CHEMISTRY 103 – Help Sheet #5
Stoichiometry-Part II

Do the topics appropriate for your course

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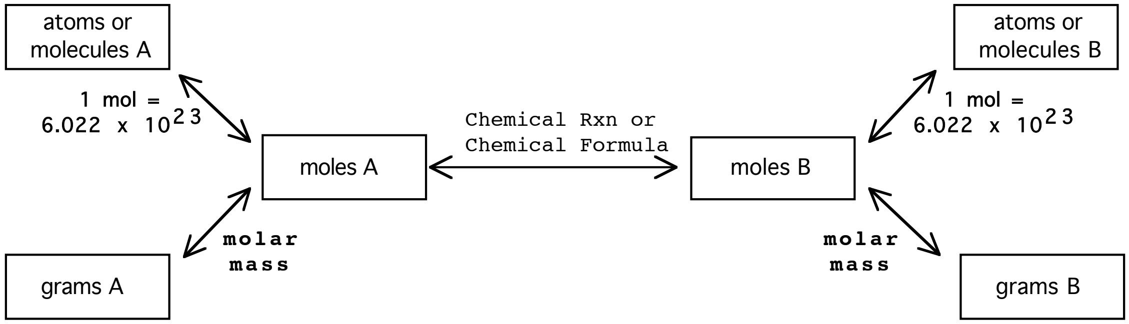
https://clc.chem.wisc.edu (Resources page)

Nuggets: *Stoichiometry, Limiting reagents, Percent yield, Empirical formulas from combustion*



STOICHIOMETRY – calculations using stoichiometric coefficients from balanced reactions

Example 1: How many grams $NH_3(g)$ can be prepared from 84.0g $N_2(g)$ in this reaction: $N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$

Answer 1: 102g NH_3 {This is a "gA → gB" calculation (see diagram above); it requires 3 conversions (the steps are shown in the flow chart)

Step 1. $N_2 + 3H_2 \longrightarrow 2NH_3$

Step 2 3-step conversion: $gA\left(\frac{1molA}{gA}\right)\left(\frac{molB}{molA}\right)\left(\frac{gB}{1molB}\right) = gB$

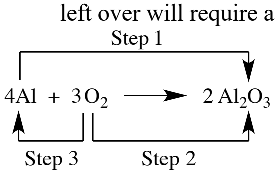
Step 3 3-step conversion: $84.0gN_2\left(\frac{1molN_2}{28.0gN_2}\right)\left(\frac{2molNH_3}{1molN_2}\right)\left(\frac{17.0gNH_3}{1molNH_3}\right) = 102gNH_3$

LIMITING REAGENTS: one reagent runs out first – this is the limiting reagent; ***a limiting reagent problem can be identified when 2 reactant quantities are given in the problem;*** many ways to solve these types of problems - one way: calculate the amount of products possible from each reactant quantity; the smaller amount produced is the theoretical amount that can be made; the reactant that gives this smaller amount is the limiting reagent

Example 2: a. How many grams $Al_2O_3(s)$ can be made from 25.0g Al(s) and 20.0g $O_2(g)$ using: $4Al(s) + 3O_2(g) \rightarrow 2Al_2O_3(s)$?

b. Which reactant is the limiting reagent?
c. Which reagent is the excess reagent?
d. How much of the excess reagent remains after the reaction is complete?

Answer 2: This is a limiting reagent problem since ***2 reactant quantities were given in the problem.*** The amount produced can be solved by doing two "grams A → grams B" calculations, and then comparing the two possible amounts of $Al_2O_3(s)$ produced. The amount of excess reagent left over will require a third "grams A → grams B" calculation requiring 3 steps.



Step 1: gA → gB calculation: g Al → g Al_2O_3

$25.0g\ Al\left(\frac{1mol\ Al}{27.0g\ Al}\right)\left(\frac{2mol\ Al_2O_3}{4mol\ Al}\right)\left(\frac{102g\ Al_2O_3}{1mol\ Al_2O_3}\right) = 47.2g\ Al_2O$

Step 2: gA → gB calculation: g O_2 → g Al_2O_3

$20.0g\ O_2\left(\frac{1mol\ O_2}{32.0g\ O_2}\right)\left(\frac{2mol\ Al_2O_3}{3mol\ O_2}\right)\left(\frac{102g\ Al_2O_3}{1mol\ Al_2O_3}\right) = 42.5g\ Al_2O_3$

a. **42.5g Al_2O_3 can be made** (the smaller quantity of $Al_2O_3(s)$ from Step 1 and Step 2 is how much can theoretically be produced)

b. **$O_2(g)$ is the LR** (since it produced the smaller amount $Al_2O_3(s)$ from Step 2)

c. **Al(s) is the excess reagent** (since it produced the larger amount $Al_2O_3(s)$ from Step 1)

d. **2.5g Al left over**; **Amount Excess Reagent Left Over = Starting Amount Excess Reagent – Used Amount Excess Reagent**;
Used Amount Excess Reagent can be calculated with a "grams A → grams B" calculation of: g LR → g Excess reagent:
Step 3: gA → gB calculation: g O_2 → g Al (this is g LR → g Excess Reagent)

$20.0g\ O_2\left(\frac{1mol\ O_2}{32.0g\ O_2}\right)\left(\frac{4mol\ Al}{3mol\ O_2}\right)\left(\frac{27.0g\ Al}{1mol\ Al}\right) = 22.5g\ Al$; 22.5g Al is the amount of the Excess Reagent ***used***

Amount Left Over = Starting Amount – Used Amount = 25.0g Al – 22.5g Al = 2.5g Al left over

PERCENT YIELD = $\frac{\text{actual yield}}{\text{theoretical yield}}$ x 100%

Actual yield is the actual amount obtained and is always given in the problem; theoretical yield is usually calculated. In a lab setting, if the %yield > 100% then there is an error (e.g., the sample may be wet, etc.)

EMPIRICAL FORMULA from mass CO_2 and H_2O (combustion reaction)

A. Compound contains **C and H only**

1. Convert $gCO_2 \rightarrow$ mol $CO_2 \rightarrow$ **mol C**
2. Convert $gH_2O \rightarrow$ mol $H_2O \rightarrow$ **mol H**
3. Write formula and divide by smallest moles
4. If needed, fractions: $^1/_2$ (0.5) $\rightarrow$ x 2; $^1/_3$ or $^2/_3$ (0.33, 0.66) $\rightarrow$ x 3; $^1/_4$ or $^3/_4$ (0.25, 0.75) $\rightarrow$ x 4

B. Compound contains **C, H, and O** (this process can be used for a C, H, and N compound; just replace the O with N!)

1. Convert $gCO_2 \rightarrow$ mol $CO_2 \rightarrow$ **mol C $\rightarrow$ gC** (need both mol C *and* gC)
2. Convert $gH_2O \rightarrow$ mol $H_2O \rightarrow$ **mol H $\rightarrow$ gH** (need both mol H *and* gH)
3. Calculate gO from: total g sample = gC + gH + gO (gO = total g sample - gC - gH)
4. Convert gO $\rightarrow$ **mol O**
5. Write formula and divide by smallest moles
6. If needed, fractions: $^1/_2$ (0.5) $\rightarrow$ x 2; $^1/_3$ or $^2/_3$ (0.33, 0.66) $\rightarrow$ x 3; $^1/_4$ or $^3/_4$ (0.25, 0.75) $\rightarrow$ x 4

Example 3: Butane, a ***hydrocarbon,*** was burned and 15.14g CO_2 and 7.751g H_2O are recovered. What is the empirical formula of butane?

Answer 3: C_2H_5

Step 1. **mol C:** $15.14\text{g } CO_2\left(\frac{1\text{mol } CO_2}{44.01\text{g } CO_2}\right)\left(\frac{1\text{mol C}}{1\text{mol } CO_2}\right) = 0.3441\text{mol C}$

Step 2. **mol H:** $7.751\text{g } H_2O\left(\frac{1\text{mol } H_2O}{18.02\text{g } H_2O}\right)\left(\frac{2\text{mol H}}{1\text{mol } H_2O}\right) = 0.8603\text{mol H}$

Step 3. **Write formula:** $C_{0.3441}H_{0.8603}$ and divide by smallest number of mol = 0.3441: $C_{\frac{0.3441}{0.3441}}H_{\frac{0.8603}{0.3441}} \rightarrow C_1H_{2.500}$

Step 4. **Fractions:** multiply by 2: $C_{(1 \text{ x } 2)}H_{(2.500 \text{ x } 2)} \rightarrow$ empirical formula = $\mathbf{C_2H_5}$

Example 4: When 2.000g of a compound containing ***carbon, hydrogen, and oxygen*** is combusted, 1.912g CO_2 and 0.7830g H_2O are recovered. What is the empirical formula?

Answer 4: CH_2O_2

Step 1. **mol C:** $1.912\text{g } CO_2\left(\frac{1\text{mol } CO_2}{44.01\text{g } CO_2}\right)\left(\frac{1\text{mol C}}{1\text{mol } CO_2}\right) = 0.04344\text{mol C}$ **AND** **gC:** $0.04344\text{molC}\left(\frac{12.01\text{gC}}{1\text{molC}}\right) = 0.5217\text{g C}$

Step 2. **mol H:** $0.7830\text{g } H_2O\left(\frac{1\text{mol } H_2O}{18.02\text{g } H_2O}\right)\left(\frac{2\text{mol H}}{1\text{mol } H_2O}\right) = 0.08690\text{mol H}$ **AND** **gH:** $0.08690\text{mol H}\left(\frac{1.008\text{g H}}{1\text{mol H}}\right) = 0.08760\text{g H}$

Step 3. **gO:** g_{sample} = gO + gC + gH $\rightarrow$ solve for gO: gO = g_{sample} – gC – gH = 2.000 – 0.5217 – 0.08760 = 1.3907g O

Step 4. **mol O:** $1.3907\text{g O}\left(\frac{1\text{mol O}}{16.00\text{g O}}\right) = 0.08692\text{mol O}$

Step 5. **Write formula:** $C_{0.04344}H_{0.08690}O_{0.08692}$; divide by smallest number of mol = 0.04344: $C_{\frac{0.04344}{0.04344}}H_{\frac{0.08690}{0.04344}}O_{\frac{0.08692}{0.04344}} = C_1H_{2.000}O_{2.000}$;

Empirical formula = $\mathbf{CH_2O_2}$

Step 6. **Fractions:** no fractions; this step not needed

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1. If 25.0g N_2 reacts with excess H_2, how many grams of NH_3 would be produced?

$$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$$

2. Nitric acid, HNO_3, is manufactured by the Oswald process, in which nitrogen dioxide, NO_2, reacts with H_2O. How many grams of NO_2 are required to produce 5.00g HNO_3.

$3NO_2(g) + H_2O(l) \rightarrow 2HNO_3(aq) + NO(g)$

a. 7.50 b. 15.0 c. 3.65 d. 0.120 e. 5.48

3. Calculate the masses (in grams) of Cr_2O_3 (chromium(III) oxide), N_2, and H_2O produced from 10.8g of $(NH_4)_2Cr_2O_7$ (ammonium dichromate) in the following balanced reaction:

$(NH_4)_2Cr_2O_7(s) \rightarrow Cr_2O_3(s) + N_2(g) + 4H_2O(l)$

4. a. When 9.20g of C_2H_6O are reacted with 40.6g of PBr_3, what mass of C_2H_5Br can be produced?

$3C_2H_6O + PBr_3 \rightarrow 3C_2H_5Br + H_3PO_3$

b. Which reactant is the limiting reagent?
c. Which reactant is the excess reagent?
d. How much of the excess reagent is left over?
e. If 10.9g PBr_3 was recovered after the experiment, what was the %yield of this reaction?

5. Tungsten metal can be produced by reacting yellow tungsten oxide, WO_3, with hydrogen.

$WO_3(s) + 3H_2(g) \rightarrow W(s) + 3H_2O(l)$

How many grams of tungsten can be obtained from 1.25×10^5g H_2 and 6.55×10^6 g WO_3?

6. If 75.0g of SiO_2 and 30.0g C react according to the equation below, what is the maximum number of moles of CO that can be produced? $SiO_2 + C \rightarrow CO + SiO$

a. 1.25 b. 1.67 c. 2.25 d. 2.50 e. none of these

7. I. Given the following balanced combustion reaction below, if there were 3.0mol of C_2H_4 and 6.0mol of O_2, how many moles of CO_2 could theoretically be produced?

$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$

a. 6mol b. 4mol c. 9mol d. 3mol e. 7mol

II. After the above reaction was completed, 3.5mol of CO_2 were actually obtained. What is the percent yield of this reaction? (Note: You can only do this part with the correct answer to Part I.)

8. Consider the reaction:

$2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$

Identify the limiting reagent in each of the reaction mixtures below. Note: Not a multiple choice question.
a. 0.50mol of H_2 and 0.75mol of O_2
b. 0.80mol of H_2 and 0.75mol of O_2
c. 1.00g of H_2 and 0.35mol of O_2
d. 5.00g of H_2 and 64.00g of O_2

9. When a compound containing carbon and hydrogen is combusted, 3.38g CO_2 and 0.692g H_2O are recovered. a. What is the empirical formula? b. The molar mass of the compound is 78.1g/mol. What is the molecular formula?

10. When 5.000g of a compound containing carbon, hydrogen, and oxygen is combusted, 8.910g CO_2 and 3.648g H_2O are recovered. a. What is the empirical formula? b. The molar mass of the compound is 74.1g/mol. What is the molecular formula?

11. A compound contains carbon, hydrogen, and nitrogen. When 0.9731 gram of this substance is combusted, 2.3744grams CO_2 and 1.2153grams of H_2O are collected. What is the empirical formula?

12. A 1.257g sample of a compound, B_xH_y, is reacted in pure oxygen to form 3.163g of B_2O_3. What is the empirical formula for B_xH_y?

ANSWERS

1. 30.4g NH_3 $\{25.0g\ N_2\left(\frac{1mol\ N_2}{28.0g\ N_2}\right)\left(\frac{2mol\ NH_3}{1mol\ N_2}\right)\left(\frac{17.0g\ NH_3}{1mol\ NH_3}\right) = 30.36g\ NH_3\}$

2. e $\{5.00g\ HNO_3\left(\frac{1mol\ HNO_3}{63.02g\ HNO_3}\right)\left(\frac{3mol\ NO_2}{2mol\ HNO_3}\right)\left(\frac{46.01g\ NO_2}{1mol\ NO_2}\right) = 5.476g\ NO_2\}$

3. 6.52g Cr_2O_3 $\{10.8g\ (NH_4)_2Cr_2O_7\left(\frac{1mol\ (NH_4)_2Cr_2O_7}{252.08g\ (NH_4)_2Cr_2O_7}\right)\left(\frac{1mol\ Cr_2O_3}{1mol\ (NH_4)_2Cr_2O_7}\right)\left(\frac{152.00g\ Cr_2O_3}{1mol\ Cr_2O_3}\right) = 65.12g\ Cr_2O_3\}$

1.20g N_2 $\{10.8g\ (NH_4)_2Cr_2O_7\left(\frac{1mol\ (NH_4)_2Cr_2O_7}{252.08g\ (NH_4)_2Cr_2O_7}\right)\left(\frac{1mol\ N_2}{1mol\ (NH_4)_2Cr_2O_7}\right)\left(\frac{28.02g\ N_2}{1mol\ N_2}\right) = 1.200g\ N_2\}$

3.09g H_2O $\{10.8g\ (NH_4)_2Cr_2O_7\left(\frac{1mol\ (NH_4)_2Cr_2O_7}{252.08g\ (NH_4)_2Cr_2O_7}\right)\left(\frac{4mol\ H_2O}{1mol\ (NH_4)_2Cr_2O_7}\right)\left(\frac{18.02g\ H_2O}{1mol\ H_2O}\right) = 3.088g\ H_2O\}$

4. a. 21.8g C_2H_5Br {limiting reagent problem since 2 reactant quantities are given;

$9.20g\ C_2H_6O\left(\frac{1mol\ C_2H_6O}{46.07g\ C_2H_6O}\right)\left(\frac{3mol\ C_2H_5Br}{3mol\ C_2H_6O}\right)\left(\frac{108.96g\ C_2H_5Br}{1mol\ C_2H_5Br}\right) = 21.76g\ C_2H_5Br$;

$40.6g\ PBr_3\left(\frac{1mol\ PBr_3}{270.67g\ PBr_3}\right)\left(\frac{3mol\ C_2H_5Br}{1mol\ PBr_3}\right)\left(\frac{108.96g\ C_2H_5Br}{1mol\ C_2H_5Br}\right) = 49.03g\ C_2H_5Br$;

the smaller amount of C_2H_5Br is the theoretical yield that can be produced}

b. C_2H_6O is LR {the chemical that produced the smaller amount of C_2H_5Br}

c. PBr_3 is the excess reagent {the chemical that produced the larger amount of C_2H_5Br}

d. 22.6g PBr_3 {Left over = starting amount – amount used; amount used = g A → g B going from LR → Excess Reagent;

$9.20g\ C_2H_6O\left(\frac{1mol\ C_2H_6O}{46.07g\ C_2H_6O}\right)\left(\frac{1mol\ PBr_3}{3mol\ C_2H_6O}\right)\left(\frac{270.67g\ PBr_3}{1mol\ PBr_3}\right) = 18.02g\ C_2H_5Br$ ***used***;

Left over = 40.6g PBr_3 – 18.02g PBr_3 = 22.58g PBr_3 left over}

e. 50.0% {%yield = (actual yield/theoretical yield) x 100%; %yield = (10.9g C_2H_5Br/21.8g C_2H_5Br) x 100% = 50.0%}

5. 3.80 x 10^6g W {limiting reagent problem since 2 reactant quantities are given;

$1.25 \times 10^5 g\ H_2\left(\frac{1mol\ H_2}{2.016g\ H_2}\right)\left(\frac{1mol\ W}{3mol\ H_2}\right)\left(\frac{183.9g\ W}{1mol\ W}\right) = 3.801 \times 10^6 g\ W$;

$6.55 \times 10^6 g\ WO_3\left(\frac{1mol\ WO_3}{231.9g\ WO_3}\right)\left(\frac{1mol\ W}{1mol\ WO_3}\right)\left(\frac{183.9g\ W}{1mol\ W}\right) = 5.194 \times 10^6 g\ W$;

the smaller amount of W is the theoretical yield that can be produced}

6. a {limiting reagent problem since 2 reactant quantities are given;

$75.0g\ SiO_2\left(\frac{1mol\ SiO_2}{60.09g\ SiO_2}\right)\left(\frac{1mol\ CO}{1mol\ SiO_2}\right) = 1.248mol\ CO$; $30.0g\ C\left(\frac{1mol\ C}{12.01g\ C}\right)\left(\frac{1mol\ CO}{1mol\ C}\right) = 2.498mol\ CO$;

the smaller amount of CO is the theoretical yield}

7. I. b {limiting reagent problem; $(3\text{mol } C_2H_4)\left(\frac{2\text{mol } CO_2}{1\text{mol } C_2H_4}\right) = 6\text{mol } CO_2$; $(6\text{mol } O_2)\left(\frac{2\text{mol } CO_2}{3\text{mol } O_2}\right) = 4\text{mol } CO_2$;

choose smaller amount $\rightarrow$ 4mol CO_2}

II. 87.5% {$\%\text{yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \text{ x } 100\%$; $\%\text{yield} = \left(\frac{3.5\text{mol } CO_2}{4.0\text{mol } CO_2}\right) \text{ x } 100\% = 87.5\%$ }

8. a. H_2 b. H_2 c. O_2 d. H_2

9. a. CH {$3.38\text{g } CO_2\left(\frac{1\text{mol } CO_2}{44.01\text{g } CO_2}\right)\left(\frac{1\text{mol C}}{1\text{mol } CO_2}\right) = 0.07680\text{mol C}$; $0.692\text{g } H_2O\left(\frac{1\text{mol } H_2O}{18.02\text{g } H_2O}\right)\left(\frac{2\text{mol H}}{1\text{mol } H_2O}\right) = 0.07680\text{mol H}$;

write chemical formula: $C_{0.07680}H_{0.07680}$; divide by smallest number of mol = 0.07680: $C_{\frac{0.07680}{0.07680}}H_{\frac{0.07680}{0.07680}} \rightarrow C_1H_1$ = EF}

b. C_6H_6 {$\text{ratio} = \frac{\text{molar mass}_{\text{molecular formula}}}{\text{molar mass}_{\text{empirical formula}}} = \frac{78.1}{13.02} = 5.998 = 6$; multiply EF by 6; $C_{(1 \text{ x } 6)}H_{(1 \text{ x } 6)} = C_6H_6$ = MF}

10. a. $C_3H_6O_2$ {$8.910\text{g } CO_2\left(\frac{1\text{mol } CO_2}{44.01\text{g } CO_2}\right)\left(\frac{1\text{mol C}}{1\text{mol } CO_2}\right) = 0.2025\text{mol C}$; gC = 0.2025mol C x (12.01g C/1mol C) = 2.4320g C;

$3.648\text{g } H_2O\left(\frac{1\text{mol } H_2O}{18.02\text{g } H_2O}\right)\left(\frac{2\text{mol H}}{1\text{mol } H_2O}\right) = 0.4049\text{mol H}$; gH = 0.4049mol H x (1.008g H/1mol H) = 0.4081g H;

g_{sample} = gO + gC + gH $\rightarrow$ solve for gO: gO = g_{sample} – gC – gH = 5.00 – 2.4320 – 0.4081 = 2.1599g O

$2.1599\text{g O}\left(\frac{1\text{mol O}}{16.00\text{g O}}\right) = 0.1350\text{mol O}$;

$C_{0.2025}H_{0.4049}O_{0.1350}$; divide by 0.1350: $C_{\frac{0.2025}{0.1350}}H_{\frac{0.4049}{0.1350}}O_{\frac{0.1350}{0.1350}} = C_{1.500}H_{2.999}O_1$; fraction of 0.5 $\rightarrow$ $^1/_2$ $\rightarrow$ x2: $C_{(1.500 \text{ x } 2)}H_{(2.999 \text{ x } 2)}O_{(1 \text{ x } 2)} = C_3H_{5.998}O_2 = C_3H_6O_2$ = EF}

b. $C_3H_6O_2$ {$\text{ratio} = \frac{\text{molar mass}_{\text{molecular formula}}}{\text{molar mass}_{\text{empirical formula}}} = \frac{74.1}{74.08} = 1.000$; multiply EF by 1; $C_{(3 \text{ x } 1)}H_{(6 \text{ x } 1)}O_{(2 \text{ x } 1)} = C_3H_6O_2$ = MF}

11. $C_4H_{10}N$ {$2.3744\text{g } CO_2\left(\frac{1\text{mol } CO_2}{44.01\text{g } CO_2}\right)\left(\frac{1\text{mol C}}{1\text{mol } CO_2}\right) = 0.053951\text{mol C}$; $\text{gC} = 0.053951\text{mol C}\left(\frac{12.01\text{g C}}{1\text{mol C}}\right) = 0.64795\text{g C}$;

$1.2153\text{g } H_2O\left(\frac{1\text{mol } H_2O}{18.02\text{g } H_2O}\right)\left(\frac{2\text{mol H}}{1\text{mol } H_2O}\right) = 0.13488\text{mol H}$; $\text{gH} = 0.13488\text{mol H}\left(\frac{1.008\text{g H}}{1\text{mol H}}\right) = 0.13596\text{g H}$;

g_{sample} = gN + gC + gH $\rightarrow$ solve for gN: gN = g_{sample} – gC – gH = 0.9731 – 0.64795 – 0.13596 = 0.18919g N

$\text{mol N} = 0.18919\text{g N}\left(\frac{1\text{mol N}}{14.01\text{g N}}\right) = 0.013504\text{mol N}$; $C_{0.053951}H_{0.13488}N_{0.013504}$;

divide by 0.013504: $C_{\frac{0.053951}{0.013504}}H_{\frac{0.13488}{0.013504}}N_{\frac{0.013504}{0.013504}} = C_{3.9952}H_{9.9882}N_1 = C_4H_{10}N_1$ = EF}

12. BH_3 {find mol B: $3.163\text{g } B_2O_3\left(\frac{1\text{mol } B_2O_3}{69.62\text{g } B_2O_3}\right)\left(\frac{2\text{mol B}}{1\text{mol } B_2O_3}\right) = 0.09086\text{mol B}$;

$\text{gB} = 0.09086\text{mol B}\left(\frac{10.81\text{g B}}{1\text{mol B}}\right) = 0.9822\text{g B}$; gH: g_{sample} = gB + gH; gH = 1.257 – 0.9822 = 0.2748g H;

find mol H: $0.2748\text{g H}\left(\frac{1\text{mol H}}{1.008\text{g H}}\right) = 0.2726\text{mol H}$;

write formula: $B_{0.09086}H_{0.2726}$ and divide by 0.09086: $B_{\frac{0.09086}{0.09086}}H_{\frac{0.2726}{0.09086}} = B_1H_{3.00} = BH_3$ = EF}