

## 1.E: Exercises

### Conceptual Questions

#### 1.2 Modeling in Physics

1. What is physics?
2. Some have described physics as a “search for simplicity.” Explain why this might be an appropriate description.
3. If two different theories describe experimental observations equally well, can one be said to be more valid than the other (assuming both use accepted rules of logic)?
4. What determines the validity of a theory?
5. Certain criteria must be satisfied if a measurement or observation is to be believed. Will the criteria necessarily be as strict for an expected result as for an unexpected result?
6. Can the validity of a model be limited or must it be universally valid? How does this compare with the required validity of a theory or a law?

#### 1.3 Units and Standards

7. Identify some advantages of metric units.
8. What are the SI base units of length, mass, and time?
9. What is the difference between a base unit and a derived unit? (b) What is the difference between a base quantity and a derived quantity? (c) What is the difference between a base quantity and a base unit?
10. For each of the following scenarios, refer to Figure 1.4 and Table 1.2 to determine which metric prefix on the meter is most appropriate for each of the following scenarios. (a) You want to tabulate the mean distance from the Sun for each planet in the solar system. (b) You want to compare the sizes of some common viruses to design a mechanical filter capable of blocking the pathogenic ones. (c) You want to list the diameters of all the elements on the periodic table. (d) You want to list the distances to all the stars that have now received any radio broadcasts sent from Earth 10 years ago.

### Problems

#### 1.3 Units and Standards

For the remaining questions, you need to use Figure 1.4 to obtain the necessary orders of magnitude of lengths, masses, and times.

1. Find the order of magnitude of the following physical quantities.
  - a. The mass of Earth’s atmosphere:  $5.1 \times 10^{18}$  kg;
  - b. The mass of the Moon’s atmosphere: 25,000 kg;
  - c. The mass of Earth’s hydrosphere:  $1.4 \times 10^{21}$  kg;
  - d. The mass of Earth:  $5.97 \times 10^{24}$  kg;
  - e. The mass of the Moon:  $7.34 \times 10^{22}$  kg;
  - f. The Earth–Moon distance (semi-major axis):  $3.84 \times 10^8$  m;
  - g. The mean Earth–Sun distance:  $1.5 \times 10^{11}$  m;
  - h. The equatorial radius of Earth:  $6.38 \times 10^6$  m;
  - i. The mass of an electron:  $9.11 \times 10^{-31}$  kg;
  - j. The mass of a proton:  $1.67 \times 10^{-27}$  kg;
  - k. The mass of the Sun:  $1.99 \times 10^{30}$  kg.
2. Use the orders of magnitude you found in the previous problem to answer the following questions to within an order of magnitude.
  - a. How many electrons would it take to equal the mass of a proton?
  - b. How many Earths would it take to equal the mass of the Sun?
  - c. How many Earth–Moon distances would it take to cover the distance from Earth to the Sun?
  - d. How many Moon atmospheres would it take to equal the mass of Earth’s atmosphere?
  - e. How many moons would it take to equal the mass of Earth?
  - f. How many protons would it take to equal the mass of the Sun?
3. Roughly how many heartbeats are there in a lifetime?
4. A generation is about one-third of a lifetime. Approximately how many generations have passed since the year 0 AD?

5. Roughly how many times longer than the mean life of an extremely unstable atomic nucleus is the lifetime of a human?
6. Calculate the approximate number of atoms in a bacterium. Assume the average mass of an atom in the bacterium is 10 times the mass of a proton.
7. (a) Calculate the number of cells in a hummingbird assuming the mass of an average cell is 10 times the mass of a bacterium.  
(b) Making the same assumption, how many cells are there in a human?
8. Assuming one nerve impulse must end before another can begin, what is the maximum firing rate of a nerve in impulses per second?
9. About how many floating-point operations can a supercomputer perform each year?
10. Roughly how many floating-point operations can a supercomputer perform in a human lifetime?
11. The following times are given using metric prefixes on the base SI unit of time: the second. Rewrite them in scientific notation without the prefix. For example, 47 Ts would be rewritten as  $4.7 \times 10^{13}$  s.
  - a. 980 Ps;
  - b. 980 fs;
  - c. 17 ns;
  - d. 577  $\mu$ s.
12. The following times are given in seconds. Use metric prefixes to rewrite them so the numerical value is greater than one but less than 1000. For example,  $7.9 \times 10^{-2}$  s could be written as either 7.9 cs or 79 ms.
  - a.  $9.57 \times 10^5$  s;
  - b. 0.045 s;
  - c.  $5.5 \times 10^{-7}$  s;
  - d.  $3.16 \times 10^7$  s.
13. The following lengths are given using metric prefixes on the base SI unit of length: the meter. Rewrite them in scientific notation without the prefix. For example, 4.2 Pm would be rewritten as  $4.2 \times 10^{15}$  m.
  - a. 89 Tm;
  - b. 89  $\mu$ m;
  - c. 711 mm;
  - d. 0.45  $\mu$ m.
14. The following lengths are given in meters. Use metric prefixes to rewrite them so the numerical value is bigger than one but less than 1000. For example,  $7.9 \times 10^{-2}$  m could be written either as 7.9 cm or 79 mm.
  - a.  $7.59 \times 10^7$  m;
  - b. 0.0074 m;
  - c.  $8.8 \times 10^{-11}$  m;
  - d.  $1.63 \times 10^{13}$  m.
15. The following masses are written using metric prefixes on the gram. Rewrite them in scientific notation in terms of the SI base unit of mass: the kilogram. For example, 40 Mg would be written as  $4 \times 10^4$  kg.
  - a. 23 mg;
  - b. 320 Tg;
  - c. 42 ng;
  - d. 7 g;
  - e. 9 Pg.
16. The following masses are given in kilograms. Use metric prefixes on the gram to rewrite them so the numerical value is bigger than one but less than 1000. For example,  $7 \times 10^{-4}$  kg could be written as 70 cg or 700 mg.
  - a.  $3.8 \times 10^{-5}$  kg;
  - b.  $2.3 \times 10^{17}$  kg;
  - c.  $2.4 \times 10^{-11}$  kg;
  - d.  $8 \times 10^{15}$  kg;
  - e.  $4.2 \times 10^{-3}$  kg.

## 1.4 Unit Conversion

17. The volume of Earth is on the order of  $10^{21} \text{ m}^3$ . (a) What is this in cubic kilometers ( $\text{km}^3$ )? (b) What is it in cubic miles ( $\text{mi}^3$ )? (c) What is it in cubic centimeters ( $\text{cm}^3$ )?
18. The speed limit on some interstate highways is roughly 100 km/h. (a) What is this in meters per second? (b) How many miles per hour is this?
19. A car is traveling at a speed of 33 m/s. (a) What is its speed in kilometers per hour? (b) Is it exceeding the 90 km/h speed limit?
20. In SI units, speeds are measured in meters per second (m/s). But, depending on where you live, you're probably more comfortable of thinking of speeds in terms of either kilometers per hour (km/h) or miles per hour (mi/h). In this problem, you will see that 1 m/s is roughly 4 km/h or 2 mi/h, which is handy to use when developing your physical intuition. More precisely, show that (a)  $1.0 \text{ m/s} = 3.6 \text{ km/h}$  and (b)  $1.0 \text{ m/s} = 2.2 \text{ mi/h}$ .
21. American football is played on a 100-yd-long field, excluding the end zones. How long is the field in meters? (Assume that  $1 \text{ m} = 3.281 \text{ ft}$ .)
22. Soccer fields vary in size. A large soccer field is 115 m long and 85.0 m wide. What is its area in square feet? (Assume that  $1 \text{ m} = 3.281 \text{ ft}$ .)
23. What is the height in meters of a person who is 6 ft 1.0 in. tall?
24. Mount Everest, at 29,028 ft, is the tallest mountain on Earth. What is its height in kilometers? (Assume that  $1 \text{ m} = 3.281 \text{ ft}$ .)
25. The speed of sound is measured to be 342 m/s on a certain day. What is this measurement in kilometers per hour?
26. Tectonic plates are large segments of Earth's crust that move slowly. Suppose one such plate has an average speed of 4.0 cm/yr. (a) What distance does it move in 1.0 s at this speed? (b) What is its speed in kilometers per million years?
27. The average distance between Earth and the Sun is  $1.5 \times 10^{11} \text{ m}$ . (a) Calculate the average speed of Earth in its orbit (assumed to be circular) in meters per second. (b) What is this speed in miles per hour?
28. The density of nuclear matter is about  $10^{18} \text{ kg/m}^3$ . Given that 1 mL is equal in volume to  $\text{cm}^3$ , what is the density of nuclear matter in megagrams per microliter (that is,  $\text{Mg}/\mu\text{L}$ )?
29. The density of aluminum is  $2.7 \text{ g/cm}^3$ . What is the density in kilograms per cubic meter?
30. A commonly used unit of mass in the English system is the pound-mass, abbreviated lbm, where  $1 \text{ lbm} = 0.454 \text{ kg}$ . What is the density of water in pound-mass per cubic foot?
31. A furlong is 220 yd. A fortnight is 2 weeks. Convert a speed of one furlong per fortnight to millimeters per second.
32. It takes  $2\pi$  radians (rad) to get around a circle, which is the same as  $360^\circ$ . How many radians are in  $1^\circ$ ?
33. Light travels a distance of about  $3 \times 10^8 \text{ m/s}$ . A light-minute is the distance light travels in 1 min. If the Sun is  $1.5 \times 10^{11} \text{ m}$  from Earth, how far away is it in lightminutes?
34. A light-nanosecond is the distance light travels in 1 ns. Convert 1 ft to light-nanoseconds.
35. An electron has a mass of  $9.11 \times 10^{-31} \text{ kg}$ . A proton has a mass of  $1.67 \times 10^{-27} \text{ kg}$ . What is the mass of a proton in electron-masses?
36. A fluid ounce is about 30 mL. What is the volume of a 12 fl-oz can of soda pop in cubic meters?

## 1.5 Dimensional Analysis

37. A student is trying to remember some formulas from geometry. In what follows, assume  $A$  is area,  $V$  is volume, and all other variables are lengths. Determine which formulas are dimensionally consistent. (a)  $V = \pi r^2 h$ ; (b)  $A = 2\pi r^2 + 2\pi r h$ ; (c)  $V = 0.5bh$ ; (d)  $V = \pi d^2$ ; (e)  $V = \frac{\pi d^3}{6}$
38. Consider the physical quantities  $s$ ,  $v$ ,  $a$ , and  $t$  with dimensions  $[s] = L$ ,  $[v] = LT^{-1}$ ,  $[a] = LT^{-2}$ , and  $[t] = T$ . Determine whether each of the following equations is dimensionally consistent. (a)  $v^2 = 2as$ ; (b)  $s = vt^2 + 0.5at^2$ ; (c)  $v = s/t$ ; (d)  $a = v/t$ .
39. Consider the physical quantities  $m$ ,  $s$ ,  $v$ ,  $a$ , and  $t$  with dimensions  $[m] = M$ ,  $[s] = L$ ,  $[v] = LT^{-1}$ ,  $[a] = LT^{-2}$ , and  $[t] = T$ . Assuming each of the following equations is dimensionally consistent, find the dimension of the quantity on the left-hand side of the equation: (a)  $F = ma$ ; (b)  $K = 0.5mv^2$ ; (c)  $p = mv$ ; (d)  $W = mas$ ; (e)  $L = mvr$ .
40. Suppose quantity  $s$  is a length and quantity  $t$  is a time. Suppose the quantities  $v$  and  $a$  are defined by  $v = ds/dt$  and  $a = dv/dt$ . (a) What is the dimension of  $v$ ? (b) What is the dimension of the quantity  $a$ ? What are the dimensions of (c)  $\int v dt$ , (d)  $\int a dt$ , and (e)  $da/dt$ ?
41. Suppose  $[V] = L^3$ ,  $[p] = ML^{-3}$ , and  $[t] = T$ . (a) What is the dimension of  $\int \rho dV$ ? (b) What is the dimension of  $dV/dt$ ? (c) What is the dimension of  $\rho(dV/dt)$ ?
42. The arc length formula says the length  $s$  of arc subtended by angle  $\Theta$  in a circle of radius  $r$  is given by the equation  $s = r\Theta$ . What are the dimensions of (a)  $s$ , (b)  $r$ , and (c)  $\Theta$ ?

## 1.6 Estimates and Fermi Calculations

43. Assuming the human body is made primarily of water, estimate the volume of a person.
44. Assuming the human body is primarily made of water, estimate the number of molecules in it. (Note that water has a molecular mass of 18 g/mol and there are roughly  $10^{24}$  atoms in a mole.)
45. Estimate the mass of air in a classroom.
46. Estimate the number of molecules that make up Earth, assuming an average molecular mass of 30 g/mol. (Note there are on the order of  $10^{24}$  objects per mole.)
47. Estimate the surface area of a person.
48. Roughly how many solar systems would it take to tile the disk of the Milky Way?
49. (a) Estimate the density of the Moon. (b) Estimate the diameter of the Moon. (c) Given that the Moon subtends at an angle of about half a degree in the sky, estimate its distance from Earth.
50. The average density of the Sun is on the order  $10^3 \text{ kg/m}^3$ . (a) Estimate the diameter of the Sun. (b) Given that the Sun subtends at an angle of about half a degree in the sky, estimate its distance from Earth. 64. Estimate the mass of a virus.
51. A floating-point operation is a single arithmetic operation such as addition, subtraction, multiplication, or division. (a) Estimate the maximum number of floating-point operations a human being could possibly perform in a lifetime. (b) How long would it take a supercomputer to perform that many floating-point operations?
52. Calculate the approximate mass and volume (both in SI units) of ketchup that your college uses every year (assume water's density of  $1,000 \text{ kg/m}^3$ )? Be sure to state all assumptions and be explicit in your calculations.

## Challenge Problems

53. The first atomic bomb was detonated on July 16, 1945, at the Trinity test site about 200 mi south of Los Alamos. In 1947, the U.S. government declassified a film reel of the explosion. From this film reel, British physicist G. I. Taylor was able to determine the rate at which the radius of the fireball from the blast grew. Using dimensional analysis, he was then able to deduce the amount of energy released in the explosion, which was a closely guarded secret at the time. Because of this, Taylor did not publish his results until 1950. This problem challenges you to recreate this famous calculation.
  - a. Using keen physical insight developed from years of experience, Taylor decided the radius  $r$  of the fireball should depend only on time since the explosion,  $t$ , the density of the air,  $\rho$ , and the energy of the initial explosion,  $E$ . Thus, he made the educated guess that  $r = kE^a \rho^b t^c$  for some dimensionless constant  $k$  and some unknown exponents  $a$ ,  $b$ , and  $c$ . Given that  $[E] = \text{ML}^2\text{T}^{-2}$ , determine the values of the exponents necessary to make this equation dimensionally consistent. (Hint: Notice the equation implies that  $k = rE^{-a} \rho^{-b} t^{-c}$  and that  $[k] = 1$ .)
  - b. By analyzing data from high-energy conventional explosives, Taylor found the formula he derived seemed to be valid as long as the constant  $k$  had the value 1.03. From the film reel, he was able to determine many values of  $r$  and the corresponding values of  $t$ . For example, he found that after 25.0 ms, the fireball had a radius of 130.0 m. Use these values, along with an average air density of  $1.25 \text{ kg/m}^3$ , to calculate the initial energy release of the Trinity detonation in joules (J). (Hint: To get energy in joules, you need to make sure all the numbers you substitute in are expressed in terms of SI base units.) (c) The energy released in large explosions is often cited in units of "tons of TNT" (abbreviated "t TNT"), where 1 t TNT is about 4.2 GJ. Convert your answer to (b) into kilotons of TNT (that is, kt TNT). Compare your answer with the quick-and-dirty estimate of 10 kt TNT made by physicist Enrico Fermi shortly after witnessing the explosion from what was thought to be a safe distance. (Reportedly, Fermi made his estimate by dropping some shredded bits of paper right before the remnants of the shock wave hit him and looked to see how far they were carried by it.)

## Contributors and Attributions

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