 8-6), 272 (Exercises 8-37, 8-38)
  - reference clock, 37
  - reference event, 38
  - reference flash, 38
  - reference frame, 5; *see also* free-float frame
  - refraction, index of, and speed of light, 185 (Exercise 6-4)
  - regions of spacetime, 34–36 (Section 2.4), 171–183 (Chapter 6)
  - relations between events, 172–177 (Section 6.2)

- relative acceleration as witness to gravity, 30–36 (Sections 2.3, 2.4), 280–287 (Sections 9.4, 9.5, 9.6)
- relative synchronization of clocks, 130
- relativistic chemistry, 254 (Exercise 8-2)
- “relativistic” mass, 250–251
- relativistic mechanics, 192 (Box 7-1)
- relativistic momentum, 217–219 (Exercise 7-12)
- relativistic oscillator, 135–136 (Exercise 4-3)
- relativity
- general, 34, 35, 132 (Box 4-1), 133, 276, 281
  - principle of, 53–62 (Sections 3.1, 3.2, 3.3), 78
  - special, 5, 18, 73, 78 (Exercise 3-1), 79 (Exercise 3-6), 131–134 (Section 4.10), 270–273 (Exercises 8-33 to 8-39)
- relativity of simultaneity, 62–63 (Section 3.4), 128–131 (Section 4.9)
- and contraction of length, 64
  - See also* paradoxes
- resonant scattering, 271 (Exercise 8-35)
- measurement of Doppler shift by, 271–272 (Exercise 8-36)
- rest energy, 201, 203, 250
- “rest mass,” 251
- Riemann, G. F. B., 295
- “rigid body” not an invariant concept, 116–117 (Exercise L-12), 119–120 (Exercise L-14)
- rising manhole paradox, 116 (Exercise L-11)
- rising railway coach, 47 (Exercise 2-9)
- rocket frame, 41–43 (Section 2.9)
- rocket, photon, and interstellar travel, 274 (Exercise 8-41)
- rods, latticework of, 37–39 (Section 2.6)
- Roll, Peter G., 36
- rotation or contraction?, 92–93 (Exercise 3-17)
- Rumford, Count (Benjamin Thompson), 223
- Ruml, Frances Towne, 29
- runner on the train paradox, 168 (Exercise 5-7)
- sacred unit
- mile, 1–4
  - second, 5–7
- Satellite (dog), 26
- satellite
- conscience-guided, 277–279
  - pressure of light on, 254 (Exercise 8-3)
- scattering
- Compton, 229, 231, 267–270 (Exercises 8-29, 8-30, 8-32)
  - resonant, 271–272 (Exercises 8-35, 8-36)
- scissors paradox, 88 (Exercise 3-14)
- Schmidt, Maarten, 294
- second
- defined, 58–59 (Box 3-2)
  - as sacred unit, 5–7
  - as unit of distance and time, 11–13 (Section 1.4)
- Shalimar, Peace Treaty of 108–109 (Box L-1)
- Sheldon, Eric, 19
- shift, *see* Doppler shift; red shift
- Shurcliff, William A., 19, 77, 198, 213
- simultaneity,
- relativity of, 62–63 (Section 3.4), 64, 128–131 (Section 4.9)
  - and transverse plane, 66–67
  - See also* paradoxes
- Sirius, density of companion of, 258–259 (Exercise 8-7)
- skateboard and grid paradox, 116–117 (Exercise L-12)
- Smith, Richard C., 19
- Sommerfeld, Arthur, 53
- solar constant, 242, 254 (Exercise 8-3)
- solar wind, 245
- space
- “absolute” (Newton), 284
  - as different from time, 18
  - is ours!, 123–124 (Section 4.4)
- spacelike relation between events, 11, 172–177 (Section 6.2)
- space travel, practical, 135 (Exercise 4-1)
- space war, 79–81 (Exercise 3-7)
- spacetime
- as absolute elsewhere, 181
  - active future of, 182
  - emptiness of, 56–57 (Box 3-1)
  - exploded view of regions of, 182 (Figure 6-5)
  - “Et tu . . . ?”, 106–107 (Sample Problem L-2)
  - light cone as partition of, 177–183 (Section 6.3)
  - Lorentz geometry of, 8, 192 (Box 7-1)
  - mapmaking in, 164–166 (Exercise 5-3)
  - neutral region of, 182
  - overview of, 1–19 (Chapter 1)
  - passive past of, 182
  - regions of, 34–36 (Section 2.4), 171–183 (Chapter 6)
  - surveying, 5–8 (Section 1.2)
  - touring without reference frame, 160–162 (Section 5.9)
  - trekking through, 137–163 (Chapter 5)
  - units of, 20–21 (Exercises 1-2 and 1-3)
  - unity of, 7, 15–18 (Section 1.5)
  - unreachable region of, 182
- spacetime curvature, 280–287 (Sections 9.4, 9.5, 9.6)
- contractile, 286–287 (Box 9-1)
  - equation (Einstein), 286
  - gravitation as, 284–287 (Section 9.6)
  - noncontractile, 286–287 (Box 9-1)
- spacetime diagram, *see* spacetime map
- spacetime displacement as 4-vector, 191–194
- spacetime geometry, *see* spacetime; spacetime curvature
- spacetime interval, *see* interval; invariance of interval
- spacetime map, 22 (Exercise 1-7), 137–139 (Section 5.1)
- constructing, 164–166 (Exercise 5-3)
- special relativity, 5, 18

- down with, 79 (Exercise 3-6)
  - four ideas of, 73
  - and swimming, 78 (Exercise 3-1)
  - tests of, 131–134 (Section 4.10), 270–273 (Exercises 8-33 through 8-39)
- spectral lines, Doppler broadening of, 264 (Exercise 8-25)
- speed, measuring, 40–41 (Section 2.8)
- speeding light bulb, 264 (Exercise 8-21)
- speeding pipes thought experiment, 66
- speeding train thought experiment, 65–66
- speed of light, *see* light speed
- speed of walking, maximum, 186 (Exercise 6-6)
- speed trap, radar, 166–168 (Exercise 5-5)
- speeds, comparing, 20 (Exercise 1-1)
- Stanford linear accelerator, 215 (Exercise 7-6)
- starlight
  - aberration of, 81 (Exercise 3-9)
  - deflection of by Sun, 50–51 (Exercise 2-13)
- Starship Enterprise, 106–107
- stellar aberration, 81 (Exercise 3-9)
- stellar objects, compact, 288–289 (Box 9-2)
- storm, communications, 48 (Exercise 2-11)
- stretch factor, 99, 155–160 (Section 5.8)
  - and Lorentz contraction, 157
  - as measure of speed, 157
- stripped down free-float frame, 121–122 (Section 4.2)
- Sun
  - conversion of mass to energy in, 242–245 (Sample Problem 8-5)
  - deflection of starlight by, 50–51 (Exercise 2-13)
  - Doppler shift at limb of, 264 (Exercise 8-22)
  - explosion of, 171
  - gravitational red shift of light from, 258 (Exercise 8-6)
  - helium in, 242–245 (Sample Problem 8-5)
  - mass of in units of meters, 258
  - tide-driving power of, 32–33 (Box 2-1)
- sunspot, 179–180 (Sample Problem 6-3)
- Super (superluminal bomb), 108–109 (Box L-1)
- super cosmic rays, 215–216 (Exercise 7-7)
- superluminal expansion of quasar 3C273?, 90–92 (Exercise 3-16)
- supernova, 177, 289
- super-rocket frame, 69, 71, 140–142
- super-speed Super, 112 (Exercise L-1)
- surveying spacetime, 5–8 (Section 1.2)
- Surveyors, Parable of, 1–4 (Section 1.1), 16–17 (Box 1-1)
- swimming and relativity, 78 (Exercise 3-1)
- symmetric elastic collision, 240–241 (Sample Problem 8-3)
- synchronization of clocks, relative, 130
- synchronizing lattice clocks, 37–38, 45–46 (Exercises 2-3, 2-4)
- system of particles, 221 (Section 8.1), 244–251 (Section 8-8)
  - mass of, 214 (Exercise 7-2), 224–228 (Section 8.3), 247–248
  - not isolated, 228
  - system property, heat as, 224
- tangent vector to worldline, 194–195
- tau (Greek  $\tau$ ), symbol for proper time, 155
- Taylor
  - Bradley James, 179
  - Katherine Rose, 311
  - Joseph H., 291
  - Meredith Christine, 171
  - Samantha Marie, 23 (Exercise 1-10)
- teraflop, 22 (Exercise 1-8)
- test particle, 36 (Section 2.5), 47–48 (Exercise 2-10)
- tests of relativity, 131–134 (Section 4.10), 270–273 (Exercises 8-33 through 8-39)
- Thompson, Benjamin (Count Rumford), 223
- thought experiments
  - speeding pipes, 66
  - speeding train, 65–66
- three-vectors, Euclidean, 192 (Box 7-1)
- threshold energy, 236, 259 (Exercise 8-12), 261 (Exercise 8-16)
- tidal effects of large frame, 30–34 (Section 2.3), 280–281 (Section 9.4)
- tide-driving power of Moon and Sun, 32–33 (Box 2-1)
- tides, 32–33 (Box 2-1), 281, 286–287 (Box 9-1)
- tilted meter stick paradox 115–116 (Exercise L-10)
- time
  - “absolute” (Newton), 160
  - as different from space, 18
  - of an event, 38, 137–139 (Section 5.1)
  - Hubble, 264
  - and length, 11–13 (Section 1.4)
  - and Lorentz transformation, 102
  - meter of, 12
  - proper, 10, 148–152 (Section 5.6), 155, 184
  - wristwatch 10, 148–152 (Section 5.6)
- time delay in communication, 39–40
- timelike relation between events, 11, 172–177 (Section 6.2)
- timelike worldline of a particle, 172
- time stretching
  - experimental evidence of, 131–134 (Section 4.10), 272–273 (Exercise 8-39)
  - with  $K^+$  mesons, 72–73 (Sample Problem 3-2)
  - with mu-mesons, 23–24 (Exercise 1-11)
  - with pi-plus mesons, 24 (Exercise (1-12)
  - and spacetime interval, 21 (Exercise 1-4)
  - See also* Twin Paradox
- time traveler, 127–128 (Section 4.8)
- touring spacetime without a reference frame, 160–162 (Section 5.9)
- traffic light, physicist and, 263–264 (Exercise 8-20)
- train, mass effects of in collision, 214 (Exercise 7-3)

- train paradoxes, 62–63, 168 (Exercise 5-7), 187–188 (Exercise 6-8)
- train thought experiment, 65–66
- transformation
- Galilean, 113 (Exercise L-3)
  - Lorentz, 95–111 (Special Topic)
- transformation of angles, 114–115 (Exercise L-6)
- transformation of velocity direction, 115 (Exercises L-7, L-8)
- transforming worldlines, 164 (Exercise 5–2)
- transverse dimension, invariance of, 65–67 (Section 3.6)
- travel, interstellar, 274 (Exercise 8-41)
- traveler, time, 127–128 (Section 4.8)
- Travelers, Parable of the Two, 281–283 (Section 9.5)
- traveling clock, synchronization using, 45–46 (Exercise 2-4)
- Treaty of Shalimar, 108–109 (Box L-1)
- tree analogy to momenergy, 210
- Twin Paradox, 125–126 (Section 4.6)
- atomic clocks (“airliner”) test of, 131
  - circling airplane test of, 133
  - general relativity needed for?, 132 (Box 4-1)
  - one-way, 135 (Exercise 4-2)
  - oscillating iron atom test of, 134, 272–273 (Exercise 8-39)
  - put to rest, 169–170 (Exercise 5-8)
  - radioactive particle test of, 133
  - using Doppler shift, 264 (Exercise 8-24)
- twins, paradox of identically accelerated, 117–118 (Exercise L-13)
- Two Travelers, Parable of, 281–283 (Section 9.5)
- unit, same for space and time, 11–13 (Section 1.4)
- units, 213 (Table 7-1)
- units of energy, 203
- units of momenergy, 194
- units of momentum, 200
- units of spacetime, 11–13 (Section 1.4), 20–21 (Exercises 1-2, 1-3)
- unit tangent vector to worldline, 194–195
- unity of spacetime, 15–18 (Section 1.5)
- universe
- expanding, 82 (Exercise 3-10), 264 (Exercise 8-23), 297 (Table 9-2)
  - models of, 296–297 (Section 9.9)
- unreachable region, 182
- uranium bomb, 249
- uranium fission, 237
- use and abuse of the concept of mass, 244–251 (Section 8.8)
- Van Dam, Hendrik, 79 (Exercise 3-6)
- vector, defined, 192 (Box 7-1)
- velocities, addition of, 82–84 (Exercise 3-11), 103–110 (Section L.7)
- velocity
- measuring, 40–41 (Section 2.8)
  - velocity of recession from Doppler shift, 114 (Exercise L-5), 264 (Exercise 8-23)
  - velocity of recession from period of light, 82 (Exercise 3-10)
  - velocity direction, transformation of, 115 (Exercises L-7, L-8)
- Verne, Jules, 25–26
- virtual particles, 56–57 (Box 3-1)
- visual appearance of relativistic objects, 64, 92–93 (Exercise 3-17)
- von Jagow, Peter, 44
- walking, maximum speed of, 186 (Exercise 6-6)
- war
- American Civil, 25
  - space, 79–81 (Exercise 3-7)
- waves, gravity, 288–292 (Section 9.7)
- weighing heat, 223
- Weights and Measures, General Conference on, 12, 58
- Weisskopf, V. W., 296
- Weyl, Herman, quote, 189
- Wheeler’s First Moral Principle, 20
- white dwarf star, 258–259 (Exercise 8-7), 288 (Box 9-2)
- wind, solar 245
- worldline, 143–147 (Section 5.4)
- kinked, 152–155 (Section 5.7)
  - timelike, of a particle, 172
  - transforming, 164 (Exercise 5-2)
  - unit tangent vector to, 194–195
  - wristwatch (proper) time along, 148–152 (Section 5.6)
- wristwatch time, 10–11
- along a worldline, 148–152 (Section 5.6)
- X-ray, *see* photon
- y*-velocity, transformation of, 115 (Exercise L-7)
- year as unit of distance and time, 11–13 (Section 1.4)
- zero mass for photon, 230
- zero-total-momentum frame, 246–251
- zoo of particles, backyard, 235 (Box 8-1)