The Limiting Reactant

7.2

A balanced chemical equation shows the mole ratios of the reactants and products. To emphasize this, the coefficients of equations are sometimes called **stoichiometric coefficients**. Reactants are said to be present in **stoichiometric amounts** when they are present in a mole ratio that corresponds exactly to the mole ratio predicted by the balanced chemical equation. This means that when a reaction is complete, there are no reactants left. In practice, however, there often *are* reactants left.

In the previous section, you looked at an "equation" for making a salad. You looked at situations in which you had the right amounts of ingredients to make one or more salads, with no leftover ingredients.

1 head of lettuce + 2 cucumbers + 5 radishes → 1 salad

What if you have two heads of lettuce, 12 cucumbers, and 25 radishes, as in Figure 7.5? How many salads can you make? Because each salad requires two heads of lettuce, you can make only two salads. Here the amount of lettuce limits the number of salads you can make. Some of the other two ingredients are left over.

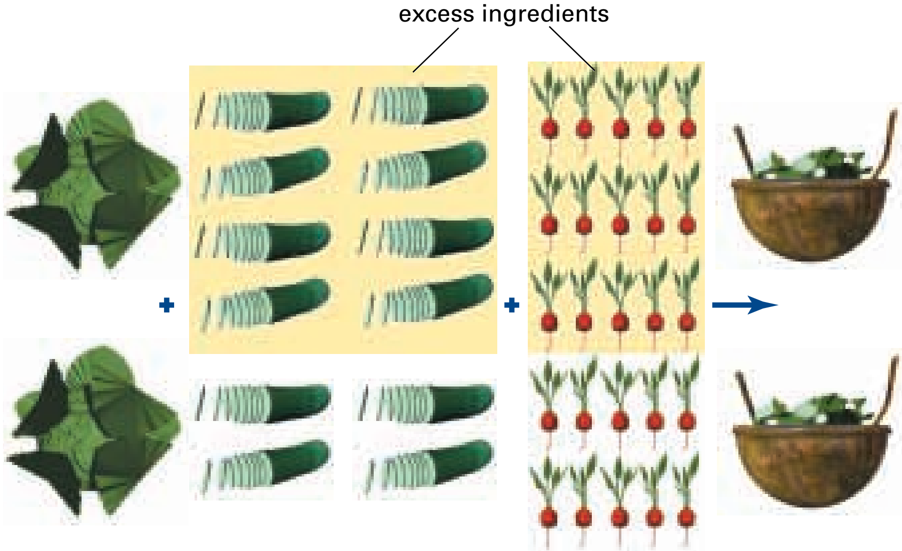

Figure 7.5 Which ingredient limits how many salads can be made?

Chemical reactions often work in the same way. For example, consider the first step in extracting zinc from zinc oxide:

$$ZnO_{(s)} + C_{(s)} \rightarrow Zn_{(s)} + CO_{(g)}$$

If you were carrying out this reaction in a laboratory, you could obtain samples of zinc oxide and carbon in a 1:1 mole ratio. In an industrial setting, however, it is impractical to spend time and money ensuring that zinc oxide and carbon are present in stoichiometric amounts. It is also unnecessary. In an industrial setting, engineers add more carbon, in the form of charcoal, than is necessary for the reaction. All the zinc oxide reacts, but there is carbon left over.

Section Preview/ Specific Expectations

In this section, you will

- **calculate,** for any given reactant or product in a chemical equation, the corresponding mass or quantity (in moles or molecules) of any other reactant or product
- **perform** an investigation to determine the limiting reactant in a chemical reaction
- **assess** the importance of determining the limiting reactant
- **solve** problems involving percentage yield and limiting reactants
- **communicate** your understanding of the following terms: *stoichiometric coefficients, stoichiometric amounts, limiting reactant, excess reactant*

Figure 7.6 All the gasoline in this car's tank has reacted. Thus, even though there is still oxygen available in the air, the combustion reaction cannot proceed.

Having one or more reactants in excess is very common. Another example is seen in gasoline-powered vehicles. Their operation depends on the reaction between fuel and oxygen. Normally, the fuel-injection system regulates how much air enters the combustion chamber, and oxygen is the limiting reactant. When the fuel is very low, however, fuel becomes the limiting reactant and the reaction cannot proceed, as in Figure 7.6.

In nature, reactions almost never have reactants in stoichiometric amounts. Think about respiration, represented by the following chemical equation:

$$C_6H_{12}O_{6(s)} + 6O_{2(g)} \rightarrow 6CO_{2(g)} + 6H_2O_{(\ell)}$$

When an animal carries out respiration, there is an unlimited amount of oxygen in the air. The amount of glucose, however, depends on how much food the animal has eaten.

ThoughtLab The Limiting Item

Imagine that you are in the business of producing cars. A simplified "equation" for making a car is

1 car body + 4 wheels + 2 wiper blades → 1 car

Procedure

1. Assume that you have 35 car bodies, 120 wheels, and 150 wiper blades in your factory. How many complete cars can you make?
2. (a) Which item "limits" the number of complete cars that you can make? Stated another way, which item will "run out" first?
   (b) Which items are present in excess amounts?
   (c) How much of each "excess" item remains after the "reaction"?

Analysis

1. Does the *amount* that an item is in excess affect the quantity of the product that is made? Explain.
2. There are fewer car bodies than wheels and wiper blades. Explain why car bodies are not the limiting item, in spite of being present in the smallest amount.

Determining the Limiting Reactant

The reactant that is completely used up in a chemical reaction is called the **limiting reactant**. In other words, the limiting reactant determines how much product is produced. When the limiting reactant is used up, the reaction stops. In real-life situations, there is almost always a limiting reactant.

A reactant that remains after a reaction is over is called the **excess reactant**. Once the limiting reactant is used, no more product can be made, regardless of how much of the excess reactants may be present.

When you are given amounts of two or more reactants to solve a stoichiometric problem, you first need to identify the limiting reactant. One way to do this is to find out how much product would be produced by each reactant if the other reactant were present in excess. The reactant that produces the least amount of product is the limiting reactant. Examine the following Sample Problem to see how to use this approach to identify the limiting reactant.

Sample Problem

Identifying the Limiting Reactant

Problem

Lithium nitride reacts with water to form ammonia and lithium hydroxide, according to the following balanced chemical equation:

$$Li_3N_{(s)} + 3H_2O_{(\ell)} \rightarrow NH_{3(g)} + 3LiOH_{(aq)}$$

If 4.87 g of lithium nitride reacts with 5.80 g of water, find the limiting reactant.

What Is Required?

You need to determine whether lithium nitride or water is the limiting reactant.

What Is Given?

Reactant: lithium nitride, $Li_3N \rightarrow 4.87$ g
Reactant: water, $H_2O \rightarrow 5.80$ g
Product: ammonia, NH_3
Product: lithium hydroxide, LiOH

Plan Your Strategy

Convert the given masses into moles. Use the mole ratios of reactants and products to determine how much ammonia is produced by each amount of reactant. The limiting reactant is the reactant that produces the smaller amount of product.

Act on Your Strategy

$$n \text{ mol } Li_3N = \frac{4.87 \cancel{\text{g}}\ Li_3N}{34.8 \cancel{\text{g}}/\text{mol}}$$
$$= 0.140 \text{ mol } Li_3N$$

$$n \text{ mol } H_2O = \frac{5.80 \cancel{\text{g}}\ H_2O}{18.0 \cancel{\text{g}}/\text{mol}}$$
$$= 0.322 \text{ mol } H_2O$$

Calculate the amount of NH_3 produced, based on the amount of Li_3N.

$$n \text{ mol of } NH_3 = \frac{1 \text{ mol } NH_3}{1 \cancel{\text{mol } Li_3N}}(0.140 \cancel{\text{mol } Li_3N})$$
$$= 0.140 \text{ mol } NH_3$$

Calculate the amount of NH_3 produced, based on the amount of H_2O.

Continued ...

PROBLEM TIP

To determine the limiting reactant, you can calculate how much of either ammonia or lithium hydroxide would be produced by the reactants. In this problem, ammonia was chosen because only one mole is produced, simplifying the calculation.

Continued ...
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$$n \text{ mol NH}_3 = \frac{1 \text{ mol NH}_3}{3 \cancel{\text{ mol H}_2\text{O}}} \times (0.322 \cancel{\text{ mol H}_2\text{O}})$$
$$= 0.107 \text{ mol NH}_3$$

The water would produce less ammonia than the lithium nitride. Therefore, the limiting reactant is water. Notice that there is more water than lithium nitride, in terms of mass and moles. Water is the limiting reactant, however, because 3 mol of water are needed to react with 1 mol of lithium nitride.

Check Your Solution

According to the balanced chemical equation, the ratio of lithium nitride to water is 1/3. The ratio of lithium nitride to water, based on the mole amounts calculated, is 0.14:0.32. Divide this ratio by 0.14 to get 1.0:2.3. For each mole of lithium nitride, there are only 2.3 mol water. However, 3 mol are required by stoichiometry. Therefore, water is the limiting reactant.

Practice Problems

23. The following balanced chemical equation shows the reaction of aluminum with copper(II) chloride. If 0.25 g of aluminum reacts with 0.51 g of copper(II) chloride, determine the limiting reactant.

$$2Al_{(s)} + 3CuCl_{2(aq)} \rightarrow 3Cu_{(s)} + 2AlCl_{3(aq)}$$

24. Hydrogen fluoride, HF, is a highly toxic gas. It is produced by the double displacement reaction of calcium fluoride, CaF_2, with concentrated sulfuric acid, H_2SO_4.

$$CaF_{2(s)} + H_2SO_{4(\ell)} \rightarrow 2HF_{(g)} + CaSO_{4(s)}$$

Determine the limiting reactant when 10.0 g of CaF_2 reacts with 15.5 g of H_2SO_4.

25. Acrylic, a common synthetic fibre, is formed from acrylonitrile, C_3H_3N. Acrylonitrile can be prepared by the reaction of propylene, C_3H_6, with nitric oxide, NO.

$$4C_3H_{6(g)} + 6NO_{(g)} \rightarrow 4C_3H_3N_{(g)} + 6H_2O_{(g)} + N_{2(g)}$$

What is the limiting reactant when 126 g of C_3H_6 reacts with 175 g of NO?

26. 3.76 g of zinc reacts with 8.93×10^{23} molecules of hydrogen chloride. Which reactant is present in excess?

You now know how to use a balanced chemical equation to find the limiting reactant. Can you find the limiting reactant by experimenting? You know that the limiting reactant is completely consumed in a reaction, while any reactants in excess remain after the reaction is finished. In Investigation 7-A, you will observe a reaction and identify the limiting reactant, based on your observations.

Investigation 7-A

SKILL FOCUS

- Predicting
- Performing and recording
- Analyzing and interpreting
- Communicating results

Limiting and Excess Reactants

In this investigation, you will predict and observe a limiting reactant. You will use the single replacement reaction of aluminum with aqueous copper(II) chloride:

$$2Al_{(s)} + 3CuCl_{2(aq)} \rightarrow 3Cu_{(s)} + 2AlCl_{3(aq)}$$

Note that copper(II) chloride, $CuCl_2$, is light blue in aqueous solution. This is due to the $Cu^{2+}{}_{(aq)}$ ion. Aluminum chloride, $AlCl_{3(aq)}$, is colourless in aqueous solution.

Question

How can observations tell you which is the limiting reactant in the reaction of aluminum with aqueous copper(II) chloride?

Prediction

Your teacher will give you a beaker that contains a 0.25 g piece of aluminum foil and 0.51 g of copper(II) chloride. Predict which one of these reactants is the limiting reactant.

Materials

100 mL beaker or 125 mL Erlenmeyer flask
stirring rod
0.51 g $CuCl_2$
0.25 g Al foil

Safety Precautions

The reaction mixture may get hot. Do not hold the beaker as the reaction proceeds.

Procedure

1. To begin the reaction, add about 50 mL of water to the beaker that contains the aluminum foil and copper(II) chloride.
2. Record the colour of the solution and any metal that is present at the beginning of the reaction.
3. Record any colour changes as the reaction proceeds. Stir occasionally with the stirring rod.
4. When the reaction is complete, return the beaker, with its contents, to your teacher for proper disposal. Do not pour anything down the drain.

Analysis

1. According to your observations, which reactant was present in excess? Which reactant was the limiting reactant?
2. How does your prediction compare with your observations?
3. Do stoichiometric calculations to support your observations of the limiting reactant. Refer to the previous ThoughtLab if you need help.
4. If your prediction of the limiting reactant was incorrect, explain why.

Conclusions

5. Write a conclusion to explain how your experimental observation supported your theoretical calculations.

Applications

6. Magnesium ($Mg_{(s)}$) and hydrogen chloride ($HCl_{(aq)}$) react according to the following skeleton equation:

$$Mg_{(s)} + HCl_{(aq)} \rightarrow MgCl_{2(aq)} + H_{2(g)}$$

(a) Balance the skeleton equation.

(b) Examine the equation carefully. What evidence would you have that a reaction was taking place between the hydrochloric acid and the magnesium?

(c) You have a piece of magnesium of unknown mass, and a beaker of water in which is dissolved an unknown amount of hydrogen chloride. Design an experiment to determine which reactant is the limiting reactant.

Write a balanced chemical equation.

↓

Identify the limiting reactant. Express it as an amount in moles.

↓

Calculate the amount of the required substance based on the amount of the limiting reactant.

↓

Convert the amount of the required substance to mass or number of particles, as directed by the question.

Figure 7.7 **Be sure to determine the limiting reactant in any stoichiometric problem before you solve it.**

PROBEWARE

If you have access to probeware, do the Chemistry 11 lab, Stoichiometry, now.

The Limiting Reactant in Stoichiometric Problems

You are now ready to use what you know about finding the limiting reactant to predict the amount of product that is expected in a reaction. This type of prediction is a routine part of a chemist's job, both in academic research and industry. To produce a compound, for example, chemists need to know how much product they can expect from a given reaction. In analytical chemistry, chemists often analyze an impure substance by allowing it to react in a known reaction. They predict the expected mass of the product(s) and compare it with the actual mass of the product(s) obtained. Then they can determine the purity of the compound.

Since chemical reactions usually occur with one or more of the reactants in excess, you often need to determine the limiting reactant before you carry out stoichiometric calculations. You can incorporate this step into the process you have been using to solve stoichiometric problems, as shown in Figure 7.7.

Sample Problem

The Limiting Reactant in a Stoichiometric Problem

Problem

White phosphorus consists of a molecule made up of four phosphorus atoms. It burns in pure oxygen to produce tetraphosphorus decaoxide.

$$P_{4(s)} + 5O_{2(g)} \rightarrow P_4O_{10(s)}$$

A 1.00 g piece of phosphorus is burned in a flask filled with 2.60×10^{23} molecules of oxygen gas. What mass of tetraphosphorus decaoxide is produced?

What Is Required?

You need to find the mass of tetraphosphorus decaoxide that is produced.

What Is Given?

You know the balanced chemical equation. You also know the mass of phosphorus and the number of oxygen molecules that reacted.

Plan Your Strategy

First convert each reactant to moles and find the limiting reactant. Using the mole to mole ratio of the limiting reactant to the product, determine the number of moles of tetraphosphorus decaoxide that is expected. Convert this number of moles to grams.

Act on Your Strategy

$$n \text{ mol } P_4 = \frac{1.00 \cancel{\text{g}} \; P_4}{123.9 \cancel{\text{g}}/\text{mol } P_4}$$
$$= 8.07 \times 10^{-3} \text{ mol } P_4$$

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$$n \text{ mol } O_2 = \frac{2.60 \times 10^{23} \cancel{\text{ molecules}}}{6.02 \times 10^{23} \cancel{\text{ molecules}}/\text{mol}}$$
$$= 0.432 \text{ mol } O_2$$

Calculate the amount of P_4O_{10} that would be produced by the P_4.

$$\frac{n \text{ mol } P_4O_{10}}{8.07 \times 10^{-3} \text{ mol } P_4} = \frac{1 \text{ mol } P_4O_{10}}{1 \text{ mol } P_4}$$
$$(\cancel{8.07 \times 10^{-3} \text{ mol } P_4})\frac{n \text{ mol } P_4O_{10}}{\cancel{8.07 \times 10^{-3} \text{ mol } P_4}} = \frac{1 \text{ mol } P_4O_{10}}{\cancel{1 \text{ mol } P_4}}(8.07 \times 10^{-3} \cancel{\text{ mol } P_4})$$
$$= 8.07 \times 10^{-3} \text{ mol } P_4O_{10}$$

Calculate the amount of P_4O_{10} that would be produced by the O_2.

$$\frac{n \text{ mol } P_4O_{10}}{0.432 \text{ mol } O_2} = \frac{1 \text{ mol } P_4O_{10}}{5 \text{ mol } O_2}$$
$$(\cancel{0.432 \text{ mol } O_2})\frac{n \text{ mol } P_4O_{10}}{\cancel{0.432 \text{ mol } O_2}} = \frac{1 \text{ mol } P_4O_{10}}{5 \cancel{\text{ mol } O_2}}(0.432 \cancel{\text{ mol } O_2})$$
$$= 8.64 \times 10^{-2} \text{ mol } P_4O_{10}$$

Since P_4 would produce less P_4O_{10} than O_2 would, P_4 is the limiting reactant.

$$P_{4(s)} \quad + \quad 5O_{2(g)} \longrightarrow P_4O_{10(s)}$$

0.00807 mol $\longrightarrow$ 0.00807 mol

unknown ratio **known ratio**

$$\frac{n \text{ mol } P_4O_{10}}{0.00807 \text{ mol } P_4} = \frac{1 \text{ mol } P_4O_{10}}{1 \text{ mol } P_4}$$
$$(0.00807 \cancel{\text{ mol } P_4})\frac{n \text{ mol } P_4O_{10}}{\cancel{0.00807 \text{ mol } P_4}} = (0.00807 \cancel{\text{ mol } P_4})\frac{1 \text{ mol } P_4O_{10}}{1 \cancel{\text{ mol } P_4}}$$
$$= 0.00807 \text{ mol } P_4O_{10}$$

0.00807 mol P_4O_{10}
$\times$ 284 g/mol P_4O_{10}

2.29 g P_4O_{10}

Check Your Solution

There were more than 5 times as many moles of O_2 as moles of P_4, so it makes sense that P_4 was the limiting reactant. An expected mass of 2.29 g of tetraphosphorus decaoxide is reasonable. It is formed in a 1:1 ratio from phosphorus. It has a molar mass that is just over twice the molar mass of phosphorus.

Practice Problems

27. Chloride dioxide, ClO_2, is a reactive oxidizing agent. It is used to purify water.

$$6ClO_{2(g)} + 3H_2O_{(\ell)} \rightarrow 5HClO_{3(aq)} + HCl_{(aq)}$$

(a) If 71.00 g of ClO_2 is mixed with 19.00 g of water, what is the limiting reactant?

(b) What mass of $HClO_3$ is expected in part (a)?

(c) How many molecules of HCl are expected in part (a)?

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28. Hydrazine, N_2H_4, reacts exothermically with hydrogen peroxide, H_2O_2

$$N_2H_{4(\ell)} + 7H_2O_{2(aq)} \rightarrow 2HNO_{3(g)} + 8H_2O_{(g)}$$

(a) 120 g of N_2H_4 reacts with an equal mass of H_2O_2. Which is the limiting reactant?

(b) What mass of HNO_3 is expected?

(c) What mass, in grams, of the excess reactant remains at the end of the reaction?

29. In the textile industry, chlorine is used to bleach fabrics. Any of the toxic chlorine that remains after the bleaching process is destroyed by reacting it with a sodium thiosulfate solution, $Na_2S_2O_{3(aq)}$.

$$Na_2S_2O_{3(aq)} + 4Cl_{2(g)} + 5H_2O_{(\ell)} \rightarrow 2NaHSO_{4(aq)} + 8HCl_{(aq)}$$

135 kg of $Na_2S_2O_3$ reacts with 50.0 kg of Cl_2 and 238 kg of water. How many grams of $NaHSO_4$ are expected?

30. Manganese(III) fluoride can be formed by the reaction of manganese(II) iodide with fluorine.

$$2MnI_{2(s)} + 13F_{2(g)} \rightarrow 2MnF_{3(s)} + 4IF_{5(\ell)}$$

(a) 1.23 g of MnI_2 reacts with 25.0 g of F_2. What mass of MnF_3 is expected?

(b) How many molecules of IF_5 are produced in part (a)?

(c) What reactant is in excess? How much of it remains at the end of the reaction?

COURSE CHALLENGE

You will use the concepts of stoichiometry and limiting reactants in the Chemistry Course Challenge. If you have two reactants and you want to use up all of one reactant, which is the limiting reactant?

CHEM FACT

Carbon disulfide, CS_2, is an extremely volatile and flammable substance. It is so flammable that it can ignite when exposed to boiling water! Because carbon disulfide vapour is more than twice as dense as air, it can "blanket" the floor of a laboratory. There have been cases where the spark from an electrical motor has ignited carbon disulfide vapour in a laboratory, causing considerable damage. For this reason, specially insulated electrical motors are required in laboratory refrigerators and equipment.

Section Wrap-up

You now know how to identify a limiting reactant. This allows you to predict the amount of product that will be formed in a reaction. Often, however, your prediction will not accurately reflect reality. When a chemical reactions occurs—whether in a laboratory, in nature, or in industry—the amount of product that is formed is often different from the amount that was predicted by stoichiometric calculations. You will learn why this happens, and how chemists deal with it, in section 7.3.

Section Review

1 C Why do you not need to consider reactants that are present in excess amounts when carrying out stoichiometric calculations? Use an everyday analogy to explain the idea of excess quantity.

2 (a) C Magnesium reacts with oxygen gas, O_2, from the air. Which reactant do you think will be present in excess?

(b) C Gold is an extremely unreactive metal. Gold does react, however, with *aqua regia* (a mixture of concentrated nitric acid, $HNO_{3(aq)}$, and hydrochloric acid, $HCl_{(aq)}$). The complex ion $AuCl_4^-$, as well as NO_2 and H_2O, are formed. This reaction is always carried out with *aqua regia* in excess. Why would a chemist not have the gold in excess?

(c) C In general, what characteristics or properties of a chemical compound or atom make it suitable to be used as an *excess* reactant?

3 I Copper is a relatively inert metal. It is unreactive with most acids. It does, however, react with nitric acid.

$$3Cu_{(s)} + 8HNO_{3(aq)} \rightarrow 3Cu(NO_3)_{2(aq)} + 2NO_{(g)} + 4H_2O_{(\ell)}$$

What mass of NO is produced when 57.4 g of Cu reacts with 165 g of HNO_3?

4 I Iron can be produced when iron(III) oxide reacts with carbon monoxide gas.

$$Fe_2O_{3(s)} + 3CO_{(g)} \rightarrow 2Fe_{(s)} + 3CO_{2(g)}$$

11.5 g of Fe_2O_3 reacts with 2.63×10^{24} molecules of CO. What mass of Fe is expected?

5 I The reaction of an aqueous solution of iron(III) sulfate with aqueous sodium hydroxide produces aqueous sodium sulfate and a solid precipitate, iron(III) hydroxide.

$$Fe_2(SO_4)_{3(aq)} + 6NaOH_{(aq)} \rightarrow 3Na_2SO_{4(aq)} + 2Fe(OH)_{3(s)}$$

What mass of $Fe(OH)_3$ is produced when 10.0 g of $Fe_2(SO_4)_3$ reacts with an equal mass of NaOH?

6 I Carbon disulfide is used as a solvent for water-insoluble compounds, such as fats, oils, and waxes. Calculate the mass of carbon disulfide that is produced when 17.5 g of carbon reacts with 225 g of sulfur dioxide according to the following equation:

$$5C_{(s)} + 2SO_{2(g)} \rightarrow CS_{2(\ell)} + 4CO_{(g)}$$

7 I A chemist adds some zinc shavings to a beaker containing a blue solution of copper chloride. The contents of the beaker are stirred. After about an hour, the chemist observes that the blue colour has not completely disappeared.

(a) Write a balanced chemical equation to describe this reaction.

(b) What other observations would you expect the chemist to make?

(c) According to the chemist's observations, which reactant was the limiting reactant?

(d) The beaker contained 3.12 g of copper chloride dissolved in water. What does this tell you, quantitatively, about the amount of zinc that was added?

Nitric acid reacts with copper metal to produce poisonous, brown nitrogen dioxide, NO_2, gas.

Unit Investigation Prep

Consider what you have learned about limiting reactants when you design your quantitative analysis experiment at the end of Unit 2. Imagine you add one reactant (A) to an unknown amount of a second reactant (B). You intend to analyze the products (C) in order to calculate the amount of B. In this case, which reactant should be the limiting reactant, A or B? How do you know which reactant is the limiting reactant when you do not know the amount of reactant B?