ANSWERS TO ODD-NUMBERED EXERCISES

chapter 1

1-1a 10.2 meters **b** 270 meters **c** 10^3 meters **d** 10^4 kilometers $\approx$ 2 times Boston–San Francisco distance **1-3a** 2.6×10^{13} meters **b** 5.3×10^{-6} second **c** 1.85×10^{-10} hours **d** 52 weeks **e** 5.4×10^9 furlongs **1-5a** 4 years **b** 4/5 the speed of light $= 2.4 \times 10^8$ meters/second **1-7a** 4 meters **b** $\sqrt{7}$ meters $= 2.65$ meters **c** $\sqrt{15}$ meters $= 3.87$ meters **d** 2 meters **e** 4 meters (same as part a) **1-9a** 2×10^5 years **b** $v = 0.995$ **c** 6.33×10^4 years, $v = 0.9995$ **d** $v = 1 - 5 \times 10^{-11} = 0.99999999995$ **1-11a** 2×10^{-4} second **b** 133 half-lives; $(1/2)^{133} \approx 10^{-40}$ **c** 3 half-lives **d** zero space separation (creation and decay occur at the same place in rocket frame) **e** 3 half-lives $= 4.5 \times 10^{-6}$ second

chapter 2

2-1a hit the ceiling **b** same answer **c** Rider cannot tell when elevator reaches top. **2-3** Set clock to 10 seconds, start when reference flash arrives. **2-5a** Experiment in progress for $1/0.96 = 1.04$ meters of time. In this time, test particle falls 6×10^{-17} meters, about 10^{-2} diameter of a nucleus. **b** 3×10^{-4} second, 10^5 meters **2-7** 3.6 millimeters; 19.7 seconds. Spacetime region: 20 meters $\times$ 20 meters $\times$ 20 meters of space $\times$ 59 $\times$ 10^8 meters of time **2-9a** decrease (think of each ball bearing in an elliptical orbit around the center of Earth) **b** apart **c** No, you cannot distinguish rising from falling. At the top you notice nothing inside the coach. **2-11** $v_{max} = 0.735$ the speed of light. **2-13a** Effective time of fall: 4.67 seconds. Net velocity of fall: 1284 meters/second. **b** Angle of deflection: 4.3×10^{-6} radian $= 2.5 \times 10^{-4}$ degree $= 0.88$ second of arc

chapter 3

3-1a 60 seconds **b** 45 seconds against the current, 22.5 seconds with the current, 67.5 seconds round trip **c** No **3-3** If different kinds of clocks ran at different rates in a free-float rocket frame, then this difference could be used to detect the relative velocity of the laboratory from inside the rocket, which violates the Principle of Relativity. This does not mean that the common rate of rocket clocks will be the same as measured in rocket and laboratory frames. **3-5a** 11.5 light-years **b** 9.43 years **c** $v = 0.6$ **d** 8 years = the interval between the two events. **3-7** The bullet misses. Coincidence of A and A' (event 1) and firing of the bullet at the other end of spaceship O (event 2) cannot be simultaneous in both rocket reference frames. The right panel of the figure is wrong. Consistent with the Train Paradox (Section 3.4), spaceship O' (standing in for the train frame) will observe the bullet to be fired before coincidence of A and A', thus accounting for the fact that bullet misses. **3-9a** $\sin \psi = v_{Earth}$ (in meters/meter) **b** $\sin \psi \approx \psi \approx 10^{-4}$ radian $= 21$ seconds of arc **c** $\sin \psi$ and $\tan \psi$ are both approximately equal to ψ for small ψ. Therefore the difference between the two predictions cannot be used to distinguish between relativistic and nonrelativistic predictions. **d** in a direction 0.524 radians = 30 degrees ahead of transverse **3-11g(1)** $v_{rel} = 10^{-7}$, $v'_{bullet} = 2 \times 10^{-6}$. Their product is 2×10^{-13}, very small compared with 1; therefore we expect v_{bullet} to be the sum of v'_{bullet} and v_{rel}, the form verified in everyday experience at low speeds. **(2)** $v_{bullet} = 24/25 = 0.96$ **(3)** $v_{bullet} = v_{light} = +1$ **(4)** $v_{bullet} = v_{light} = -1$. Yes, expected from the Principle of Relativity. **3-13a** 0.32 meters = 1.1 nanosecond **b** 6.0×10^5 periods **c** No shift would imply the speed of light is the same for the frame of Earth going one way around Sun as compared with frame of Earth going the opposite direction around Sun. **d** $dc = -(2/n^2)(\Delta l/T)dn$ and $dc/c = -2$

dn/n For $dn = 3 \times 10^{-3}$ and $n = 6.0 \times 10^5$, we have the maximum value of $dc/c = 1 \times 10^{-8}$ (sign not important). Hence $dc \approx 3$ meters/second is the maximum change in the speed of light that could have escaped detection in this very sensitive experiment. **3-15a** visual distance apart $= v\Delta t$; time lapse between images $= (1 - v)\Delta t$; visual speed of approach $= v_{approach} = v/(1 - v)$; $v_{approach} = 4$ when $v = 4/5$; $v_{approach} = 99$ when $v = 0.99$ **b** visual distance apart $= v\Delta t$; time lapse between images $= (1 + v)\Delta t$; visual speed of recession $= v_{recede} = v/(1 + v)$; for $v_{approach} = 4$ when $v = 4/5$, then $v_{recede} = 4/9 = 0.44$; for $v_{approach} = 99$ when $v = 0.99$, then $v_{recede} = 0.497$ **3-17a** Light leaves E one meter of time earlier than light from G in order to enter the eye at the same time. In this time the cube moves v meter of distance, equal to x in the top right figure. **b** The angle ϕ is given by the expression $\sin \phi = v$. For $v \longrightarrow 0$, this visual angle of rotation goes to zero, as we experience in everyday life. For $v \longrightarrow 1$, this visual angle of rotation goes to 90 degrees, and the cube shows us its back side as it passes overhead. **c** The word "really" is not appropriate; each mode of observation is valid; some will be more useful than others for different applications. (Requested speech to each observer not included here.) **d** The "cube" will look sheared, with top EF pulled backward a distance x with respect to bottom GH in the left panel.

special topic

L-1a $v_{rel} = 3/17 = 0.176$ for speed of Super 6 times speed of light **b** $v_{rel} = 1/3 = 0.333$ for infinite speed of Super **L-3b** 128 days **e(1)** 0.1 meter of time; too small for either wristwatch or electronic clock **(2)** about 10^4 meters of time; too small for wristwatch but easily detected by electronic clock **(3)** distance is 10^{12} meters, or about 6.7 times the Earth-Sun distance. **L-5d** $v_{rel} = 0.944$ **L-11** The manhole is tilted, so it passes over the meter stick without collision. **L-13a** At the beginning and the end of their trip (and all during their trip), Dick and Jane are separated by 12 light-years as measured in the Earth frame. Final velocity: $v = 3/4$. Aging of each astronaut = proper time along either worldline = sum of the spacetime intervals along each segment of either worldline $= \sqrt{15} + \sqrt{12} + \sqrt{7}$ years = 10 years. **b** Yes. Yes. **c(1)** Jane stops accelerating 13.6 years earlier than Dick. **(2)** 30 years **(3)** 30 years **(4)** 43.6 years **(5)** Dick: 50 years old. Jane: 63.6 years old. **(6)** 18.1 lightyears, which is just $\gamma = 1.51$ times their 12-light-year separation measured in the Earth frame by Mom and Dad. **(d)(1)** Yes **(2)** Yes Yes **(3)** Jane's **(4)** Yes. No. **(5)** It's the old story: relativity of simultaneity, in this case the fact that Dick and Jane stop accelerating simultaneously only in the Earth frame. **e** Then, by symmetry, Dick will be older than Jane in their final rest frame. All the numbers will otherwise be the same. **f** Then they will start and stop simultaneously in Earth frame and also in the final rocket frame; they will be the same age at these stopping events in both frames. **L-15c** For the extreme relativistic case when $v_{rel} \longrightarrow 1$, then $v_{t=t'} \longrightarrow 1$ also.

chapter 4

4-1a 11.6 years **b** 18.6 years **c** 30.2 years **d** 7.67 years **e** 14.67 years **f** 22.34 years **g** 5.75 light-years **h** 7.67 years, 5.07 years **i** 14.67 years, $30.2 - 5.1 = 25.1$ years **4-3a** The engineer is wrong. **b** Frequency of oscillation increases by $\sqrt{2}$ when voltage doubles. **c** frequency in cycles/second $= f = (qV_o/8mL^2)^{1/2}$, where m and q are mass and charge of the electron, V_o is the voltage applied, and L is the width of the box = 1 meter. **d** Minimum round-trip time across box at the speed of light is $2L/c$ so $f_{max} = c/2L$. **e** For the Newtonian region, $f/f_{max} = [qV_o/(2mc^2)]^{1/2}$. For the extreme relativistic region, $f/f_{max} = 1$. The quantity qV_o is a measure of electron potential energy at the wall or electron kinetic energy at the screen.

We expect the Newtonian analysis to be correct when this energy of motion is very much less than the rest energy mc^2. The extreme relativistic analysis will be correct when qV_o is very much greater than mc^2. The crossover occurs (the two dashed curves intersect) where $qV_o \approx 2mc^2$ or $V_o \approx 10^6$ volts. **f** For low speeds, the ratio f_{proper}/f_{max} will follow the Newtonian curve. At extreme relativistic speeds, the proper time for one period → 0 and the proper frequency → infinity.

chapter 5

5-1a(1) 1 year (2) 1.94 years (3) 0.87 year (4) 3.81 years **b** 5.20 years **c** solid-line traveler will be younger **5-3a** event A is at $(x, t) = (0, 0)$; event B is at $(0, 1)$; event C is at $(1.5, 3.5)$ or $(-1.5, 3.5)$; event D is at $(3, 6)$ or $(-3, 6)$ **b** event D is at $(x, t) = (0, 0)$; event C is at $(0, -2)$; event B is at $(0, -4)$; event A is at $(-0.75, -5.25)$ or $(+0.75, -5.25)$ **c** $v_{rel} = \pm 0.6$ **d** Yes **5-5d** 3136 cycles/second **e** 31.4 cycles/second **5-7** Hint: As with most paradoxes in relativity, the solution has to do with the relativity of simultaneity.

chapter 6

6-1a Events 1 and 2: (1) Proper time: 4 meters (2) Yes (3) Yes (4) No **Events 1 and 3:** (1) Proper distance: 4 meters (2) No (3) No (4) Yes **Events 2 and 3:** (1) zero (2) Yes (3) No (4) No **b** $v_{rel} = 3/5$ in $+x$-direction for both **6-3a** Set $t' = 0$ in the first inverse Lorentz transformation equation (L-11) and solve for v_{rel}. **b** Set $x' = 0$ in the second equation (L-11) and solve for v_{rel}. (Why does the result look so funny?) **6-5a** Yes, explosion. (Sorry!) **b** No change in prediction. (The impact at A and activation of the detonation switch are spacelike events; the laser pulse cannot connect them.)

chapter 7

7-1a $[5m, \sqrt{24}m, 0, 0]$ **b** $[m, 0, 0, 0]$ **c** $[\sqrt{10}m, 0, 0, 3m]$ **d** $[5m, 0, -\sqrt{24}m, 0]$ **e** $[10\ m, 2.66\ m, 5.32\ m, 7.98\ m]$. **7-3a** 0.05 milligram **b** 0.1 milligram **7-7a** wristwatch time: 32 seconds; Earth time: 1000 centuries **b** $E/m \approx 10^{36}$. 1.7 million metric tons. **7-9a** $E_B = 9$ units **b** $p_B = \sqrt{32}$ units $= 5.66$ units **c** $m_B = 7$ units **d** greater: $m_C = 15$ units $> m_A + m_B = 9$ units **7-11a** proton: 938 MeV; electron: 0.511 MeV **b** $v_{limit} \approx 0.12$. Proton kinetic energy at limit ≈ 6 MeV. Electron kinetic energy at limit $\approx 3.4 \times 10^{-3}$ MeV $= 3.4$ keV. Yes, designer of color TV tubes (electron kinetic energy ≈ 25 keV) must use special relativity.

chapter 8

8-1a approximately 35×10^{-9} kilograms $= 35$ micrograms **b** approximately 600 kilograms. More. **c** approximately 6×10^{13} seconds or about 2 million years! Chemical burning in Eric's body produces large quantities of waste products. Elimination of these products carries away mass enormously faster than mass is carried away as energy. **8-3a** Force is approximately 3×10^{-9} newtons, or the weight of 3×10^{-10} kilograms. You should not be able to feel it. **b** pressure on a perfectly absorbing satellite $\approx 5 \times 10^{-6}$ newton/meter^2; on a perfectly reflecting satellite $\approx 9 \times 10^{-6}$ newton/meter^2; somewhere in between for a partially absorbing surface. Total energy absorbed/meter^2, not color of the incident light, determines pressure. **c** acceleration approximately 10^{-9} g **d** particle radius approximately 10^{-6} meter, independent of the distance from Sun **8-7** density approximately 5×10^{10} kilograms/meter^3 $= 5 \times 10^7$ grams/centimeter^3, or 50 million times the density of water! **8-9** $E_A = (M^2 + m^2)/(2m)$ **8-11a** From conservation equations, show that $\cos \phi > 1$, which is impossible. **b** If the total momentum is zero after the collision, it must be zero before the collision. But the alleged single photon before the collision cannot have zero momentum. Therefore the reaction is impossible. **8-13** $2E_C = E_A + (E_A{}^2 - m^2)^{1/2}$ and $2E_D = E_A - (E_A{}^2 - m^2)^{1/2}$. If the particle is at rest, then $E_A = m$ and $E_C = E_D = m/2$. **8-15a** $E_C = m(E + m)/[E + m - (E^2 - m^2)^{1/2} \cos \phi_C]$ **8-17a** 1.8 TeV **b** $E \approx 1700$ TeV **8-19e** No **8-21** When the bulb is seen way ahead, its light is very intense and radically blue-shifted. While still seen ahead, there is an angle of observation (depending on the speed) at which the light is red, but dim. As the bulb is seen to pass the observer, its light is infrared and very dim. As the bulb is seen to retreat into the distance, its light is extremely dim and radically red-shifted. **8-23a** $v = 0.38$ **b** 13×10^9 years **c** Allowance for gravitational slowing will *decrease* the estimated time back to the start of the expansion. **8-25** $\Delta f/f \approx [3kT/(mc^2)]^{1/2}$. The observed frequency will increase for molecules approaching the observer and decrease for molecules receding from the observer. The overall effect—at temperatures for which Newtonian expressions are valid—is to produce a spread of frequencies approximated by the expression above ("Doppler line broadening"). **8-27** $E' = m/2$, $E = m$, $\phi = 30$ degrees. **8-35a** The incident gamma ray (with excitation energy E) imparts a small kinetic energy K to the iron atom, for which Newtonian expression is valid: $K = p^2/2m = E^2/2m$, since $p = E$ for the gamma ray. Then (energy of recoil)/(energy for excitation) $= K/E \approx E/(2m) \approx 1.4 \times 10^{-7}$. But fractional resonance width (6×10^{-13}) is smaller than this by a factor of almost a million, so the iron nucleus cannot accept the gamma ray and conserve energy. **b** One gram is about 10^{22} atoms. If the m in the above equation increases by the factor 10^{22}, then the energy of recoil is a factor 10^{22} smaller, and the nucleus will not notice the residual mismatch in energy. **8-37** $\Delta f/f = -gz/c^2$, $v = 0.7 \times 10^{-6}$ meter/second towards emitter **8-39** $\Delta f/(f_o \Delta T) \approx (3/2)k/(mc^2) \approx 1.2 \times 10^{-15}$ per degree.