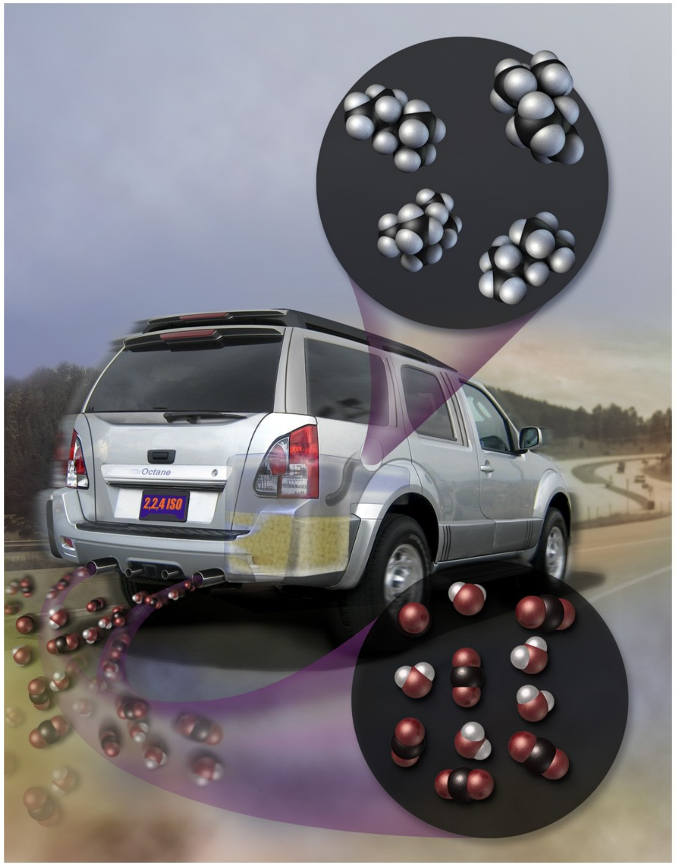
Chapter 8
Quantities in Chemical Reactions

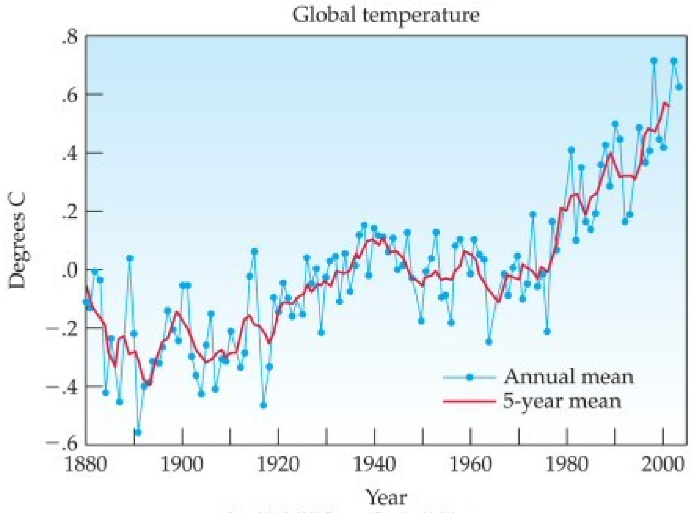
Michael Stogsdill
Mott Community College
Chem 118
Introductory Chemistry

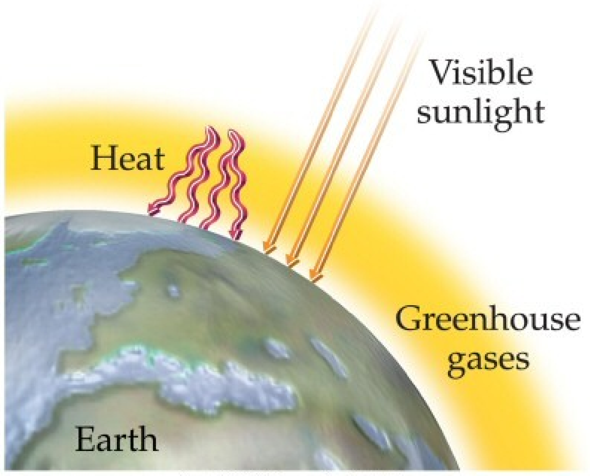


Map: Introductory Chemistry (Tro) https://chem.libretexts.org/@go/page/45050 (accessed Mar 25, 2022).

Global Warming

- Scientists have measured an average 0.6 °C rise in atmospheric temperature since 1860.
- During the same period atmospheric CO_2 levels have risen 25%.
- Are the two trends causal?

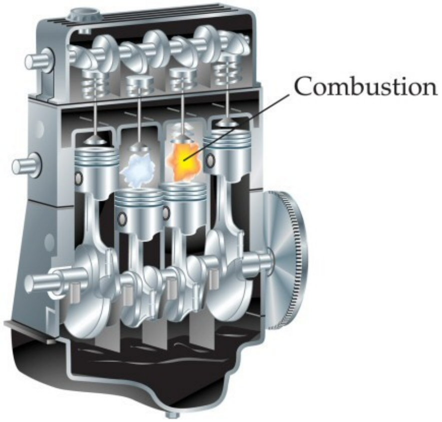




The Source of Increased CO_2

- The primary source of the increased CO_2 levels are combustion reactions of fossil fuels we use to get energy.
  - ✓ 1860 corresponds to the beginning of the Industrial Revolution in the U.S. and Europe.

$$CH_4(g) + 2\,O_2(g) \rightarrow CO_2(g) + 2\,H_2O(g) \qquad 2\,C_8H_{18}(l) + 25\,O_2(g) \rightarrow 16\,CO_2(g) + 18\,H_2O(g)$$



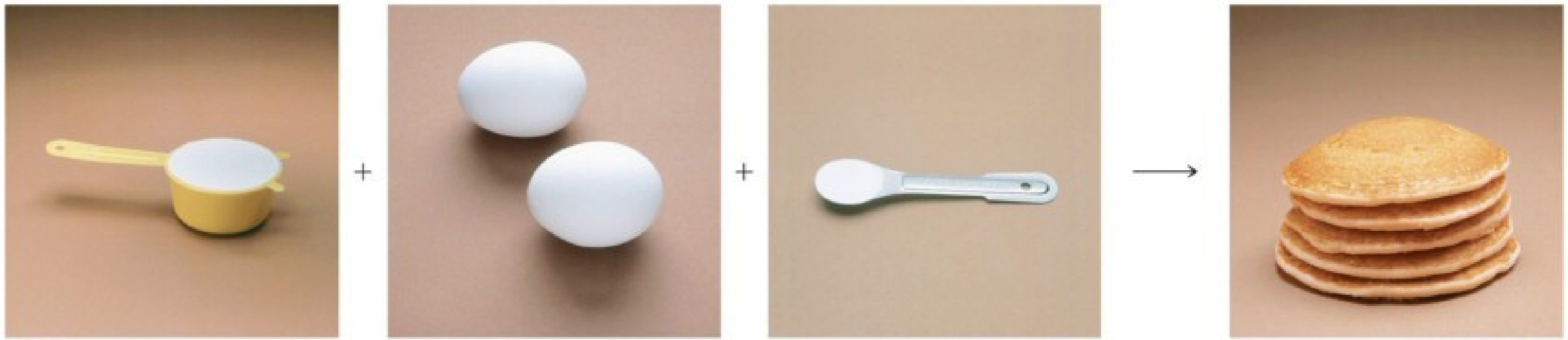
Stoichiometry

Quantities in Chemical Reactions

- The amount of every substance used and made in a chemical reaction is related to the amounts of all the other substances in the reaction.
  - ✓ Law of Conservation of Mass.
  - ✓ Balancing equations by balancing atoms.
- The study of the numerical relationship between chemical quantities in a chemical reaction is called **stoichiometry**.

Making Pancakes

- The number of pancakes you can make depends on the amount of the ingredients you use.



1 cup flour + 2 eggs + ½ tsp baking powder → 5 pancakes

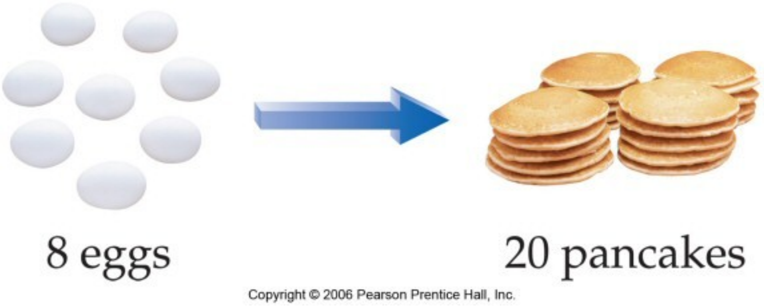
- This relationship can be expressed mathematically.

1 cup flour ≡ 2 eggs ≡ ½ tsp baking powder ≡ 5 pancakes

Making Pancakes, Continued

- If you want to make more or less than 5 pancakes, you can use the number of eggs you have to determine the number of pancakes you can make.
  - ✓ Assuming you have enough flour and baking powder.

$$8 \text{ eggs} \times \frac{5 \text{ pancakes}}{2 \text{ eggs}} = 20 \text{ pancakes}$$



Making Molecules
Mole-to-Mole Conversions

- The balanced equation is the “recipe” for a chemical reaction.
- The equation $3\ H_2(g) + N_2(g) \rightarrow 2\ NH_3(g)$ tells us that 3 molecules of H_2 react with exactly 1 molecule of N_2 and make exactly 2 molecules of NH_3 or:

$$3 \text{ molecules } H_2 \equiv 1 \text{ molecule } N_2 \equiv 2 \text{ molecules } NH_3$$

- Since we count molecules by moles:

$$3 \text{ moles } H_2 \equiv 1 \text{ mole } N_2 \equiv 2 \text{ moles } NH_3$$

Example 8.1—How Many Moles of NaCl Result from the Complete Reaction of 3.4 Mol of Cl_2?

$$2\ Na(s) + Cl_2(g) \rightarrow 2\ NaCl$$

Given: **Find:**	3.4 mol Cl_2 mol NaCl
Solution Map:	mol Cl_2 → mol NaCl $\frac{2\text{ mol NaCl}}{1\text{ mol Cl}_2}$
Relationships:	1 mol Cl_2 ≡ 2 NaCl
Solution:	$3.4\ \text{mol Cl}_2 \times \frac{2\text{ mol NaCl}}{1\text{ mol Cl}_2}$ $= 6.8\text{ mol NaCl}$
Check:	Since the reaction makes 2 molecules of NaCl for every 1 mole of Cl_2, the number makes sense.

Practice

- According to the following equation, how many moles of water are made in the combustion of 0.10 moles of glucose?

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$$

How Many Moles of Water Are Made in the Combustion of 0.10 Moles of Glucose?

Given:	0.10 moles $C_6H_{12}O_6$
Find:	moles H_2O
Solution Map:	mol $C_6H_{12}O_6$ → mol H_2O $\frac{6 \text{ mol } H_2O}{1 \text{ mol } C_6H_{12}O_6}$
Relationships:	$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$ $\therefore$ 1 mol $C_6H_{12}O_6 \equiv$ 6 mol H_2O

Solution:

$$0.10 \cancel{\text{mol } C_6H_{12}O_6} \times \frac{6 \text{ mol } H_2O}{1 \cancel{\text{mol } C_6H_{12}O_6}} = 0.6 \text{ mol } H_2O$$

Check:

0.6 mol H_2O = 0.60 mol H_2O

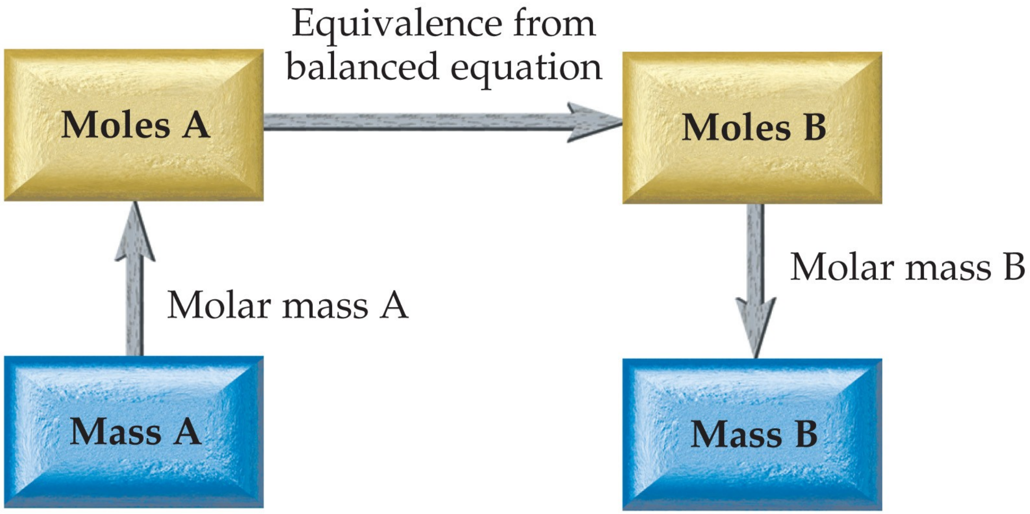
Since 6x moles of H_2O as $C_6H_{12}O_6$, the number makes sense.

Making Molecules
Mass-to-Mass Conversions

- We know there is a relationship between the mass and number of moles of a chemical.

1 mole = Molar Mass in grams.

- The molar mass of the chemicals in the reaction and the balanced chemical equation allow us to convert from the amount of any chemical in the reaction to the amount of any other.



Example 8.2—How Many Grams of Glucose Can Be Synthesized from 58.5 g of CO_2 in Photosynthesis?

- Photosynthesis:

$$6\ CO_2(g) + 6\ H_2O(g) \rightarrow C_6H_{12}O_6(s) + 6\ O_2(g)$$

- The equation for the reaction gives the mole relationship between amount of $C_6H_{12}O_6$ and CO_2, but we need to know the mass relationship, so the solution map will be:

g CO_2 → mol CO_2 → mol $C_6H_{12}O_6$ → g $C_6H_{12}O_6$

Example 8.2—How Many Grams of Glucose Can Be Synthesized from 58.5 g of CO_2 in Photosynthesis?

Given: 58.5 g CO_2

Find: g $C_6H_{12}O_6$

Solution Map: g CO_2 → mol CO_2 → mol $C_6H_{12}O_6$ → g $C_6H_{12}O_6$

$$\frac{1\text{ mol}}{44.01\text{ g}} \qquad \frac{1\text{ mol } C_6H_{12}O_6}{6\text{ mol } CO_2} \qquad \frac{180.2\text{ g}}{1\text{ mol}}$$

Relationships: 1 mol $C_6H_{12}O_6$ = 180.2g, 1 mol CO_2 = 44.01g, 1 mol $C_6H_{12}O_6$ ≡ 6 mol CO_2

Solution:

$$58.5\text{ g } CO_2 \times \frac{1\text{ mol } CO_2}{44.01\text{ g } CO_2} \times \frac{1\text{ mol } C_6H_{12}O_6}{6\text{ mol } CO_2} \times \frac{180.2\text{ g } C_6H_{12}O_6}{1\text{ mol } C_6H_{12}O_6}$$

$$= 39.9\text{ g } C_6H_{12}O_6$$

Check: Since 6x moles of CO_2 as $C_6H_{12}O_6$, but the molar mass of $C_6H_{12}O_6$ is 4x CO_2, the number makes sense.

Practice—How Many Grams of O_2 Can Be Made from the Decomposition of 100.0 g of PbO_2?

$$2\,PbO_2(s) \rightarrow 2\,PbO(s) + O_2(g)$$

Given: 100.0 g PbO_2, $2\,PbO_2 \rightarrow 2\,PbO + O_2$

Find: g O_2

Solution Map: g PbO_2 → mol PbO_2 → mol O_2 → g O_2

$$\frac{1\text{ mol}}{239.2\text{ g}} \qquad \frac{1\text{ mol }O_2}{2\text{ mol }PbO_2} \qquad \frac{32.00\text{ g}}{1\text{ mol}}$$

Relationships: 1 mol O_2 = 32.00g, 1 mol PbO_2 = 239.2g, 1 mol O_2 ≡ 2 mol PbO_2

Solution:

$$100.0\text{ g }PbO_2 \times \frac{1\text{ mol }PbO_2}{239.2\text{ g }PbO_2} \times \frac{1\text{ mol }O_2}{2\text{ mol }PbO_2} \times \frac{32.00\text{ g }O_2}{1\text{ mol }O_2}$$

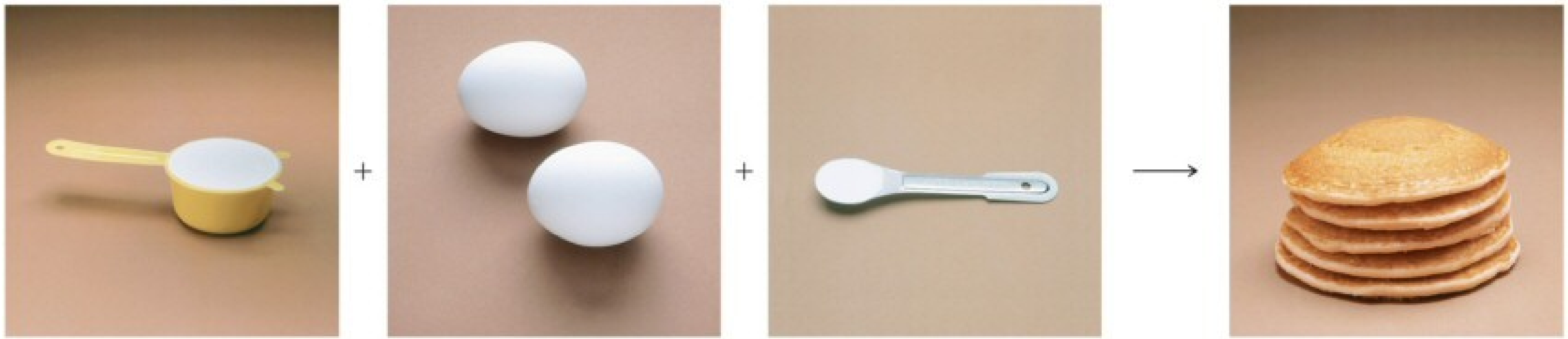
$$= 6.689\text{ g }O_2$$

Check: Since ½ moles of O_2 as PbO_2, and the molar mass of PbO_2 is 7x O_2, the number makes sense.

Limiting Reagents

More Making Pancakes

- We know that:



1 cup flour + 2 eggs + ½ tsp baking powder → 5 pancakes

- But what would happen if we had 3 cups of flour, 10 eggs, and 4 tsp of baking powder?

More Making Pancakes, Continued

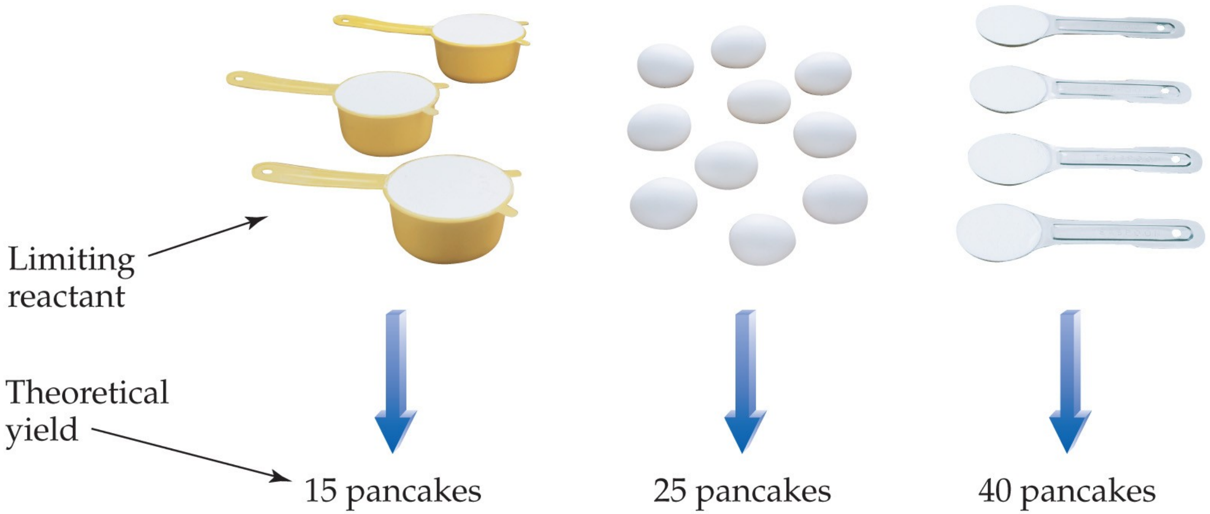
$$3 \text{ cups flour} \times \frac{5 \text{ pancakes}}{1 \text{ cups flour}} = 15 \text{ pancakes}$$

$$10 \text{ eggs} \times \frac{5 \text{ pancakes}}{2 \text{ eggs}} = 25 \text{ pancakes}$$

$$4 \text{ tsp baking powder} \times \frac{5 \text{ pancakes}}{0.5 \text{ tsp baking powder}} = 40 \text{ pancakes}$$

More Making Pancakes, Continued

- Each ingredient could potentially make a different number of pancakes.
- But all the ingredients have to work together!
- We only have enough flour to make 15 pancakes, so once we make 15 pancakes, the flour runs out no matter how much of the other ingredients we have.



More Making Pancakes, Continued

- The flour limits the amount of pancakes we can make. In chemical reactions we call this the **limiting reagent**.
  - ✓ Also known as limiting reactant.
- The maximum number of pancakes we can make depends on this ingredient. In chemical reactions, we call this the **theoretical yield**.
  - ✓ It also determines the amounts of the other ingredients we will use!

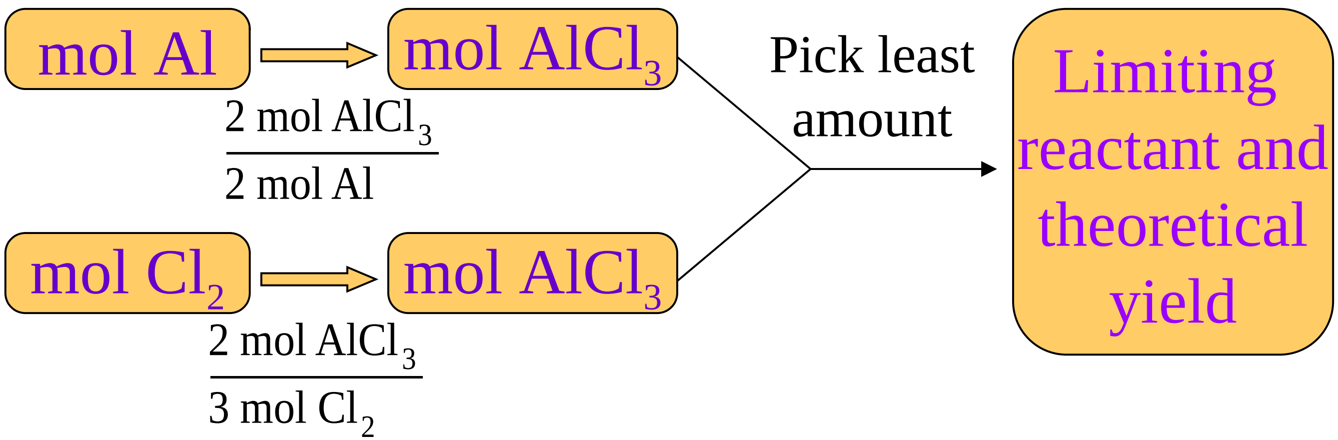
Example 8.4—What Is the Limiting Reagent and Theoretical Yield When 0.552 Mol of Al React with 0.887 Mol of Cl_2?

$$2\ Al(s) + 3\ Cl_2(g) \rightarrow 2\ AlCl_3$$

Given: 0.552 mol Al, 0.887 mol Cl_2

Find: mol $AlCl_3$

Solution Map:



Relationships: 3 mol $Cl_2 \equiv 2\ AlCl_3$; 2 mol Al $\equiv$ 2 mol $AlCl_3$

Solution:

$$0.552\ \text{mol Al} \times \frac{2\ \text{mol AlCl}_3}{2\ \text{mol Al}} = 0.552\ \text{mol AlCl}_3$$

Limiting Reactant

$$0.877\ \text{mol Cl}_2 \times \frac{2\ \text{mol AlCl}_3}{3\ \text{mol Cl}_2} = 0.5847\ \text{mol AlCl}_3$$

Theoretical Yield

Practice—How Many Moles of Si_3N_4 Can Be Made from 1.20 Moles of Si and 1.00 Moles of N_2 in the Reaction $3\ Si + 2\ N_2 \rightarrow Si_3N_4$?

Practice—How Many Moles of Si_3N_4 Can Be Made from 1.20 Moles of Si and 1.00 Moles of N_2 in the Reaction $3\ Si + 2\ N_2 \rightarrow Si_3N_4$?, Continued

Given: 1.20 mol Si, 1.00 mol N_2

Find: mol Si_3N_4

Solution Map:

mol Si → mol Si_3N_4 ($\frac{1\ \text{mol}\ Si_3N_4}{3\ \text{mol Si}}$)

mol N_2 → mol Si_3N_4 ($\frac{1\ \text{mol}\ Si_3N_4}{2\ \text{mol}\ N_2}$)

Pick least amount → Limiting reactant and theoretical yield

Relationships:

2 mol N_2 ≡ 1 Si_3N_4; 3 mol Si ≡ 1 Si_3N_4

Solution:

Limiting Reactant

$$1.20\ \text{mol Si} \times \frac{1\ \text{mol}\ Si_3N_4}{3\ \text{mol Si}} = 0.400\ \text{mol}\ Si_3N_4$$

$$1.00\ \text{mol}\ N_2 \times \frac{1\ \text{mol}\ Si_3N_4}{2\ \text{mol}\ N_2} = 0.500\ \text{mol}\ Si_3N_4$$

Theoretical Yield

Calculating Yield

More Making Pancakes

- Let's now assume that as we are making pancakes, we spill some of the batter, burn a pancake, drop one on the floor, or other uncontrollable events happen so that we only make 11 pancakes. The actual amount of product made in a chemical reaction is called the **actual yield**.
- We can determine the efficiency of making pancakes by calculating the percentage of the maximum number of pancakes we actually make. In chemical reactions, we call this the **percent yield**.

$$\frac{\text{Actual Yield}}{\text{Theoretical Yield}} \times 100\% = \text{Percent Yield} \qquad \frac{11\text{ pancakes}}{15\text{ pancakes}} \times 100\% = 73\%$$

Theoretical and Actual Yield

- As we did with the pancakes, in order to determine the theoretical yield, we should use reaction stoichiometry to determine the amount of product each of our reactants could make.
- The theoretical yield will always be the least possible amount of product.
  - ✓ The theoretical yield will always come from the limiting reactant.
- Because of both controllable and uncontrollable factors, the actual yield of product will always be less than the theoretical yield.

Measuring Amounts in the Lab

- In the lab, our balances do not measure amounts in moles, unfortunately, they measure amounts in grams.
- This means we must add two steps to each of our calculations: first convert the amount of each reactant to moles, then convert the amount of product into grams.

Example 8.6—When 11.5 g of C Are Allowed to React with 114.5 g of Cu_2O in the Reaction Below, 87.4 g of Cu Are Obtained.

$$Cu_2O(s) + C(s) \rightarrow 2\ Cu(s) + CO(g)$$

Given: 11.5 g C, 114.5 g Cu_2O, 87.4 g Cu

Find: Limiting reactant, theoretical yield, percent yield

Solution Map:

g C → mol C → mol Cu → g Cu

$$\frac{1\ \text{mol}}{12.01\ \text{g}} \qquad \frac{2\ \text{mol Cu}}{1\ \text{mol C}} \qquad \frac{1\ \text{mol}}{63.54\ \text{g}}$$

Choose smallest

g Cu_2O → mol Cu_2O → mol Cu → g Cu

$$\frac{1\ \text{mol}}{143.02\ \text{g}} \qquad \frac{2\ \text{mol Cu}}{1\ \text{mol}\ Cu_2O} \qquad \frac{1\ \text{mol}}{63.54\ \text{g}}$$

Relationships:

$$\frac{\text{Actual Yield}}{\text{Theoretical Yield}} \times 100\% = \text{Percent Yield}$$

Example 8.6—When 11.5 g of C Are Allowed to React with 114.5 g of Cu_2O in the Reaction Below, 87.4 g of Cu Are Obtained.

$Cu_2O(s) + C(s) \rightarrow 2\ Cu(s) + CO(g)$, Continued

Solution:

$$11.5\ \text{g C} \times \frac{1\ \text{mol C}}{12.01\ \text{g C}} \times \frac{2\ \text{mol Cu}}{1\ \text{mol C}} \times \frac{63.54\ \text{g Cu}}{1\ \text{mol Cu}} = 122\ \text{g Cu}$$

$$114.5\ \text{g}\ Cu_2O \times \frac{1\ \text{mol}\ Cu_2O}{143.02\ \text{g}\ Cu_2O} \times \frac{2\ \text{mol Cu}}{1\ \text{mol}\ Cu_2O} \times \frac{63.54\ \text{g Cu}}{1\ \text{mol Cu}} = 101.7\ \text{g Cu}$$

The smallest amount is 101.7 g Cu, therefore that is the theoretical yield.

$$\frac{\text{Actual Yield}}{\text{Theoretical Yield}} \times 100\% = \text{Percent Yield}$$

The reactant that produces 101.7 g Cu is the Cu_2O,

Therefore, Cu_2O is the limiting reactant.

$$\frac{87.4\ \text{g Cu}}{101.7\ \text{g Cu}} \times 100\% = 85.9\%\ \text{Yield}$$

Check:

Since the percentage yield is < 100, the answer makes sense.

Practice—How Many Grams of $N_2(g)$ Can Be Made from 9.05 g of NH_3 Reacting with 45.2 g of CuO?

$$2\ NH_3(g) + 3\ CuO(s) \rightarrow N_2(g) + 3\ Cu(s) + 3\ H_2O(l)$$

If 4.61 g of N_2 Are Made, What Is the Percent Yield?

Practice—How Many Grams of $N_2(g)$ Can Be Made from 9.05 g of NH_3 Reacting with 45.2 g of CuO? $2\ NH_3(g) + 3\ CuO(s) \rightarrow N_2(g) + 3\ Cu(s) + 3\ H_2O(l)$ If 4.61 g of N_2 Are Made, What Is the Percent Yield?, Continued

Given: 9.05 g NH_3, 45.2 g CuO

Find: g N_2

Solution Map:

g NH_3 → mol NH_3 → mol N_2 → g N_2

g CuO → mol CuO → mol N_2 → g N_2

Choose smallest

Relationships:

$$\frac{1\ \text{mol}}{17.03\ \text{g}} \quad \frac{1\ \text{mol}\ N_2}{2\ \text{mol}\ NH_3} \quad \frac{1\ \text{mol}}{28.02\ \text{g}}$$

$$\frac{1\ \text{mol}}{79.55\ \text{g}} \quad \frac{1\ \text{mol}\ N_2}{3\ \text{mol CuO}} \quad \frac{1\ \text{mol}}{28.02\ \text{g}}$$

$$\frac{\text{Actual Yield}}{\text{Theoretical Yield}} \times 100\% = \text{Percent Yield}$$

Practice—How Many Grams of $N_2(g)$ Can Be Made from 9.05 g of NH_3 Reacting with 45.2 g of CuO? $2\ NH_3(g) + 3\ CuO(s) \rightarrow N_2(g) + 3\ Cu(s) + 3\ H_2O(l)$ If 4.61 g of N_2 Are Made, What Is the Percent Yield?, Continued

Solution:

$$9.05\ \text{g NH}_3 \times \frac{1\ \text{mol NH}_3}{17.03\ \text{g NH}_3} \times \frac{1\ \text{mol N}_2}{2\ \text{mol NH}_3} \times \frac{28.02\ \text{g N}_2}{1\ \text{mol N}_2} = 7.42\ \text{g N}_2$$

$$45.2\ \text{g CuO} \times \frac{1\ \text{mol CuO}}{79.55\ \text{g CuO}} \times \frac{1\ \text{mol N}_2}{3\ \text{mol CuO}} \times \frac{28.02\ \text{g N}_2}{1\ \text{mol N}_2} = 5.30\ \text{g N}_2$$

Theoretical yield

$$\frac{4.61\ \text{g N}_2}{5.30\ \text{g N}_2} \times 100\% = 87.0\%\ \text{Yield}$$

Check:

Since the percent yield is less than 100, the answer makes sense.

Enthalpy Change

Enthalpy Change

- We previously described processes as exothermic if they released heat, or endothermic if they absorbed heat.
- The **enthalpy of reaction** is the amount of thermal energy that flows through a process.
  - ✓ At constant pressure.
  - ✓ ΔH_{rxn}

Sign of Enthalpy Change

- For exothermic reactions, the sign of the enthalpy change is negative:
  - ✓ Thermal energy is produced by the reaction.
  - ✓ The surroundings get hotter.
  - ✓ $\Delta H = -$
  - ✓ For the reaction $CH_4(s) + 2\ O_2(g) \rightarrow CO_2(g) + 2\ H_2O(l)$, the $\Delta H_{rxn} = -802.3$ kJ per mol of CH_4.
- For endothermic reactions, the sign of the enthalpy change is positive:
  - ✓ Thermal energy is absorbed by the reaction.
  - ✓ The surroundings get colder.
  - ✓ $\Delta H = +$
  - ✓ For the reaction $N_2(s) + O_2(g) \rightarrow 2\ NO(g)$, the $\Delta H_{rxn} = +182.6$ kJ per mol of N_2.

Enthalpy and Stoichiometry

- The amount of energy change in a reaction depends on the amount of reactants.
  - ✓ You get twice as much heat out when you burn twice as much CH_4.
- Writing a reaction implies that amount of energy changes for the stoichiometric amount given in the equation.

For the reaction $C_3H_8(l) + 5\ O_2(g) \rightarrow 3\ CO_2(g) + 4\ H_2O(g)$

$\Delta H_{rxn} = -2044$ kJ

So 1 mol $C_3H_8 \equiv 5$ mol $O_2 \equiv 3$ mol $CO_2 \equiv 4$ mol $H_2O \equiv -2044$ kJ.

Example 8.7—How Much Heat Is Associated with the Complete Combustion of 11.8 x 10^3 g of $C_3H_8(g)$?

Given:	11.8 x 10^3 g C_3H_8,
Find:	*heat*, kJ
Solution Map:	g C_3H_8 → mol C_3H_8 → kJ $\frac{1\ \text{mol}\ C_3H_8}{44.09\ \text{g}}$ $\frac{-2044\ \text{kJ}}{1\ \text{mol}\ C_3H_8}$
Relationships:	1 mol C_3H_8 = -2044 kJ, Molar mass = 44.11 g/mol
Solution:	$$11.8\times10^{3}\ \text{g}\ C_3H_8\times\frac{1\ \text{mol}\ C_3H_8}{44.11\ \text{g}\ C_3H_8}\times\frac{-2044\ \text{kJ}}{1\ \text{mol}\ C_3H_8}=-5.47\times10^{5}\ \text{kJ}$$
Check:	The sign is correct and the value is reasonable.

Practice—How Much Heat Is Evolved When a 0.483 g Diamond Is Burned?

$(\Delta H_{combustion} = -395.4\ kJ/mol\ C)$

Practice—How Much Heat Is Evolved When a 0.483 g Diamond Is Burned? ($\Delta H_{combustion}$ = −395.4 kJ/mol C), Continued

Given:	0.483 g C
Find:	*heat*, kJ
Solution Map:	g C → mol C → kJ $\frac{1 \text{ mol C}}{12.01 \text{ g}}$ $\frac{-395.4 \text{ kJ}}{1 \text{ mol C}}$
Relationships:	1 mol C = −395.4 kJ, Molar mass = 12.01 g/mol

Solution:

$$0.483 \text{ g C} \times \frac{1 \text{ mol C}}{12.01 \text{ g}} \times \frac{-395.4 \text{ kJ}}{1 \text{ mol}} = -15.9 \text{ kJ}$$

Check:	The sign is correct and the value is reasonable since there is less than 0.1 mol C.