Simplifying (dividing each value by the lowest), we obtain a ratio of 1.000 : 1.99 : 1.000, or almost exactly 1 : 2 : 1, making the empirical formula for the lactic acid CH_2O.

(b) Given a molar mass for lactic acid of 90 g/mol, and a molar mass for CH_2O (the empirical formula) of 30.03 g/mol, the molecular formula must be triple the empirical ratio, or $C_3H_6O_3$.

Applying Inquiry Skills

7. (a) **Procedure**

   1. Use a centigram balance to measure the masses of a penny and of a quarter, to 0.01 g.
   2. Use a decigram balance to measure the total masses of the pennies and of the quarters, to 0.1 g.
   3. Divide the total mass of the pennies by the mass of one penny to calculate the number of pennies.
   4. Divide the total mass of the quarters by the mass of one quarter to calculate the number of quarters.
   5. Express the numbers of the two types of coins as a ratio.

   (b) A parallel procedure a scientist might use:

   1. Use a reference to find the molar masses of each kind of atom in the compound, to 0.01 g/mol.
   2. Use a combustion analyzer to measure the total masses of each kind of atom in the compound, to 0.01 g.
   3. Divide the total mass of each type of atom by the molar mass, to calculate the amount of atoms.
   4. Express the numbers of the different types of atoms as a simplest integral ratio.

CHAPTER 4 REVIEW

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Understanding Concepts

1. Every compound has a specific proportion of constituent substances. This led scientists to the concept of specific kinds of atoms for each element, and to comparing their combining masses to obtain a relative scale of masses of atoms.
2. The relative atomic mass would be (exactly) 24 u.
3. A hydrogen atom would be 18/12 of its current mass, or 1.5×1.01 u, or 1.52 u.
4. Relative atomic masses cannot be assigned correctly unless the combining ratio is correctly known; so the correct molecular formula is necessary.
5. Elements consist of atoms with identical numbers of protons and electrons. The nuclei of atoms of elements, however, may vary in numbers of neutrons, which has negligible effect on chemical properties, but does change the atom's mass significantly. For nearly every element there are several of these *isotopes*, and the average mass of atoms of such an element is a value that depends on the mass of these isotopes and also their proportion in nature. The classic example is chlorine, where roughly 3/4 of any sample will consist of chlorine-35 atoms (molar mass 35.00 g/mol), and roughly 1/4 of the sample will be chlorine-37 atoms (molar mass 37.00 g/mol). The molar mass of chlorine, then, is the *average* molar mass of all the chlorine atoms in a sample, which works out to 35.45 g/mol.
6. For silicon, with significant amounts of three isotopes, and if we assume the molar mass of isotopes is the same as the mass number, to two decimals (which is approximately valid, although the last digit is uncertain ...)

$$M = [(0.9221 \times 28.00) + (0.0470 \times 29.00) + (0.0309 \times 30.00)] \text{ g/mol}$$

$$M = 28.11 \text{ g/mol} \qquad \text{(The actual value is 28.09 g/mol.)}$$

7. (a) 12 u exactly (by definition)

   (b) 12 g exactly (by definition)

   (c) Avogadro's constant is (by definition) the number of entities in exactly 12 g of pure carbon-12. This number is used to define the mole, which is the (numerical) amount of any substance that is this number of entities (atoms, ions, molecules, or formula units).

   (d) The symbol *M* represents the quantity, molar mass, in g/mol units.

8. (a) Formula: $CaCO_{3(s)}$

$$M = [(40.08) + (12.01) + (16.00 \times 3)]$$

$$M = 100.09 \text{ g/mol}$$

(b) Formula: $N_2O_{4(g)}$

$M = [(14.01 \times 2) + (16.00 \times 4)]$

$M = 92.02$ g/mol

(c) Formula: $Na_2CO_3 \cdot 10H_2O_{(s)}$

$M = [(22.99 \times 2) + (12.01) + (16.00 \times 3) + (18.02 \times 10)]$

$M = 286.19$ g/mol

Note: The last solution above assumes that students will have memorized the molar mass of water — an extremely useful quantity to commit to memory. For future study, memorization of the molar mass of carbon dioxide, 44.01 g/mol, will be almost as useful, because it is a product in so many reactions.

9. (a) $m_{NaCl} = 1.000$ kg

$M_{NaCl} = 58.44$ g/mol

$n_{NaCl} = 1.000 \text{ k}\cancel{\text{g}} \times \frac{1 \text{ mol}}{58.44 \cancel{\text{g}}}$

$n_{NaCl} = 0.01711$ kmol $= 17.11$ mol

1.000 kg of table salt is 17.11 mol.

(b) $m_{CO_2} = 1.000$ kg

$M_{CO_2} = 44.01$ g/mol

$n_{CO_2} = 1.000 \text{ k}\cancel{\text{g}} \times \frac{1 \text{ mol}}{44.01 \cancel{\text{g}}}$

$n_{CO_2} = 0.02272$ kmol $= 22.72$ mol

1.000 kg of dry ice is 22.72 mol.

(c) $m_{H_2O} = 1.000$ kg

$M_{H_2O} = 18.02$ g/mol

$n_{H_2O} = 1.000 \text{ k}\cancel{\text{g}} \times \frac{1 \text{ mol}}{18.02 \cancel{\text{g}}}$

$n_{H_2O} = 0.05549$ kmol $= 55.49$ mol

1.000 kg of water is 55.49 mol.

10. (a) $n_{O_2} = 1.50$ mol

$M_{O_2} = 32.00$ g/mol

$m_{O_2} = 1.50 \cancel{\text{mol}} \times \frac{32.00 \text{ g}}{1 \cancel{\text{mol}}}$

$m_{O_2} = 48.0$ g

1.50 mol of liquid oxygen is 48.0 g.

(b) $n_{Hg} = 1.50$ mmol

$M_{Hg} = 200.59$ g/mol

$m_{Hg} = 1.50 \text{ m}\cancel{\text{mol}} \times \frac{200.59 \text{ g}}{1 \cancel{\text{mol}}}$

$m_{Hg} = 301$ mg (or 0.301 g)

1.50 mmol of liquid mercury is 301 mg.

(c) $n_{Br_2} = 1.50$ kmol

$M_{Br_2} = 159.80$ g/mol

$m_{Br_2} = 1.50 \text{ k}\cancel{\text{mol}} \times \frac{159.80 \text{ g}}{1 \cancel{\text{mol}}}$

$m_{Br_2} = 240\ \text{kg}$

1.50 kmol of liquid bromine is 240 kg.

11.(a) $n_{HC_2H_3O_2} = 0.42\ \text{mol}$

$N_A = 6.02 \times 10^{23}\ \text{(entities)/mol}$

$$N_{HC_2H_3O_2} = 0.42\ \cancel{\text{mol}} \times \frac{6.02 \times 10^{23}}{1\ \cancel{\text{mol}}}$$

$$N_{HC_2H_3O_2} = 2.5 \times 10^{23}$$

0.42 mol of acetic acid is 2.5×10^{23} molecules.

(b) $n_{CO} = 7.6 \times 10^{-4}\ \text{mol}$

$N_A = 6.02 \times 10^{23}\ \text{(entities)/mol}$

$$N_{CO} = 7.6 \times 10^{-4}\ \cancel{\text{mol}} \times \frac{6.02 \times 10^{23}}{1\ \cancel{\text{mol}}}$$

$$N_{CO} = 4.6 \times 10^{20}$$

7.6×10^{-4} mol of carbon monoxide is 4.6×10^{20} molecules.

(c) $m_{CCl_4} = 100\ \text{g}$

$M_{CCl_4} = 153.81\ \text{g/mol}$

$N_A = 6.02 \times 10^{23}\ \text{(entities)/mol}$

$$n_{CCl_4} = 100\ \cancel{\text{g}} \times \frac{1\ \text{mol}}{153.81\ \cancel{\text{g}}}$$

$$n_{CCl_4} = 0.650\ \text{mol}$$

$$N_{CCl_4} = 0.650\ \cancel{\text{mol}} \times \frac{6.02 \times 10^{23}}{1\ \cancel{\text{mol}}}$$

$$N_{CCl_4} = 3.91 \times 10^{23}$$

or

$$N_{CCl_4} = 100\ \cancel{\text{g}} \times \frac{1\ \cancel{\text{mol}}}{153.81\ \cancel{\text{g}}} \times \frac{6.02 \times 10^{23}}{1\ \cancel{\text{mol}}}$$

$$N_{CCl_4} = 3.91 \times 10^{23}$$

100 g of carbon tetrachloride is 3.91×10^{23} molecules.

(d) $m_{H_2S} = 100\ \text{g}$

$M_{H_2S} = 34.08\ \text{g/mol}$

$N_A = 6.02 \times 10^{23}\ \text{(entities)/mol}$

$$n_{H_2S} = 100\ \cancel{\text{g}} \times \frac{1\ \text{mol}}{34.08\ \cancel{\text{g}}}$$

$$n_{H_2S} = 2.93\ \text{mol}$$

$$N_{H_2S} = 2.93\ \cancel{\text{mol}} \times \frac{6.02 \times 10^{23}}{1\ \cancel{\text{mol}}}$$

$$N_{H_2S} = 1.77 \times 10^{24}$$

or

$$N_{H_2S} = 100\ \cancel{\text{g}} \times \frac{1\ \cancel{\text{mol}}}{34.08\ \cancel{\text{g}}} \times \frac{6.02 \times 10^{23}}{1\ \cancel{\text{mol}}}$$

$$N_{H_2S} = 1.77 \times 10^{24}$$

100 g of hydrogen sulfide is 1.77×10^{24} molecules.

12. (a) $M_{C_{14}H_{18}N_2O_5} = [(12.01 \times 14) + (1.01 \times 18) + (14.01 \times 2) + (16.00 \times 5)]$ g/mol

$M_{C_{14}H_{18}N_2O_5} = 294.34$ g/mol

The molar mass of Aspartame is 294.34 g/mol

(b) $m_{C_{14}H_{18}N_2O_5} = 35$ mg

$M_{C_{14}H_{18}N_2O_5} = 294.34$ g/mol

$n_{C_{14}H_{18}N_2O_5} = 35 \text{ m}\cancel{\text{g}} \times \frac{1 \text{ mol}}{294.34 \cancel{\text{g}}}$

$n_{C_{14}H_{18}N_2O_5} = 0.12$ mmol

35 mg of Aspartame is 0.12 mmol.

(c) $n_{C_{14}H_{18}N_2O_5} = 0.12 \text{ mmol} = 1.2 \times 10^{-4}$ mol

$N_A = 6.02 \times 10^{23}$ (entities)/mol

$N_{C_{14}H_{18}N_2O_5} = 1.2 \times 10^{-4} \cancel{\text{mol}} \times \frac{6.02 \times 10^{23}}{1 \cancel{\text{mol}}}$

$N_{C_{14}H_{18}N_2O_5} = 7.2 \times 10^{19}$

$N_H = 7.2 \times 10^{19} \times 18$

$N_H = 1.3 \times 10^{21}$

35 mg of Aspartame contains 1.3×10^{21} hydrogen atoms.

13. (a) Assume one mole of compound, for convenience.

$m_{Na^+} = 22.99 \frac{\text{g}}{\cancel{\text{mol}}} \times 1 \cancel{\text{mol}} = 22.99$ g

$m_{NaN_{3(s)}} = 65.02$ g

$\% \text{ Na}^+ = \frac{22.99 \cancel{\text{g}}}{65.02 \cancel{\text{g}}} \times 100\%$

$\% \text{ Na}^+ = 35.36\%$

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The percentage, by mass, of sodium ions in $NaN_{3(s)}$ is 35.36%.

(b) Assume one mole of compound, for convenience.

$m_{Al^{3+}} = 26.98 \frac{\text{g}}{\cancel{\text{mol}}} \times 2 \cancel{\text{mol}} = 53.96$ g

$m_{Al_2O_{3(s)}} = 101.96$ g

$\% \text{ Al}^{3+} = \frac{53.96 \cancel{\text{g}}}{101.96 \cancel{\text{g}}} \times 100\%$

$\% \text{ Al}^{3+} = 52.92\%$

The percentage, by mass, of aluminum ions in $Al_2O_{3(s)}$ is 52.92%.

(c) Assume one mole of compound, for convenience.

$m_N = 14.01 \frac{\text{g}}{\cancel{\text{mol}}} \times 1 \cancel{\text{mol}} = 14.01$ g

$m_{C_8H_{11}NO_{2(s)}} = 153.20$ g

$\% \text{ N} = \frac{14.01 \cancel{\text{g}}}{153.20 \cancel{\text{g}}} \times 100\%$

$\% \text{ N} = 9.145\%$

The percentage, by mass, of nitrogen atoms in $C_8H_{11}NO_{2(aq)}$ is 9.145%.

14. (a) An empirical formula gives the simplest integral ratio of the constituent atoms of a compound, while a molecular formula also gives the correct actual number of atoms in one molecule.

(b) An empirical formula is just a proportion of atoms, and cannot give a correct number of atoms per molecule without evidence of the mass of the molecule — it is like saying Tom is twice as old as Harry, when, without the age of one, the other's age cannot be determined.

15. (a) Assume a 100.00 g sample, for percentage conversion convenience.

m_C = 49.5 g $\quad M_C$ = 12.01 g/mol

m_H = 5.15 g $\quad M_H$ = 1.01 g/mol

m_N = 28.9 g $\quad M_N$ = 14.01 g/mol

m_O = (by subtraction) = 16.5 g $\quad M_O$ = 16.00 g/mol

$$n_C = 49.5\ \cancel{g} \times \frac{1\ \text{mol}}{12.01\ \cancel{g}}$$

$$n_C = 4.12\ \text{mol}$$

$$n_H = 5.15\ \cancel{g} \times \frac{1\ \text{mol}}{1.01\ \cancel{g}}$$

$$n_H = 5.10\ \text{mol}$$

$$n_N = 28.9\ \cancel{g} \times \frac{1\ \text{mol}}{14.01\ \cancel{g}}$$

$$n_N = 2.06\ \text{mol}$$

$$n_O = 16.5\ \cancel{g} \times \frac{1\ \text{mol}}{16.00\ \cancel{g}}$$

$$n_O = 1.03\ \text{mol}$$

The mole ratio, C : H : N : O, is 4.12 : 5.10 : 2.06 : 1.03.

Simplifying (dividing each value by the lowest), we obtain a ratio of 4.00 : 4.95 : 2.00 : 1.00, or almost exactly 4 : 5 : 2 : 1, making the empirical formula for the caffeine $C_4H_5N_2O$.

(b) Since the molar mass of the caffeine is 195 g/mol, about double the value of 97.11g/mol that we get for $C_4H_5N_2O$, the molecular formula must be $C_8H_{10}N_4O_2$.

16. (a) m_C = 3.161 g $\quad M_C$ = 12.01 g/mol

m_H = 0.266 g $\quad M_H$ = 1.01 g/mol

m_O = 1.052 g $\quad M_O$ = 16.00 g/mol

$$n_C = 3.161\ \cancel{g} \times \frac{1\ \text{mol}}{12.01\ \cancel{g}}$$

$$n_C = 0.2632\ \text{mol}$$

$$n_H = 0.266\ \cancel{g} \times \frac{1\ \text{mol}}{1.01\ \cancel{g}}$$

$$n_H = 0.263\ \text{mol}$$

$$n_O = 1.052\ \cancel{g} \times \frac{1\ \text{mol}}{16.00\ \cancel{g}}$$

$$n_O = 0.06575\ \text{mol}$$

The mole ratio, C : H : O, is 0.2632 : 0.263 : 0.06575.
Simplifying (dividing each value by the lowest), we obtain a ratio of 4.00 : 4.00 : 1.00, making the empirical formula for the ester C_4H_4O.

(b) Since the molar mass of the ester is 136 g/mol, about double the value of 68.08 g/mol that we get for C_4H_4O, the molecular formula must be $C_8H_8O_2$.

17. Assume a 100.00 g sample, for percentage conversion convenience.

m_C = 63.2 g $\quad M_C$ = 12.01 g/mol

m_H = 5.26 g $\quad M_H$ = 1.01 g/mol

m_O = 31.6 g $\quad M_O$ = 16.00 g/mol

$$n_C = 63.2\ \cancel{g} \times \frac{1\ \text{mol}}{12.01\ \cancel{g}}$$

$$n_C = 5.26\ \text{mol}$$

$$n_H = 5.26\ \cancel{g} \times \frac{1\ \text{mol}}{1.01\ \cancel{g}}$$

$$n_H = 5.21\ \text{mol}$$

$$n_O = 31.6\ \cancel{g} \times \frac{1\ \text{mol}}{16.00\ \cancel{g}}$$

$$n_O = 1.98\ \text{mol}$$

Simplifying (dividing each value by the lowest), we obtain a ratio of 2.66 : 2.63 : 1.00, which is not an integral ratio. Tripling this ratio gives 7.97 : 7.89 : 3.00, or almost exactly 8 : 8 : 3, making the empirical formula for the vanillin $C_8H_8O_3$.

18. m_{Na^+} = 22.99 u × 3 = 68.97 u

m_P = 30.97 u × 1 = 30.97 u

m_O = 16.00 u × 4 = 64.00 u

$m_{Na_3PO_{4(aq)}}$ = 163.94 u

$$\%\ Na^+ = \frac{68.97\ \cancel{u}}{163.94\ \cancel{u}} \times 100\%$$

$$\%\ Na^+ = 42.07\%$$

$$\%\ P = \frac{30.97\ \cancel{u}}{163.94\ \cancel{u}} \times 100\%$$

$$\%\ P = 18.89\%$$

$$\%\ O = \frac{64.00\ \cancel{u}}{163.94\ \cancel{u}} \times 100\%$$

$$\%\ O = 39.04\%$$

The percentage composition of $Na_3PO_{4(aq)}$ is 42.07% sodium ions, 18.89% phosphorus atoms, and 39.04% oxygen atoms, by mass.

19. m_{Na^+} = 22.99 u × 3 = 68.97 u

m_{As} = 30.97 u × 1 = 74.92 u

m_O = 16.00 u × 4 = 64.00 u

$m_{Na_3AsO_{4(aq)}}$ = 207.89 u

$$\%\ Na^+ = \frac{68.97\ \cancel{u}}{207.89\ \cancel{u}} \times 100\%$$

$$\%\ Na^+ = 33.18\%$$

$$\%\ As = \frac{74.92\ \cancel{u}}{207.89\ \cancel{u}} \times 100\%$$

$$\%\ As = 36.04\%$$

$$\% \text{ O} = \frac{64.00 \cancel{\text{u}}}{207.89 \cancel{\text{u}}} \times 100\%$$

$$\% \text{ O} = 30.79\%$$

The percentage composition of $Na_3AsO_{4(aq)}$ is 33.18% sodium ions, 36.04% arsenic atoms, and 30.79% oxygen atoms, by mass.

Applying Inquiry Skills

20. (a) **Analysis**

$m_{Zn} = (36.244 - 35.603)\text{ g} = 0.641\text{ g}$ $\qquad M_{Zn} = 65.38\text{ g/mol}$

$m_{compound} = (36.933 - 35.603)\text{ g} = 1.330\text{ g}$

$m_{Cl} = (1.330 - 0.641)\text{ g} = 0.689\text{ g}$ $\qquad M_{Cl} = 35.45\text{ g/mol}$

$$n_{Zn^{2+}} = 0.641 \cancel{\text{g}} \times \frac{1\text{ mol}}{65.38 \cancel{\text{g}}}$$

$$n_{Zn^{2+}} = 0.00980\text{ mol}$$

$$n_{Cl^-} = 0.689 \cancel{\text{g}} \times \frac{1\text{ mol}}{35.45 \cancel{\text{g}}}$$

$$n_{Cl^-} = 0.0194\text{ mol}$$

Simplifying (dividing each value by the lowest), we obtain a ratio of 1.00 : 1.98, or almost exactly 1 : 2, making the empirical formula for the compound $ZnCl_2$.

(b) **Evaluation**

The design is simple and straightforward, and is likely to provide reliable evidence, from which the answer can be easily calculated.

21. (a) If the mass of the nail is measured before and after reaction, the mass difference will be copper, and can be used to determine the number of atoms.
(b) Besides the evidence from (a), the molar mass of copper and the value of Avogadro's constant will be needed.
(c) If the mass of copper(II) sulfate is initially measured, and the reaction is continued until all of the copper(II) ions react, then masses can be obtained to allow the determination of percentage by mass of copper in the compound.

22. (a) The crucible and lid are preheated to drive off any combustible or vaporizable material, so the mass of the crucible will not change later when heated.
(b) Handling hot equipment means wearing proper clothing, using heat-resistant gloves or tongs, and being careful not to set hot materials down on unprotected bench tops.

23. Subtracting the mass of the element from the mass of the oxide formed should give the mass of oxygen reacted.

Making Connections

24. Carbon monoxide and carbon dioxide are formed from the same elements; but one of these compounds is highly toxic to humans, and the other is not.

25. Moles are used for medical materials because the reaction quantities are the principal concern, and reaction equations are dependent on numerical amounts. For foods, masses are common because that is the easy and convenient way to measure how much food there is in a package or container.

26. Typical answers might include ...
(a) Food testing
Water treatment
Cement manufacturing
Plastics manufacturing
Prescription lens grinding
(b) Natural gas treatment labs
Water quality test labs
Steel composition analysis
Lubricant contamination analysis
Air quality test facilities

Exploring

27. Typical information ...
    Salicylate compounds were known to be painkillers by the 5th century B.C. In an attempt to find a relief from arthritic pain for his father, Felix Hoffmann first synthesized acetylsalicylic acid in 1893. The compound was named Aspirin and was being marketed by the Bayer corporation in 1897. By 1899 Heinrich Dreser was routinely using this drug to treat arthritis.
    GO TO www.science.nelson.com, Chemistry 11, Teacher Centre.

28. Typical information ...
    The most recent value for Avogadro's constant is obtained by precise measuring of atomic (ionic) sizes in metallic crystals, yielding a value with 9 significant digits — $6.022\ 141\ 99 \times 10^{23}$ entities.
    GO TO www.science.nelson.com, Chemistry 11, Teacher Centre.

29. Typical information ...
    Cheese has been made for at least 5500 years. The protein casein, in milk, clumps into curds upon the addition of rennin. Cottage cheese is sold in this initial stage. These curds may be heated, pressed, or strained to remove liquid whey. Cheddaring is the process of compressing curds to remove moisture. Many cheeses are also "ripened" by treatment with bacteria and/or moulds, which may be added into the cheese (internal treatment, like Roquefort) or rubbed on the surface (surface treatment, like Brie or Camembert). The texture and flavour of cheeses depends primarily on their moisture content and the agents used to ripen them. The holes in Swiss cheese are formed during ripening by gases produced by the bacteria used to create the characteristic flavour.
    GO TO www.science.nelson.com, Chemistry 11, Teacher Centre.