Introduction to Chemical Engineering Processes/Print Version

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< Introduction to Chemical Engineering Processes
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[edit] Chapter 1: Prerequisites

[edit] Consistency of units

Any value that you'll run across as an engineer will either be *unitless* or, more commonly, will have specific types of units attached to it. In order to solve a problem effectively, all the types of units should be consistent with each other, or should be in the same *system*. A system of units defines each of the basic unit types with respect to some measurement that can be easily duplicated, so that for example 5 ft. is the same length in Australia as it is in the United States. There are five commonly-used base unit types or *dimensions* that one might encounter (shown with their abbreviated forms for the purpose of dimensional analysis):

> **Length** (L), or the physical distance between two objects with respect to some standard distance
> **Time** (t), or how long something takes with respect to how long some natural phenomenon takes to occur
> **Mass** (M), a measure of the inertia of a material relative to that of a standard
> **Temperature** (T), a measure of the average kinetic energy of the molecules in a material relative to a standard
> **Electric Current** (E), a measure of the total charge that moves in a certain amount of time

There are several different consistent systems of units one can choose from. Which one should be used depends on the data available.

[edit] Units of Common Physical Properties

Every system of units has a large number of *derived* units which are, as the name implies, derived from the base units. The new units are based on the physical definitions of other quantities which involve the combination of different variables. Below is a list of several common derived system properties and the corresponding dimensions ($\doteq$ denotes unit equivalence). If you don't know what one of these properties is, you will learn it eventually

TODO

`maybe put links to these properties in?`

Mass $\doteq$ M
Area $\doteq$ L^2
Velocity $\doteq$ L/t
Force $\doteq$ M*L/t^2

Length $\doteq$ L
Volume $\doteq$ L^3
Acceleration $\doteq$ L/t^2
Energy/Work/Heat $\doteq$ M*L^2/t^2

```
Power ≐ M*L^2/t^3                   Pressure ≐ M/(L*t^2)
Density ≐ M/L^3                     Viscosity ≐ M/(L*t)
Diffusivity ≐ L^2/s                 Thermal conductivity ≐ M*L/(t^3*T)
Specific Heat Capacity≐ L^2/(T*t^2)
Specific Enthalpy, Gibbs Energy ≐ L^2/t^2
Specific Entropy ≐ L^2/(t^2*T)
```

[edit] SI (kg-m-s) System

This is the most commonly-used system of units in the world, and is based heavily on units of 10. It was originally based on the properties of water, though currently there are more precise standards in place. The major dimensions are:

```
L ≐ meters, m                  t ≐ seconds, s   M ≐ kilograms, kg
T ≐ degrees Celsius, oC        E ≐ Amperes, A
```

where ≐denotes unit equivalence. The close relationship to water is that one m^3 of water weighs (approximately) 1000 kg at 0oC.

Each of these base units can be made smaller or larger in units of ten by adding the appropriate **metric prefixes**. The specific meanings are (from the SI page on Wikipedia):

SI Prefixes

Name	yotta	zetta	exa	peta	tera	giga	mega	kilo	hecto	deca
Symbol	Y	Z	E	P	T	G	M	k	h	da
Factor	10^{24}	10^{21}	10^{18}	10^{15}	10^{12}	10^{9}	10^{6}	10^{3}	10^{2}	10^{1}
Name	deci	centi	milli	micro	nano	pico	femto	atto	zepto	yocto
Symbol	d	c	m	µ	n	p	f	a	z	y
Factor	10^{-1}	10^{-2}	10^{-3}	10^{-6}	10^{-9}	10^{-12}	10^{-15}	10^{-18}	10^{-21}	10^{-24}

If you see a length of 1 km, according to the chart, the prefix "k" means there are 10^3 of something, and the following "m" means that it is meters. So 1 km = 10^3 meters.

It is very important that you are familiar with this table, or at least as large as mega (M), and as small as nano (n). The relationship between different sizes of metric units was deliberately made simple because you will have to do it all of the time. You may feel uncomfortable with it at first if you're from the U.S. but trust me, after working with the English system you'll learn to appreciate the simplicity of the Metric system.

[edit] Derived units from the SI system

Imagine if every time you calculated a pressure, you would have to write the units in kg/(m*s^2). This would become cumbersome quickly, so the SI people set up **derived units** to use as shorthand for such combinations as these. The most common ones used by chemical engineers are as follows:

```
Force: 1 kg/(m*s^2) = 1 Newton, N     Energy: 1 N*m = 1 J
Power: 1 J/s = 1 Watt, W              Pressure: 1 N/m^2 = 1 Pa
Volume: 1 m^3 = 1000 Liters, L        Thermodynamic temperature: 1 oC =
K - 273.15, K is Kelvin
```

Another derived unit is the *mole*. A mole represents $6.022*10^{23}$ molecules of *any substance*. This number is used because it is the number of molecules that are found in 12 grams of the ^{12}C isotope. Whenever we have a reaction, as you learned in chemistry, you have to do stoichiometry calculations based on moles rather than on grams, because *the number of grams of a substance does not only depend on the number of molecules present but also on their size*, whereas the stoichiometry of a chemical reaction only depends on the number of molecules that react, not on their size. Converting units from grams to moles eliminates the size dependency.

[edit] CGS (cm-g-s) system

The so-called CGS system *uses the same base units as the SI system but expresses masses and grams in terms of cm and g instead of kg and m*. The CGS system has its own set of derived units (see w:cgs), but commonly basic units are expressed in terms of cm and g, and then the derived units from the SI system are used. In order to use the SI units, the masses *must* be in kilograms, and the distances *must* be in meters. This is a very important thing to remember, especially when dealing with force, energy, and pressure equations.

[edit] English system

The English system is fundamentally different from the Metric system in that *the fundamental inertial quantity is a force, not a mass*. In addition, units of different sizes do not typically have prefixes and have more complex conversion factors than those of the metric system.

The base units of the English system are somewhat debatable but these are the ones I've seen most often:

```
Length: L ≐ feet, ft            t ≐ seconds, s
F ≐ pounds-force, lb(f)         T ≐ degrees Fahrenheit, oF
```

The base unit of electric current remains the Ampere.

There are several derived units in the English system but, unlike the Metric system, the conversions are not neat at all, so it is best to consult a conversion table or program for the necessary changes. It is especially important to keep good track of the units in the English system because if they're not on the same basis, you'll end up with a mess of units as a result of your calculations, i.e. for a force you'll end up with units like Btu/in instead of just pounds, lb. This is why it's helpful to know the derived units in terms of the base units: it allows you to make sure everything is in terms of the same base units. *If every value is written in terms of the same base units, and the equation that is used is correct, then the units of the answer will be consistent and in terms of the same base units.*

[edit] How to convert between units

[edit] Finding equivalences

The first thing you need in order to convert between units is the equivalence between the units you want and the units you have. To do this use a **conversion table**. See w:Conversion of units for a fairly extensive (but not exhaustive) list of common units and their equivalences.

Conversions within the metric system usually are not listed, because it is assumed that one can use the prefixes and the fact that $1\ \mathrm{mL} = 1\ \mathrm{cm}^3$ to convert anything that is desired.

Conversions within the English system and especially between the English and metric system are sometimes (but not on Wikipedia) written in the form:

$$1(unit1) = (number)(unit2) = (number)(unit3) = ...$$

For example, you might recall the following conversion from chemistry class:

$$1\ \mathrm{atm} = 760\ \mathrm{mmHg} = 1.013 * 10^5\ \mathrm{Pa} = 1.013\ \mathrm{bar} = ...$$

The table on Wikipedia takes a slightly different approach: the column on the far left side is the unit we have 1 of, the middle is the definition of the unit on the left, and on the far right-hand column we have the metric equivalent. One listing is the conversion from feet to meters:

$$\text{foot (International) ft} = 1/3 \text{ yd} = 0.3048 \text{ m}$$

Both methods are common and one should be able to use either to look up conversions.

[edit] Using the equivalences

Once the equivalences are determined, use the general form:

$$\text{What you want} = \text{What you have} * \frac{\text{What you want}}{\text{What you have}}$$

The fraction on the right comes directly from the conversion tables.

Example:

Convert 800 mmHg into bars

Solution If you wanted to convert 800 mmHg to bars, using the horizontal list, you could do it directly:

$$bars = 800 \text{ mmHg} * \frac{1.013 \text{ bar}}{760 \text{ mmHg}} = 1.066 \text{ bar}$$

Using the tables from Wikipedia, you need to convert to an *intermediate* (the metric unit) and then convert from the intermediate to the desired unit. We would find that

$1 \text{ mmHg} = 133.322 \text{ Pa}$ and $1 \text{ bar} = 10^5 \text{ Pa}$

Again, we have to set it up using the same general form, just we have to do it twice:

$$bars = 800 \text{ mmHg} * \frac{133.322 \text{ Pa}}{1 \text{ mmHg}} * \frac{10^5 \text{ Pa}}{1 \text{ bar}} = 1.066 \text{ bar}$$

Setting these up takes practice, there will be some examples at the end of the section on this. It's a **very important** skill for any engineer.

One way to keep from avoiding "doing it backwards" is to write everything out and make sure your units cancel out as they should! If you try to do it backwards you'll end up with something like this:

$$bars = 800\text{ mmHg} * \frac{760\text{ mmHg}}{1.013\text{ bar}} = 6.0 * 10^5 \frac{mmHg^2}{bar}$$

If you write everything (even conversions within the metric system!) out, and make sure that everything cancels, you'll help mitigate unit-changing errors. About 30-40% of all mistakes I've seen have been unit-related, which is why there is such a long section in here about it. Remember them well.

[edit] Dimensional analysis as a check on equations

Since we know what the units of velocity, pressure, energy, force, and so on should be in terms of the base units L, M, t, T, and E, we can use this knowledge to check the feasibility of equations that involve these quantities.

Example:

Analyze the following equation for dimensional consistency: $P = g * h$ where g is the gravitational acceleration and h is the height of the fluid

Solution We could check this equation by plugging in our units:

$$P \doteq M/(L * t^2)\ ,\ h \doteq L\ ,\ g \doteq L/t^2$$
$$g * h \doteq L^2/t^2 \neq M/(L * t^2)$$

Since g*h doesn't have the same units as P, the equation must be wrong *regardless of the system of units we are using!* The correct equation, in fact, is:

$$P = \rho * g * h$$

where ρ is the density of the fluid. Density has base units of M/L^3 so

$\rho * g * h \doteq L^2/t^2 * M/L^3 \doteq M/(L * t^2)$ which are the units of pressure.

This does not tell us the equation is correct but it *does* tell us that the units are consistent, which is necessary though not sufficient to obtain a correct equation. *This is a useful way to detect algebraic mistakes that would otherwise be hard to find.* The ability to do this with an algebraic equation is a good argument against plugging in numbers too soon!

Problem:

1. Perform the following conversions, using the appropriate number of significant figures in your answer:

a) $1.5\frac{g}{s} \longrightarrow \frac{lb}{hr}$

b) $4.5 * 10^2 \text{ W} \longrightarrow \frac{btu}{min}$

c) $34\frac{\mu g}{\mu m^3} \longrightarrow \frac{oz}{in^3}$

d) $4.18\frac{J}{g * oC} \longrightarrow \frac{kWh}{lb * oF}$ (note: kWh means kilowatt-hour)

e) $1.00 \text{ m}^3 \longrightarrow L \longrightarrow dm^3 \longrightarrow mL \longrightarrow cm^3$

Problem:

2. Perform a dimensional analysis on the following equations to determine if they are reasonable:

a) $v = dt$, where v is velocity, d is distance, and t is time.

b) $F = \frac{m * v^2}{r}$ where F is force, m is mass, v is velocity, and r is radius (a distance).

c) $F_{bouy} = \rho * V * g$ where ρ is density, V is volume, and g is gravitational acceleration.

d) $\dot{m} = \frac{\dot{V}}{\rho}$ where $\dot{m}$ is mass flow rate, $\dot{V}$ is volumetric flow rate, and ρ is density.

Problem:

3. Recall that the ideal gas law is $PV = nRT$ where P is pressure, V is volume, n is number of moles, R is a constant, and T is the temperature.

a) What are the units of R in terms of the base unit types (length, time, mass, and temperature)?

b) Show how these two values of R are equivalent:

$$R = 0.0821 \frac{L * atm}{mol * K} = 8.31 \frac{J}{mol * K}$$

c) If an ideal gas exists in a closed container with a molar density of $0.03 \frac{mol}{L}$ at a pressure of $0.96 * 10^5 \text{ Pa}$, what temperature is the container held at?

d) What is the molar concentration of an ideal gas with a partial pressure of $4.5 * 10^5 \text{ Pa}$ if the total pressure in the container is 6 atm?

e) At what temperatures and pressures is a gas most and least likely to be ideal? (hint: you can't use it when you have a liquid)

f) Suppose you want to mix ideal gasses in two separate tanks together. The first tank is held at a pressure of 500 Torr and contains 50 moles of water vapor and 30 moles of water at 70oC. The second is held at 400 Torr and 70oC. The volume of the second tank is the same as that of the first, and the ratio of moles water vapor to moles of water is the same in both tanks.

You recombine the gasses into a single tank the same size as the first two. Assuming that the temperature remains constant, what is the pressure in the final tank? If the tank can withstand 1 atm pressure, will it blow up?

Problem:

4. Consider the reaction $H_2O_2 < - > H_2O + \frac{1}{2}O_2$, which is carried out by many organisms as a way to eliminate hydrogen peroxide.

a). What is the standard enthalpy of this reaction? Under what conditions does it hold?

b). What is the standard Gibbs energy change of this reaction? Under what conditions does it hold? In what direction is the reaction spontaneous at standard conditions?

c). What is the Gibbs energy change at biological conditions (1 atm and 37oC) if the initial hydrogen peroxide concentration is 0.01M? Assume oxygen is the only gas present in the cell.

d). What is the equilibrium constant under the conditions in part c? Under the conditions in part b)? What is the constant independent of?

e). Repeat parts a through d for the alternative reaction $H_2O_2 \rightarrow H_2 + O_2$. Why isn't this reaction used instead?

Problem:

5. Two ideal gasses A and B combine to form a third ideal gas, C, in the reaction $A + B \rightarrow C$. Suppose that the reaction is irreversible and occurs at a constant temperature of 25oC in a 5L container. If you start with 0.2 moles of A and 0.5 moles of B at a total pressure of 1.04 atm, what will the pressure be when the reaction is completed?

[edit] Chapter 2: Elementary mass balances

[edit] The "Black Box" approach to problem-solving

In this book, all the problems you'll solve will be "black-box" problems. This means that we take a look at a unit operation *from the outside*, looking at what goes into the system and what leaves, and extrapolating data about the properties of the entrance and exit streams from this. This type of analysis is important because it does not depend on the specific type of unit operation that is performed. *When doing a black-box analysis, we don't care about how the unit operation is designed, only what the net result is.* Let's look at an example:

Example:

Suppose that you pour 1L of water into the top end of a funnel, and that funnel leads into a large flask, and you measure that the entire liter of water enters the flask. If the funnel had no water in it to begin with, how much is left over after the process is completed?

Solution The answer, of course, is 0, because you only put 1L of water in, and 1L of water came out the other end. The answer to this does not depend on the how large the funnel is, the slope of the sides, or any other design aspect of the funnel, which is why it is a black-box problem.

[edit] Conservation equations

The formal mathematical way of describing the black-box approach is with **conservation equations** which explicitly state that what goes into the system must either come out of the system somewhere else, get used up or generated by the system, or remain in the system and **accumulate**. The relationship between these is simple:

1. The streams entering the system cause an increase of the substance (mass, energy, momentum, etc.) in the system.
2. The streams leaving the system decrease the amount of the substance in the system.
3. Generating or consuming mechanisms (such as chemical reactions) can either increase or decrease the stuff in the system.
4. What's left over is the amount of stuff in the system

With these four statements we can state the following very important general principle:

$$Accumulation = In - Out + Generation$$

Its so important, in fact, that you'll see it a million times or so, including a few in this book, and it is used to derive a variety of forms of conservation equations.

[edit] Common assumptions on the conservation equation

The conservation equation is very general and applies to any property a system can have. However, it can also lead to complicated equations, and so in order to simplify calculations when appropriate, it is useful to apply assumptions to the problem.

- **Closed system**: A closed system is one which does not have flows in or out of the substance. Almost always, when one refers to a close system it is implied to be closed to *mass flow* but not to other flows such as energy or momentum. The equation for a closed system is:

  $$Accumulation = Generation$$

  The opposite of a closed system is an **open system** in which the substance is allowed to enter and/or leave the system. The funnel in the example was an open system because mass flowed in and out of it.

- **No generation**: Certain quantities are always **conserved** in the strict sense that they are never created or destroyed. These are the most useful quantities to do balances on because then the user does not need to worry about a generation term.

  $$Accumulation = In - Out$$

  The most commonly-used conserved quantities are **mass** and **energy**. It is important to note, however, that though the *total* mass and *total* energy in a system are conserved, the mass of a single species is *not* (since it may be changed into something else). Neither is the "heat" in a system if a so-called "heat-balance" is performed. Therefore one must be careful when deciding whether to discard the generation term.

- **Steady State**: A system which does not accumulate a substance is said to be at steady-state. Often times, this allows the engineer to avoid having to solve differential equations and instead use algebra.

  $$In - Out + Generation = 0$$

> *All problems in this text assume steady state but it is not always a valid assumption*. It is mostly valid after a process has been running for long enough that all the flow rates, temperatures, pressures, and other system parameters have reached equilibrium values. It is not valid when a process is first warming up and the parameters wobble significantly. How they wobble is a subject for another course.

[edit] Conservation of mass

TOTAL mass is a conserved quantity (except in nuclear reactions, let's not go there), as is the mass of any individual species if there is no chemical reaction occurring in the system. Let us write the conservation equation *at steady state* for such a case (with no reaction):

$$In - Out = 0$$

Now, there are two major ways in which mass can enter or leave a system: diffusion and convection. However, for large-scale systems such as the ones considered here, in which the velocity entering the unit operations is fairly large and the concentration gradient is fairly small, diffusion can be neglected and the only mass entering or leaving the system is due to convective flow:

$$Mass_{in} = \dot{m}_{in} = \rho * v * A$$

A similar equation apply for the mass out. In this book generally we use the symbol $\dot{m}$ to signify a convective mass flow rate, in units of $mass/time$. Since the total flow in is the sum of individual flows, and the same with the flow out, the following **steady state mass balance** is obtained for the overall mass in the system:

$$\boxed{\sum \dot{m}_{out} - \sum \dot{m}_{in} = 0}$$

If it is a *batch* system, or if we're looking at how much has entered and left in a given period of time (rather than instantaneously), we can apply the same mass balance without the time component. In this book, a value without the dot signifies a value without a time component:

$$\sum m_{out} - \sum m_{in} = 0$$

Example:

Let's work out the previous example (the funnel) but explicitly state the mass balance. We're given the following information:

1. $m_{in} = 1L$
2. $m_{out} = 1L$

From the general balance equation,

$In - Out = Accumulation$

Therefore, $Accumulation = 1L - 1L = 0$.

Since the accumulation is 0, the system is at steady state.

This is a fairly trivial example, but it gets the concepts of "in", "out", and "accumulation" on a physical basis, which is important for setting up problems. In the next section, it will be shown how to apply the mass balance to solve more complex problems with only one component.

[edit] Introduction

In any system there will be certain parameters that are (often considerably) easier to measure and/or control than others. When you are solving any problem and trying to use a mass balance or any other equation, *it is important to recognize what pieces of information can be interconverted*. The purpose of this section is to show some of the more common alternative ways that mass flow rates are expressed, mostly because it is easier to, for example, measure a velocity than it is to measure a mass flow rate directly.

[edit] Volumetric Flow rates

A **volumetric flow rate** is a relation of how much volume of a gas or liquid solution passes through a fixed point in a system (typically the entrance or exit point of a process) in a given amount of time. It is denoted as:

$\dot{V}_n \doteq \frac{Volume}{time}$ in stream n

Volume in the metric system is typically expressed either in L (dm^3), mL (cm^3), or m^3. Note that a cubic meter is very large; a cubic meter of water weighs about 1000kg (2200 pounds) at room temperature!

[edit] Why they're useful

Volumetric flowrates can be measured directly using **flowmeters**. They are especially useful for gases since the volume of a gas is one of the found properties that are needed in order to use an *equation of state* (discussed later in the book) to calculate the molar flow rate. Of the other three, two (pressure, and temperature) can be specified by the reactor design and control systems, while one (compressibility) is strictly a function of temperature and pressure for any gas or gaseous mixture.

[edit] Limitations

Volumetric Flowrates are Not Conserved. We can write a balance on volume like anything else, but the "volume generation" term would be a complex function of system properties. Therefore if we are given a volumetric flow rate we should change it into a mass (or mole) flow rate before applying the balance equations.

Volumetric flowrates also do not lend themselves to splitting into components, since when we speak of volumes in practical terms we generally think of the total solution volume, not the partial volume of each component (the latter is a useful tool for thermodynamics, but that's another course entirely). There **are** some things that are measured in volume fractions, but this is relatively uncommon.

[edit] How to convert volumetric flow rates to mass flow rates

Volumetric flowrates are related to mass flow rates by a relatively easy-to-measure physical property. Since $\dot{m} \doteq mass/time$ and $\dot{V} \doteq volume/time$, we need a property with units of $mass/volume$ in order to convert them. The **density** serves this purpose nicely!

$\dot{V}_n * \rho_n = \dot{m}_n$ in stream n

The "i" indicates that we're talking about one particular flow stream here, since each flow may have a different density, mass flow rate, or volumetric flow rate.

[edit] Velocities

The velocity of a bulk fluid is *how much lateral distance along the system (usually a pipe) it passes per unit time*. The velocity of a bulk fluid, like any other, has units of:

$$\boxed{v_n = \frac{distance}{time} \text{ in stream n}}$$

By definition, the bulk velocity of a fluid is related to the volumetric flow rate by:

$$\boxed{v_n = \frac{\dot{V}_n}{A_n} \text{in stream n}}$$

This distinguishes it from the velocity of the fluid at a certain point (since fluids flow faster in the center of a pipe). The bulk velocity is about the same as the instantaneous velocity for relatively fast flow, or especially for flow of gasses.

For purposes of this class, all velocities given will be bulk velocities, not instantaneous velocities.

[edit] Why they're useful

(Bulk) Velocities are useful because, like volumetric flow rates, they are relatively easy to measure. They are especially useful for liquids since they have constant density (and therefore a constant pressure drop at steady state) as they pass through the orifice or other similar instruments. This is a necessary prerequisite to use the design equations for these instruments.

[edit] Limitations

Like volumetric flowrates, **velocity is not conserved**. Like volumetric flowrate, velocity changes with temperature and pressure of a gas, though for a liquid velocity is generally constant along the length of a pipe.

Also, velocities can't be split into the flows of individual components, since all of the components will generally flow at the same speed. They need to be converted into something that can be split (mass flow rate, molar flow rate, or pressure for a gas) before concentrations can be applied.

[edit] How to convert velocity into mass flow rate

In order to convert the velocity of a fluid stream into a mass flow rate, you need two pieces of information:

1. The **cross sectional area** of the pipe.
2. The **density** of the fluid.

In order to convert, first use the definition of bulk velocity to convert it into a volumetric flow rate:

$$\dot{V}_n = v_n * A_n$$

Then use the density to convert the volumetric flow rate into a mass flow rate.

$$\dot{m}_n = \dot{V}_n * \rho_n$$

The combination of these two equations is useful:

$$\boxed{\dot{m}_n = \dot{V}_n * \rho_n * A_n \text{in stream n}}$$

[edit] Molar Flow Rates

The concept of a molar flow rate is similar to that of a mass flow rate, it is the number of moles of a solution (or mixture) that pass a fixed point per unit time:

$$\boxed{\dot{n}_n \doteq \frac{moles}{time} \text{ in stream n}}$$

[edit] Why they're useful

Molar flow rates are mostly useful because *using moles instead of mass allows you to write material balances in terms of reaction conversion and stoichiometry*. In other words, there are a lot less unknowns when you use a mole balance, since the stoichiometry allows you to consolidate all of the changes in the reactant and product concentrations in terms of one variable. This will be discussed more in a later chapter.

[edit] Limitations

Unlike mass, **total moles are not conserved**. Total mass flow rate is conserved whether there is a reaction or not, but the same is not true for the number of moles. For example, consider the reaction between hydrogen and oxygen gasses to form water:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

This reaction consumes 1.5 moles of reactants for every mole of products produced, and therefore the total number of moles entering the reactor will be more than the number leaving it.

However, since neither mass nor moles of individual components is conserved in a reacting system, it's better to use moles so that the stoichiometry can be exploited, as described later.

The molar flows are also somewhat less practical than mass flow rates, since you can't measure moles directly but you can measure the mass of something, and then convert it to moles using the molar flow rate.

[edit] How to Change from Molar Flow Rate to Mass Flow Rate

Molar flow rates and mass flow rates are related by the **molecular weight** (also known as the **molar mass**) of the solution. In order to convert the mass and molar flow rates of the *entire solution*, we need to know the **average molecular weight** of the solution. This can be calculated from the molecular weights and mole fractions of the components using the formula:

$$M\bar{W}_n = [\Sigma(MW_i * y_i)]_n$$

where i is an index of *components* and n is the *stream* number. $y_i$signifies *mole fraction* of each component (this will all be defined and derived later).

Once this is known it can be used as you would use a molar mass for a single component to find the total molar flow rate.

$\dot{m}_n = \dot{n}_n * M\bar{W}_n$in stream n

[edit] The Point of the Section

Most problems you will face are significantly more complicated than the previous problem and the following one. In the engineering world, problems are presented as so-called "word problems", in which a system is described and the problem must be set up and solved (if possible) from the description. This section will attempt to illustrate through example, step by step, some common techniques and pitfalls in setting up mass balances. Some of the steps may seem somewhat excessive at this point, but if you follow them carefully on this relatively simple problem, you will certainly have an easier time following later steps.

[edit] An Example Problem

Example:

A feed stream of pure liquid water enters an evaporator at a rate of 0.5 kg/s. Three streams come from the evaporator: a vapor stream and two liquid streams. The flowrate of the vapor stream was measured to be 4*10^6 L/min and its density was 4 g/m^3. The vapor stream enters a turbine, where it loses enough energy to condense fully and leave as a single stream. One of the liquid streams is discharged as waste, the other is fed into a heat exchanger, where it is cooled. This stream leaves the heat exchanger at a rate of 1500 pounds per hour. Calculate the flow rate of the discharge and the efficiency of the evaporator.

Note that one way to define efficiency is in terms of conversion, which is intended here:

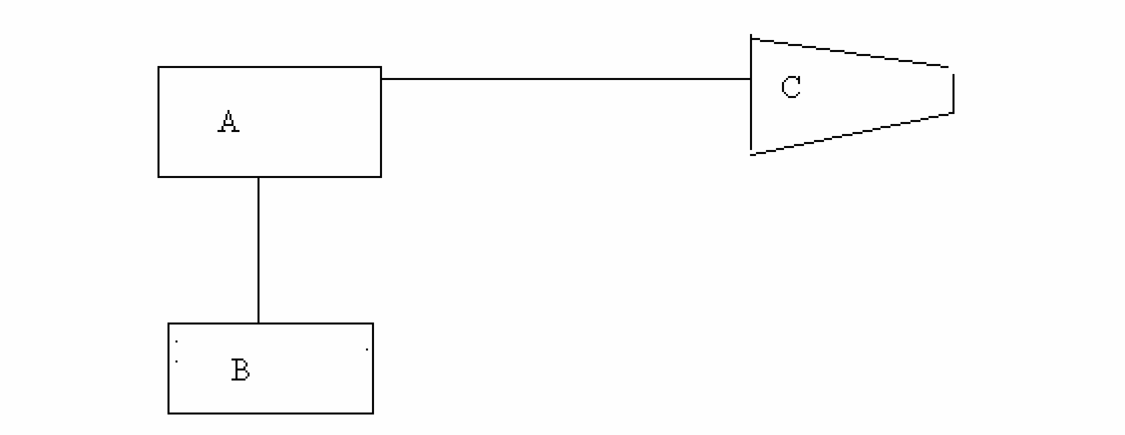
$$efficiency = \frac{\dot{m}_{vapor}}{\dot{m}_{feed}}$$

[edit] Step 1: Draw a Flowchart

The problem as it stands contains an awful lot of text, but it won't mean much until you *draw what is given to you*. First, ask yourself, what processes are in use in this problem? **Make a list** of the processes in the problem:

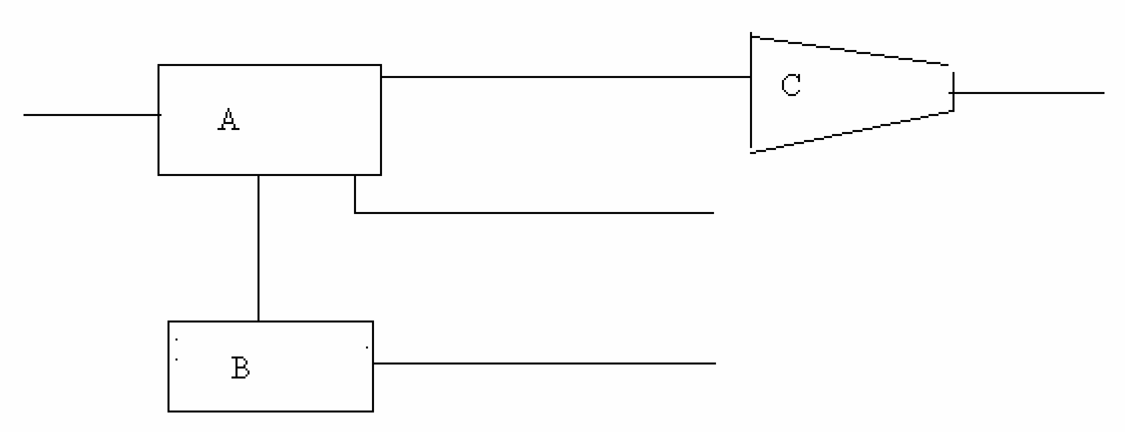
1. Evaporator (A)
2. Heat Exchanger (B)
3. Turbine (C)

Once you have a list of all the processes, you need to **find out how they are connected** (it'll tell you something like "the vapor stream enters a turbine"). Draw a basic sketch of the processes and their connections, and label the processes. It should look something like this:



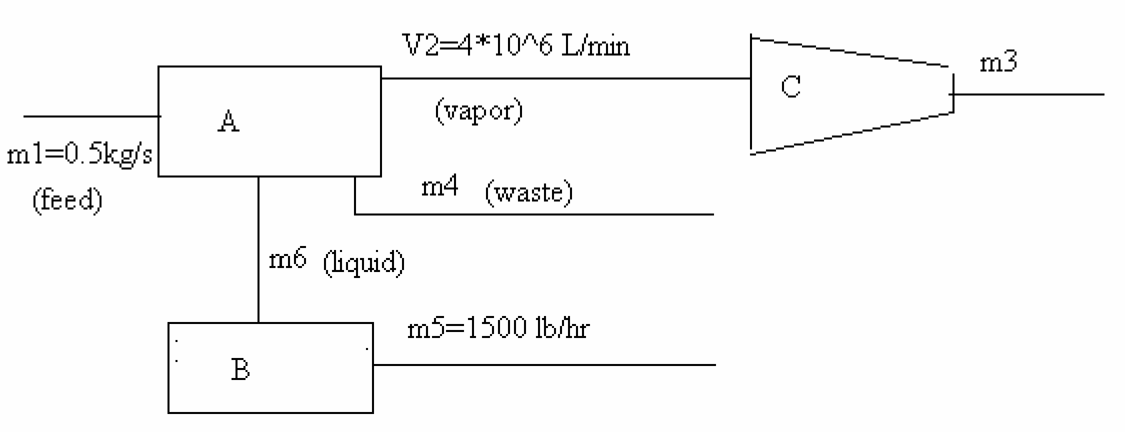
Remember, we don't care what the actual processes look like, or how they're designed. At this point, we only really label what they are so that we can go back to the problem and know which process they're talking about.

Once all your processes are connected, **find any streams that are not yet accounted for**. In this case, we have not drawn the feed stream into the evaporator, the waste stream from the evaporator, or the exit streams from the turbine and heat exchanger.



The third step is to **Label all your flows**. Label them with any information you are given. Any information you are not given, and even information you are given should be given a different variable. It is usually easiest to give them the same variable as is found in the equation you will be using (for example, if you have an unknown flow rate, call it $\dot{m}$ so it remains clear what the unknown value is physically. Give each a different subscript corresponding to the number of the feed stream (such as $\dot{m}_1$for the feed stream that you call "stream 1"). Make sure you **include all units** on the given values!

In the example problem, the flowchart I drew with all flows labeled looked like this:



Notice that for one of the streams, a *volume* flow rate is given rather than a *mass* flow rate, so it is labeled as such. This is very important, so that you avoid using a value in an equation that isn't valid (for example, there's no such thing as "conservation of volume" for most cases)!

The final step in drawing the flowchart is to **write down any additional given information in terms of the variables you have defined**. In this problem, the density of the water in the vapor stream is given, so write this on the side for future reference.

Carefully drawn flowcharts and diagrams are half of the key to solving any mass balance, or really a lot of other types of engineering problems. They are just as important as having the right units to getting the right answer.

[edit] Step 2: Make sure your units are consistent

The second step is to make sure all your units are consistent and, if not, to convert everything so that it is. In this case, since the principle that we'll need to use to solve for the flow rate of the waste stream ($\dot{m}_3$) is conservation of mass, everything will need to be on a mass-flow basis, and also in the *same* mass-flow units.

In this problem, since two of our flow rates are given in metric units (though one is a volumetric flow rate rather than a mass flow rate, so we'll need to change that) and only one in English units, it would save time and minimize mistakes to convert $\dot{V}_2$ and $\dot{m}_5$ to kg/s.

From the previous section, the equation relating volumetric flowrate to mass flow rate is:

$$\dot{V}_i * \rho_i = \dot{m}_i$$

Therefore, we need the density of water vapor in order to calculate the mass flow rate from the volumetric flow rate. Since the density is provided in the problem statement (if it wasn't, we'd need to calculate it with methods described later), the mass flow rate can be calculated:

$$\dot{V}_2 = \frac{4 * 10^6 \text{ L}}{1 \text{ min}} * \frac{1 \text{ m}^3}{1000 \text{ L}} * \frac{1 \text{ min}}{60 \text{ s}} = 66.67\frac{m^3}{s}$$

$$\rho_2 = 4\frac{g}{m^3} * \frac{1 \text{ kg}}{1000 \text{ g}} = 0.004\frac{kg}{m^3}$$

$$\dot{m}_2 = 66.67\frac{m^3}{s} * 0.004\frac{kg}{m^3} = 0.2666\frac{kg}{s}$$

Note that since the density of a gas is so small, a huge volumetric flow rate is necessary to achieve any significant mass flow rate. This is fairly typical and is a practical problem when dealing with gas-phase processes.

The mass flow rate $\dot{m}_5$ can be changed in a similar manner, but since it is already in terms of mass (or weight technically), we don't need to apply a density:

$$\dot{m}_5 = 1500\frac{lb}{hr} * \frac{1kg}{2.2lb} * \frac{1hr}{3600s} = 0.1893\frac{kg}{s}$$

Now that everything is in the same system of units, we can proceed to the next step.

[edit] Step 3: Relate your variables

Since we have the mass flow rate of the vapor stream we can calculate the efficiency of the evaporator directly:

$$efficiency = \frac{\dot{m}_2}{\dot{m}_1} = \frac{0.2666\frac{kg}{s}}{0.5\frac{kg}{s}} = 53.3\%$$

Finding $\dot{m}_4$, as asked for in the problem, will be somewhat more difficult. One place to start is to write the mass balance on the evaporator, since that will certainly contain the unknown we seek. Assuming that the process is steady state we can write:

$$In - Out = 0$$

$$\dot{m}_1 - \dot{m}_2 - \dot{m}_4 - \dot{m}_6 = 0$$

Problem: we don't know $\dot{m}_6$ so with only this equation we cannot solve for $\dot{m}_4$. Have no fear, however, because there is another way to figure out what $\dot{m}_6$ is... can you figure it out? Try to do so before you move on.

[edit] So you want to check your guess? Alright then read on.

The way to find $\dot{m}_6$ is to do a mass balance on the heat exchanger, because the mass balance for the heat exchanger is simply:

$$\dot{m}_6 - \dot{m}_5 = 0$$

Since we know $\dot{m}_5$ we can calculate $\dot{m}_6$ and thus the waste stream flowrate $\dot{m}_4$.

NOTE:
Notice the strategy here: we first start with a balance on the operation containing the stream we need information about. Then we move to balances on other operations in order to garner additional information about the unknowns in the process. This takes **practice** to figure out when you have enough information to solve the problem or you need to do more balances or look up information.

It is also of note that **any process has a limited number of independent balances you can perform**. This is not as much of an issue with a relatively simple problem like this, but will become an issue with more complex problems. Therefore, a step-by-step method exists to tell you exactly how many independent mass balances you can write on any given process, and therefore how many total independent equations you can use to help you solve problems.

[edit] Step 4: Calculate your unknowns.

Carrying out the plan on this problem:

$$\dot{m}_6 - 0.1893\frac{kg}{s} = 0$$

$$\dot{m}_6 = 0.1893\frac{kg}{s}$$

Hence, from the mass balance on the evaporator:

$$\dot{m}_4 = \dot{m}_1 - \dot{m}_2 - \dot{m}_6 = (0.5 - 0.2666 - 0.1893)\frac{kg}{s} = 0.0441\frac{kg}{s}$$

So the final answers are:

$$\text{Evaporator Efficiency} = 53.3\%$$

$$\text{Waste stream rate} = 0.0441 \frac{kg}{s}$$

[edit] Step 5: Check your work.

Ask: Do these answers make sense? Check for things like negative flow rates, efficiencies higher than 100%, or other physically impossible happenings; if something like this happens (and it will), you did something wrong. Is your exit rate higher than the total inlet rate (since no water is created in the processes, it is impossible for this to occur)?

In this case, the values make physical sense, so they may be right. It's always good to go back and check the math *and* the setup to make sure you didn't forget to convert any units or anything like that.

[edit] Chapter 2 Practice Problems

Problem:

1. *a)* A salt solution is to be concentrated by evaporating the water in a salt pan, with a condensing surface above it to gather the evaporated water. Suppose 1200g of salt solution are emptied into the pan. Once all the water is evaporated, the salt is weighed and found to weigh 100g. What percent of the original solution was water?

b) Now suppose that 0.1 L of the evaporated water was added back to the salt, to bring it to the desired concentration. How much water remains to be used elsewhere?

c) Do you think the salt solution would be safe to drink? Why or why not?

Problem:

2. *a)* In a stone quarry, limestone is to be crushed and poured into molds for manufacture of floor tiles. Suppose that a limestone company uses three trucks, each of which is capable of carrying 3000 kg of limestone. The quarry itself is 20 miles away from the processing plant, and the trucks get there at an average speed of 30 miles/hour. Once at the plant, the limestone is ground into fine powder and then melted and poured into the molds. If each of the resulting slabs weighs 2 kg and the plant operates 24 hours a day, how many slabs can the company make in a day?

b) How could this plant become more efficient? Plot the number of slabs the company can make as a function of distance from the quarry and capacity of the trucks. What factors might keep the company from simply moving as close to the quarry as possible and using the largest trucks possible?

Problem:

3. What is the volumetric flowrate of a solution with density 1.5 kg/m^3 flowing at a velocity of 5 m/s and a mass flow rate of 500 g/min? What is the area of the pipe? If it is circular, what is the radius?

Problem:

4. Suppose you have a pipe that constricts halfway through from a radius of 0.5 cm to a radius of 0.2 cm. A liquid approaches the constriction at a velocity of 0.5 m/s. What is the velocity of the fluid after the constriction? (Hint: Apply conservation of mass on both sides of the constriction).

Challenge: What kind of energy does the fluid gain? Energy is never created or destroyed, so where does it come from?

Problem:

5. Suppose that a river with a molar flow rate of 10000 mol/s meets another, larger river flowing at 500000 m^3/s at room temperature. What is the mass flow rate of the river downstream of the intersection if you assume steady state?

b} Evaluate the feasibility of the steady state assumption in this situation. Also qualitatively evaluate the probability that the flowrates are actually constant.

Problem:

6. Suppose that the population of a certain country n years after year 2000 if there is no emigration can be modeled with the equation:

$$P = 2.5 * 10^8 * e^{0.045*n}$$

Also, suppose that in the country, a net emigration of 100,000 people per month actually occurs. What is the total accumulation of people in this country from year 2000 to 2003?

b) What was the population of people in 2002, according to this model?

c) What are some possible problems with this model? For example, what doesn't it take into account? What happens when n is 100? Where did those constants come from? Would they be the same for every country, or for the same country across generations?

Solutions

[edit] Chapter 3: Mass balances on multicomponent systems

[edit] Component Mass Balance

Most processes, of course, involve more than one input and/or output, and therefore it must be learned how to perform mass balances on this type of system. The basic idea remains the same though. We can write a mass balance in the same form as the overall balance for each component:

$$In - Out + Generation = Accumulation$$

For **steady state** processes, this becomes:

$$In - Out + Generation = 0$$

The **overall** mass balance at steady state, recall, is:

$$\Sigma \dot{m}_{in} - \Sigma \dot{m}_{out} + m_{gen} = 0$$

The mass of each component can be described by a similar balance.

$$\Sigma \dot{m}_{A,in} - \Sigma \dot{m}_{A,out} + m_{A,gen} = 0$$

The biggest difference between these two equations is that **The total generation of mass $m_{gen}$is zero due to conservation of mass, but since individual species can be consumed in a reaction, $m_{A,gen} \neq 0$for a reacting system**

[edit] Concentration Measurements

You may recall from general chemistry that a **concentration** is a measure of the amount of some species in a mixture relative to the total amount of material, or relative to the amount of another species. Several different measurements of concentration come up over and over, so they were given special names.

[edit] Molarity

The first major concentration unit is the **molarity** which relates the moles of one particular species to the total volume of the solution.

$$Molarity(A) = [A] = \frac{n_A}{V_{sln}} \text{ where } n \doteq mol, V \doteq L$$

A more useful definition for flow systems that is equally valid is:

$$\boxed{[A] = \frac{\dot{n}_A}{\dot{V}_n} \text{ where } \dot{n}_A \doteq mol/s, \dot{V}_n \doteq L/s}$$

Molarity is a useful measure of concentration because it takes into account the volumetric changes that can occur when one creates a mixture from pure substances. Thus it is a very practical unit of concentration. However, since it involves volume, it can change with temperature so *molarity should always be given at a specific temperature*. Molarity of a gaseous mixture can also change with pressure, so it is not usually used for gasses.

[edit] Mole Fraction

The **mole fraction** is one of the most useful units of concentration, since it allows one to directly determine the molar flow rate of any component from the total flowrate. It also conveniently is *always* between 0 and 1, which is a good check on your work as well as an additional equation that you can always use to help you solve problems.

The mole fraction of a component A in a mixture is defined as:

$$y_A = \frac{n_A}{n_n}$$

where n_A signifies moles of A. Like molarity, a definition in terms of flowrates is also possible:

$$\boxed{y_A = \frac{\dot{n}_A}{\dot{n}_n}}$$

As mentioned before, if you add up all mole fractions in a mixture, you should always obtain 1 (within calculation and measurement error):

$$\Sigma y_i = 1$$

Note that **each stream has its own independent set of concentrations**.

[edit] Mass Fraction

Since mass is a more practical property to measure than moles, flowrates are often given as *mass* flowrates rather than *molar* flowrates. When this occurs, it is convenient to express concentrations in terms of **mass fractions** defined similarly to mole fractions:

$x_A = \frac{m_A}{m_n}$ for batch systems

$$x_A = \frac{\dot{m}_A}{\dot{m}_n}$$

where m_A is the mass of A. It doesn't matter what the units of the mass are as long as they are the same as the units of the total mass of solution.

Like the mole fraction, the total mass fraction in any stream should always add up to 1.

$$\Sigma x_i = 1$$

[edit] Calculations on Multi-component streams

Various conversions must be done with multiple-component streams just as they must for single-component streams. This section shows some methods to combine the properties of single-component streams into something usable for multiple-component streams(with some assumptions).

[edit] Average Molecular Weight

The *average molecular weight* of a mixture (gas or liquid) is the multicomponent equivalent to the molecular weight of a pure species. It allows you to convert between the mass of a mixture and the number of moles, which is important for reacting systems especially because balances must usually be done in moles, but measurements are generally in grams.

To find the value of $M\bar{W}_n = \frac{g \text{ sln}}{mole \text{ sln}}$, we split the solution up into its components as follows, for k components:

$$\frac{g \text{ sln}}{mole \text{ sln}} = \frac{\Sigma m_i}{n_n} = \Sigma \frac{m_i}{n_n}$$

$$= \Sigma(\frac{m_i}{n_i} * \frac{n_i}{n_n}) = \Sigma(MW_i * y_i)$$

Therefore, we have the following formula:

$$\boxed{M\bar{W}_n = \Sigma(MW_i * y_i)_n}$$

This derivation only assumes that **mass is additive**, which is is, so this equation is valid for *any* mixture.

[edit] Density of Liquid Mixtures

Let us attempt to calculate the density of a liquid mixture from the density of its components, similar to how we calculated the average molecular weight. This time, however, we will notice one critical difference in the assumptions we have to make. We'll also notice that there are **two** different equations we could come up with, depending on the assumptions we make.

[edit] First Equation

By definition, the density of a single component i is: $\rho_i = \frac{m_i}{V_i}$ The corresponding definition for a solution is $\rho = \frac{m \text{ sln}}{V \text{ sln}}$. Following a similar derivation to the above for average molecular weight:

$$\frac{m \text{ sln}}{V \text{ sln}} = \frac{\Sigma m_i}{V_n} = \Sigma \frac{m_i}{V_n}$$

$$= \Sigma \frac{m_i}{V_i} * \frac{V_i}{V_n} = \Sigma(\rho_i * \frac{V_i}{V_n})$$

Now we make the assumption that **The volume of the solution is proportional to the mass**. This is true for any pure substance (the proportionality constant is the density), but it is further assumed that **the proportionality constant is the same for both pure k and the solution**. This equation is therefore useful for two substances with similar pure densities. If this is true then:

$$\frac{V_i}{V} = \frac{m_i}{m_n} = x_i$$ and:

$$\boxed{\rho_n = \Sigma(x_i * \rho_i)_n}$$

[edit] Second Equation

This equation is easier to derive if we assume the equation will have a form similar to that of average molar mass. Since density is given in terms of mass, it makes sense to try using mass fractions:

$$x_k = \frac{m_i}{m_n}$$

To get this in terms of only solution properties, we need to get rid of m_A. We do this first by dividing by the density:

$$\frac{x_i}{\rho_i} = \frac{m_i}{m_n} * \frac{V_i}{m_i}$$

$$= \frac{V_i}{m_n}$$

Now if we add all of these up we obtain:

$$\Sigma(\frac{x_i}{\rho_i}) = \frac{\Sigma V_i}{m_n}$$

Now we have to make an assumption, and it's different from that in the first case. This time we assume that the **Volumes are additive**. This is true in two cases:

1. In an **ideal solution**. The idea of an ideal solution will be explained more later, but for now you need to know that ideal solutions:

- Tend to involve similar compounds in solution with each other, or when one component is so dilute that it doesn't effect the solution properties much.
- Include Ideal Gas mixtures at constant temperature and pressure.

2 In a **Completely immiscible nonreacting mixture**. In other words, if two substances don't mix at all (like oil and water, or if you throw a rock into a puddle), the total volume will not change when you mix them.

If the solution is ideal, then we can write:

$$\frac{\Sigma \dot{V}_i}{\dot{m}_n} = \frac{\dot{V}_n}{\dot{m}_n} = \frac{1}{\rho_i}$$

Hence, for an ideal solution,

$$\boxed{\frac{1}{\rho_n} = \Sigma(\frac{x_i}{\rho_i})_n}$$

Note that this is significantly different from the previous equation! This equation is more accurate for most cases. In all cases, however, it is most accurate to look up the value in a handbook such as Perry's Chemical Engineers Handbook if data is available on the solution of interest.

[edit] Introduction to the Section

In the vast majority of chemical processes, in which some raw materials are processed to yield a desired end product or set of end products, there will be more than one raw material entering the system and more than one unit operation through which the product must pass in order to achieve the desired result. The calculations for such processes, as you can probably guess, are considerably more complicated than those either for only a single component, or for a single-operation process. Therefore, several techniques have been developed to aid engineers in their analyses. This section describes these techniques and how to apply them to an example problem.

[edit] Degree of Freedom Analysis

For more complex problems than the single-component or single-operation problems that have been explored, it is essential that you have a method of determining if a problem is even solvable given the information that you have. There are three ways to describe a problem in terms of its solvability:

1. If the problem has a finite (not necessarily unique!) set of solutions then it is called **well-defined**.
2. The problem can be **overdetermined** (also known as **overspecified**), which means that you have too much information and it is either redundant or inconsistent. This could possibly be fixed by consolidating multiple data into a single function or, in extreme cases, a single value (such as a slope of a linear correlation), or it could be fixed by removing an assumption about the system that one had made.
3. The problem can be **underdetermined** (or **underspecified**), which means that you don't have enough information to solve for all your unknowns. There are several ways of dealing with this. The most obvious is to gather additional information, such as measuring additional temperatures, flow rates, and so on until you have a well-defined problem. Another way is to use additional equations or information about what we want out of a process, such as how much conversion you obtain in a reaction, how efficient a separation process is, and so on. Finally, we can **make assumptions** in order to simplify the equations, and perhaps they will simplify enough that they become solvable.

The method of analyzing systems to see whether they are over or under-specified, or if they are well-defined, is called a **degree of freedom analysis**. It works as follows for mass balances:

TODO

Check this list to make sure its right

1. Take the process you wish to analyze and determine the number of **components, C** entering and leaving the system. Most of the time, the number of components is just the number of separate molecules entering and leaving the system. Multiply this by the number of **phases, P** to get the number of unknown masses (recall that each phase has its own separate set of concentrations).
2. Subtract the number of **mass balances, B** you can write on the system (one per component) or the number of atom balances if its a reacting system (one per atom type).
3. If you are doing a mass balance or a mole balance and NOT an atom balance, ADD the number of reactions (since each reaction gives you one additional unknown, the conversion).
4. Subtract the number of **additional information, I** you are given about the process: this includes flow rates, concentrations, conversions, efficiencies, and anything else that can be converted into one of these (such as the combination of velocity and area).
5. The number you are left with is the degrees of freedom of the process.

If the degrees of freedom are **negative** that means your problem is **overspecified**. If it is **positive**, your problem is **underspecified**. If it is **zero** then you can go ahead with the mass balances on that process.

[edit] An example problem

Example:

Consider a process in which raw oranges are processed into orange juice. A possible process description follows:

1. The oranges enter a crusher, in which all of the water contained within the oranges is released.
2. The now-crushed oranges enter a strainer. The strainer is able to capture 90% of the solids, the remainder exit with the orange juice as pulp.

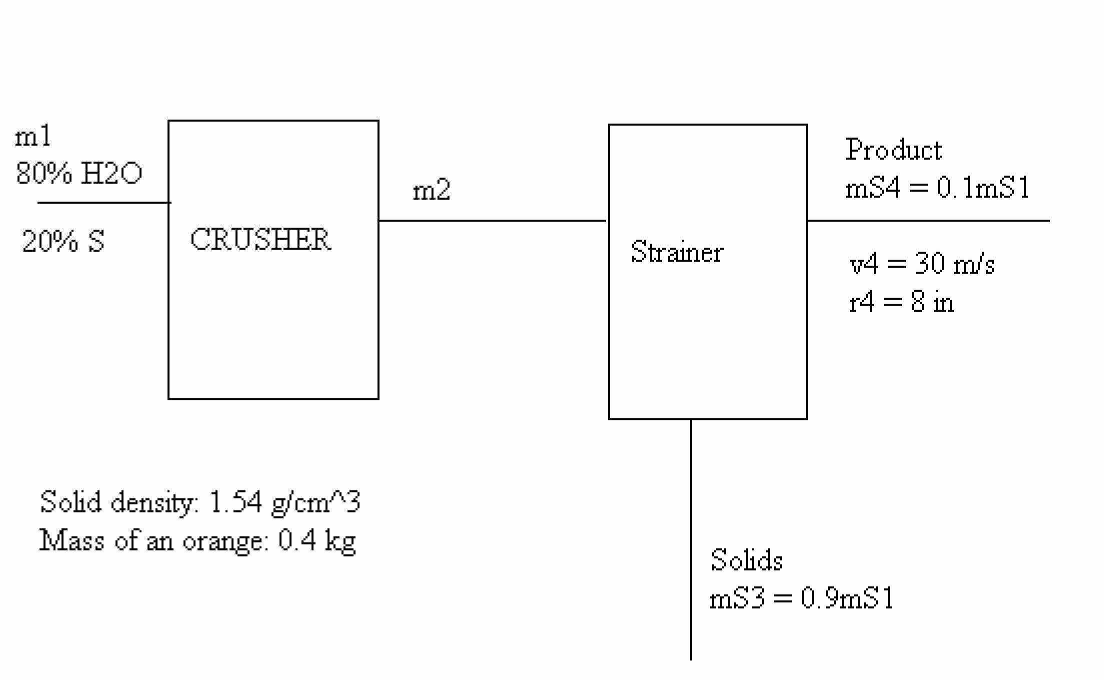
The velocity of the orange juice stream was measured to be $30\frac{m}{s}$ and the radius of the piping was 8 inches. Calculate:

a) The mass flow rate of the orange juice product. b) The number of oranges per year that can be processed with this process if it is run 8 hours a day and 360 days a year. Ignore changes due to unsteady state at startup.

Use the following data: Mass of an orange: 0.4 kg Water content of an orange: 80% Density of the solids: Since its mostly sugars, its about the density of glucose, which is $1.540\frac{g}{cm^3}$

[edit] Step 1: Draw a Flowchart

This time we have multiple processes so it's especially important to label each one as its given in the problem.



Notice how I changed the 90% capture of solids into an algebraic equation relating the mass of solids in the solid waste to the mass in the feed. This will be important later, because *it is an additional piece of information that is necessary to solve the problem.*

Also note that from here in, "solids" are referred to as S and "water" as W.

[edit] Step 2: Degree of Freedom analysis

Recall that for each stream there are C independent unknowns, where C is the number of components in the individual stream. These generally are **concentrations** of C-1 species and the **total mass flow rate**, since with C-1 concentrations we can find the last one, but we cannot obtain the total mass flow rate from only concentration.

Let us apply the previously described algorithm to determining if the problem is well-defined.

On the Overall System:

- There are two components in the feed, two in the solid waste, and two in the orange juice product stream. Therefore, there are **6** unknowns.
- We are given a conversion (1), a mass fraction of water in the feed (1), and enough information to write the mass flow rate in the product in terms of only concentration of one component (which eliminates one unknown). I'll describe how below, but its mostly unit-pushing and using the average density under the *assumption* that the solids and water are immiscable. Thus we have **3** pieces of information.
- We can write **2** independent mass balances on the overall system (one for each component).
- Thus the degrees of freedom of the overall system are 6-3-2 = **1 DOF**

NOTE:
We are given the mass of an individual orange, but since we cannot use that information alone to find a total mass flow rate of oranges in the feed, and we already have used up our allotment of C-1 independent concentrations, we cannot count this as "given information". If, however, we were told the number of oranges produced per year, then we could use the two pieces of information in tandem to eliminate a single unknown (because then we can find the mass flow rate)

On the strainer:

- This will be the same as the overall because the crusher does not change the composition of the feed at steady state.

On the crusher:

- There are **4** unknowns.
- We know the mass fraction of water in each orange and thus in the stream of oranges. (**1** given information)
- We can write **2** independent mass balances.
- Thus the crusher has 4-2-1 = **1 DOF**

Therefore it appears that the problem is underspecified.

[edit] So how to we solve it?

In order to solve an underspecified problem, one way we can obtain an additional specification is to **make an assumption**. What assumptions could we make that would reduce the number of unknowns (or equivalently, increase the number of variables we do know)?

The most common type of assumption is to assume that something that is relatively insignificant is zero.

In this case, one could ask: will the solid stream from the strainer contain any water? It might, of course, but this amount is probably very small compared to both the amount of solids that are captured and how much is strained, provided that it is cleaned regularly and designed well. If we make this assumption, then *this specifies that the mass fraction of water in the waste stream is zero* (or equivalently, that the mass fraction of solids is one). Therefore, we know one additional piece of information and the degrees of freedom for the overall system become zero.

[edit] Step 3: Convert Units

This step should be done *after* the degree of freedom analysis, because that analysis is independent of your unit system, and if you don't have enough information to solve a problem (or worse, you have too much), you shouldn't waste time converting units and should instead spend your time defining the problem more precisely and/or seeking out appropriate assumptions to make.

Here, the most sensible choice is either to convert everything to the cgs system or to the m-kg-s system, since most values are already in metric. Here, the latter route is taken.

$$r_4 = 8 \text{ in} * \frac{2.54 \text{ cm}}{in} * \frac{1 \text{ m}}{100 \text{ cm}} = 0.2032 \text{ m}$$

$$\rho_S = 1.54 \frac{g}{cm^3} = 1540 \frac{kg}{m^3}$$

Now that everything is in the same system, we can move on to the next step.

[edit] Step 4: Relate your variables

First we have to relate the velocity and area given to us to the mass flowrate of stream 4, so that we can actually use that information in a mass balance. From chapter 2, we can start with the equation:

$$\rho_n * v_n * A_n = \dot{m}_n$$

Since the pipe is circular and the area of a circle is $\pi * r^2$, we have:

$$A_4 = \pi * 0.2032^2 = 0.1297 \text{ m}^2$$

So we have that:

$$\rho_4 * 30 * 0.1297 = 3.8915 * \rho_4 = \dot{m}_4$$

Now to find the density of stream 4 we assume that volumes are additive, since the solids and water are essentially immiscible (does an orange dissolve when you wash it?). Hence we can use the ideal-fluid model for density:

$$\frac{1}{\rho_4} = \frac{x_{S4}}{\rho_S} + \frac{x_{W4}}{\rho_W} = \frac{x_{S4}}{\rho_S} + \frac{1 - x_{S4}}{\rho_W}$$

$$= \frac{x_{S4}}{1540} + \frac{1 - x_{S4}}{1000}$$

Hence, we have the equation we need with only concentrations and mass flowrates:

EQUATION 1: $\frac{x_{S4}}{1540} + \frac{1 - x_{S4}}{1000} = \frac{3.8915}{\dot{m}_4}$

Now we have an equation but we haven't used either of our two (why two?) independent mass balances yet. We of course have a choice on which two to use.

In this particular problem, since we are directly given information concerning the amount of *solid* in stream 4 (the product stream), it seems to make more sense to do the balance on this component. Since we don't have information on stream 2, and finding it would be pointless in this case (all parts of it are the same as those of stream 1), lets do an overall-system balance on the solids:

$$\Sigma \dot{m}_{S,in} - \Sigma \dot{m}_{S,out} = 0$$

NOTE:
Since there is no reaction, the generation term is 0 even for individual-species balances.

Expanding the mass balance in terms of mass fractions gives:

$$\dot{m}_1 * x_{S1} = \dot{m}_3 * x_{S3} + \dot{m}_4 * x_{S4}$$

Plugging in the known values, **with the assumption that stream 3 is pure solids (no water)** and hence $x_{S3} = 1$:

EQUATION 2: $0.2 * \dot{m}_1 = (0.9 * 0.2 * \dot{m}_1) * 1 + x_{S4} * \dot{m}_4$

Finally, we can utilize one further mass balance, so let's use the easiest one: the overall mass balance. This one again assumes that the total flowrate of stream 3 is equal to the solids flowrate.

EQUATION 3: $\dot{m}_1 = 0.9 * 0.2 * \dot{m}_1 + \dot{m}_4$

We now have three equations in three unknowns $(\dot{m}_1, \dot{m}_4, x_{S4})$ so the problem is solvable. This is where all those system-solving skills will come in handy.

If you don't like solving by hand, there are numerous computer programs out there to help you solve equations like this, such as MATLAB, POLYMATH, and many others. You'll probably want to learn how to use the one your school prefers eventually so why not now?

Using either method, the results are:

$$\dot{m}_1 = 4786 \frac{kg}{s}$$

$$\dot{m}_4 = 3925.07$$

$$x_{S4} = 0.0244$$

We're almost done here, now we just have to calculate the number of oranges per year.

$$4786 \frac{kg}{s} * 1 \frac{orange}{0.4 \text{ kg}} * 3600 \frac{s}{hr} * 8 \frac{wk \text{ hr}}{day} * 360 \frac{\text{wk day}}{year}$$

Yearly Production: $1.24 * 10^{11} \frac{oranges}{year}$

[edit] Chapter 3 Practice Problems

Problem:

1. *a)* Look up the composition of air. Estimate its average molecular weight.

b) Qualitatively describe whether the density of air should be large or small compared to the density of water.

c) Qualitatively describe whether the mass density of air should be large or small compared to that of oxygen if the same number of *moles* of the two gasses are contained in identical containers.

d) If the density of air under certain conditions is 1.06 g/m^3, how much does a gallon of air weigh?

Problem:

2. *a)* Using both of the formulas for average density, calculate estimates for the density of a 50% by mass solution of toluene and benzene. Comment on the results.

b) Repeat this calculation for varying concentrations of toluene. When does it make the most difference which formula you use? When does it make the least? Show the results graphically. Would the trend be the same for any binary solution?

c) Suppose that a 50% mixture of toluene and benzene is to be separated by crystallization. The solution is cooled until one of the components completely freezes and only the other is left as a liquid. The liquid is then removed. What will the majority of the solid be? What will the liquid be? What temperature should be used to achieve this? (give an estimate)

d) In the crystallization process in part c, suppose that the after separation, the solid crystals contained all of the benzene and 1% of the toluene from the original mixture. Suppose also that after melting the solid, the resulting liquid weighed 1435 g. Calculate the mass of the original solution.

Problem:

3.. Consider a publishing company in which books are to be bound, printed, and shipped. At 5 a.m. every morning, a shipment of 10,000 reams of paper comes in, as well as enough materials to make 150,000 books, and 30000 pounds of ink. In this particular plant, the average size of a book is 250 pages and each uses about 0.2 pounds of ink.

a) How many books can be printed for each shipment? (Hint: What is the limiting factor?)

b) Suppose that, on average, 4% of all books printed are misprints and must be destroyed. The remaining books are to be distributed to each of 6 continents in the following proportions:

North America	15%
South America	10%
Europe	20%
Africa	20%
Asia	25%
Australia	10%

Each book that is printed (including those that are destroyed) costs the company US$0.50 to print. Those that are shipped cost the following prices to ship from the US:

North America	$0.05
South America	$0.08
Europe	$0.10
Africa	$0.20
Asia	$0.12
Australia	$0.15

If each book sells for an equivalent of US$1.00, what is the maximum profit that the company can make per day?

c) **Challenge** What is the *minimum* number of books that the company can sell (from any continent) in order to return a profit? (Hint: what is the total cost of this scheme? Does it matter where the books are sold once they are distributed?)

d) How many pounds of ink per day end up in each continent under the scheme in part b? How many pages of paper?

e) Can you think of any ways you can improve this process? What may be some ways to improve the profit margin? How can inventory be reduced? What are some possible problems with your proposed solutions?

[edit] Chapter 4: Mass balances with recycle

[edit] Problem Statement

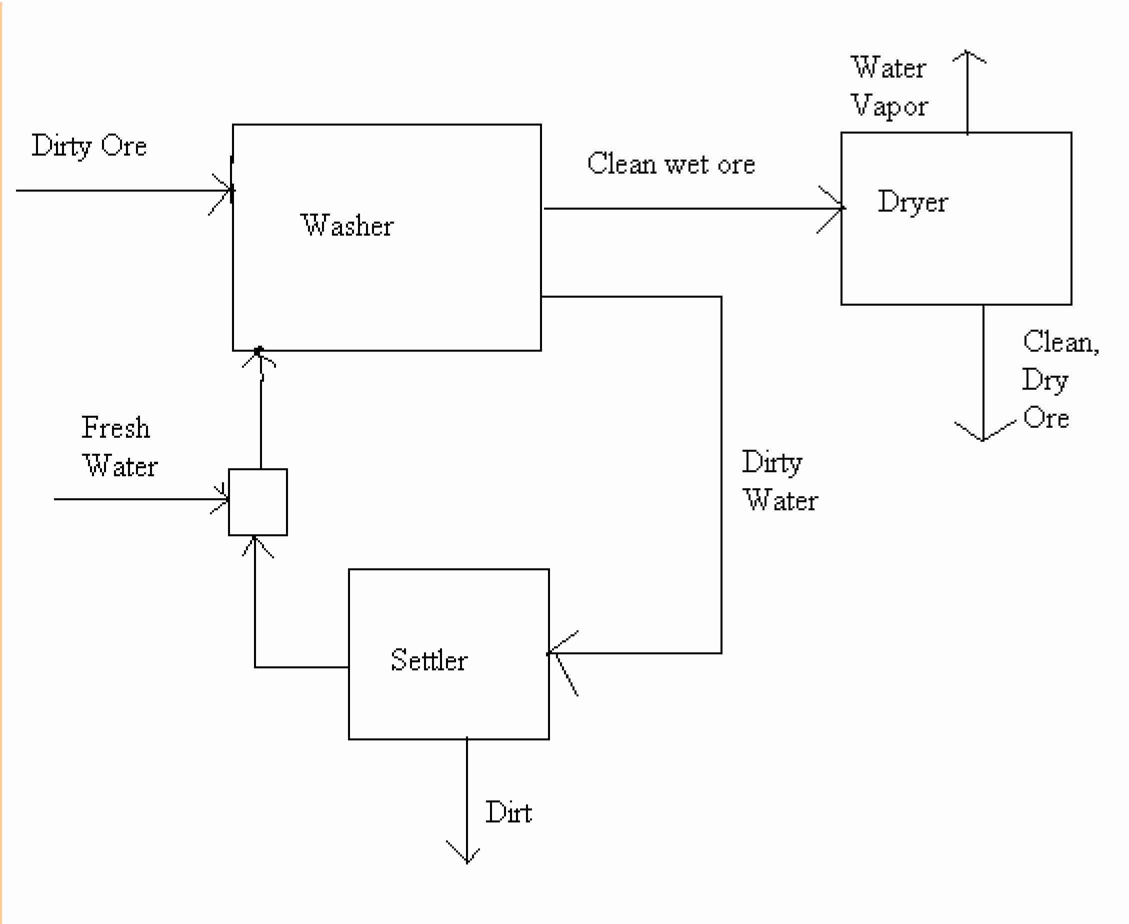
Example:

Consider a process in which freshly-mined ore is to be cleaned so that later processing units do not get contaminated with dirt. 3000 kg/hr of dirty ore is dumped into a large washer, in which water is allowed to soak the ore on its way to a drain on the bottom of the unit. The amount of dirt remaining on the ore after this process is negligible, but water remains absorbed on the ore surface such that the net mass flow rate of the cleaned ore is 3100 kg/hr.

The dirty water is cleaned in a settler, which is able to remove 90% of the dirt in the stream without removing a significant amount of water. The cleaned stream then is combined with a fresh water stream before re-entering the washer.

The wet, clean ore enters a dryer, in which all of the water is removed. Dry ore is removed from the dryer at 2900 kg/hr.

The design schematic for this process was as follows:



a) Calculate the necessary mass flow rate of fresh water to achieve this removal at steady state.

b) Suppose that the solubility of dirt in water is $0.4\frac{g}{cm^3 \ \mathrm{H_2}O}$. Assuming that the water leaving the washer is saturated with dirt, calculate the mass fraction of dirt in the stream that enters the washer (after it has been mixed with the fresh-water stream).

[edit] First Step: Draw a Flowchart

A schematic is given in the problem statement but it is very incomplete, since it does not contain any of the design specifications (the efficiency of the settler, the solubility of soil in water, and the mass flow rates). Therefore, *it is highly recommended that you draw your own picture even when one is provided for you*. Make sure you label all of the streams, and the unknown concentrations.

[edit] Appendix 1: Useful Mathematical Methods

[edit] Mean and Standard Deviation

A lot of the time, when you're conducting an experiment, you will run it more than once, especially if it is inexpensive. Scientists run experiments more than once so that the *random errors* that result from taking measurements, such as having to guess a length between two hash marks on a ruler, cancel themselves out and leave them with a more precise measurement. However, the question remains: how should you consolidate all of the data into something that's more managable to use?

[edit] Mean

Suppose you have n data points taken **under the same conditions** and you wish to consolidate them to as few as feasibly possible. One thing which could help is is to use some centralized value, which is in some way "between" all of the original data points. This, in fact, is called the **mean** of the data set.

There are many ways of computing the mean of a data set depending on how it is believed to be distributed. One of the most common methods is to use the *arithmetic mean*, which is defined as:

$$\bar{x} = \frac{\Sigma \hat{x}_k}{n}$$

Other types of mean include the w:Geometric mean, which should be used when the data are very widely distributed (ex. an exponential distribution) and the "log-mean" which occurs often in transport phenomena.

[edit] Standard Deviation

Having a value for the mean tells you what value the data points "cluster" around but it does not tell you how spread out they are from the center. A second statistical variable called the **standard deviation** is used for that. The standard deviation is essentially *the average distance between the data points and their mean*. The distance is expressed as a squared distance in order to prevent negative deviations from lessoning the effect of positive deviations.

The mathematical formulation for the standard deviation σ is:

$$\sigma^2 = \frac{\Sigma(\hat{x}_k - \bar{x})}{n-1}$$

The denominator is n-1 instead of n because statisticians found that it gives better results for small numbers of experiments; see w:Standard deviation for a more thorough explanation of this.

[edit] Putting it together

The standard deviation of a data set measured under constant conditions is a measure of how precise the data set is. Because this is true, the standard deviation of a data set is often used in conjunction with the mean in order to report experimental results. Typically, results are reported as:

$$\bar{x} \pm \sigma$$

If a distribution is assumed, knowing both the mean and standard deviation can help us to estimate the probability that the actual value of the variable is within a certain range, *if there is no systematic bias in the data*. If there is (such as use of broken equipment, negligence, and so on) then no statistics could predict the effects of that.

[edit] Linear Regression

Suppose you have a set of data points ($\hat{x}_k, \hat{y}_k$) taken **under differing conditions** which you suspect, from a graph, can be reasonably estimated by drawing a line through the points. Any line that you could draw will have (or can be written in) the following form:

$y = mx + b$ where m is the slope of the line and b is the y-intercept.

We seek the *best* line that we could possibly use to estimate the pattern of the data. This line will be most useful for both interpolating between points that we know, and extrapolating to unknown values (as long as they're close to measured values). In the most usual measure, how "good" the fit is is determined by the vertical distance between the line and the data points (R_k), which is called the **residual**:

$$R_k = (m\hat{x}_k + b) - \hat{y}_k$$

In order to normalize the residuals so that they don't cancel when one's positive and one's negative (and thus helping to avoid statistical bias), we are usually concerned with the *square* of R_k when doing least-squares regression. We use squared terms and not absolute values so that the function is differentiable, don't worry about this if you haven't taken calculus yet.

In order to take into account *all* of the data points, we simply seek to minimize the sum of the squared residuals:

$$\text{minimize } \Sigma {R_k}^2$$

Using calculus, we can take the derivative of this with respect to m and with respect to b and solve the equations to come up with the values of m and b that minimize the sum of squares (hence the alternate name of this technique: **least-squares regression**. The formulas are as follows, where n is the total number of data points you are regressing[1]:

$$\boxed{m^* = \frac{n * \Sigma(\hat{x}_k * \hat{y}_k) - \Sigma(\hat{x}_k) * \Sigma(\hat{y}_k)}{n * \Sigma({\hat{x}_k}^2) - (\Sigma(\hat{x}_k))^2}}$$

$$\boxed{b^* = \frac{\Sigma(\hat{y}_k) - m^* * \Sigma(\hat{x}_k)}{n}}$$

[edit] Example of linear regression

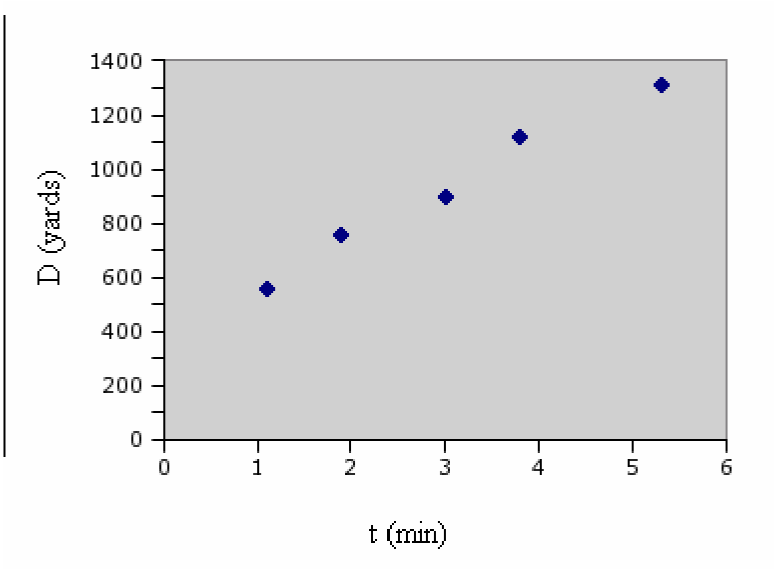
Example:

Suppose you wanted to measure how fast you got to school by a less direct route than looking at the speedometer of your car. Instead, you look at a map and read the distances between each intersection, and then you measure how long it takes to go each distance. Suppose the results were as follows (D is total distance from home):

t(min)	D (yards)
1.1	559.5
1.9	759.5
3.0	898.2
3.8	1116.3
5.3	1308.7

How far from home did you start, and what is the best estimate for your average speed?

The first thing we should do with any data like this is to graph it and see if a linear fit would be reasonable. Plotting this data, we can see by inspection that a linear fit appears to be reasonable.



Now we need to compute all of the values in our regression formulas, and to do this (by hand) we set up a table:

n = 5

Trial	t	t^2	D	D^2	t*D
1	1.1	1.21	559.5	313040	615.45
2	1.9	3.61	759.5	576840	1443.05
3	3.0	9.00	898.2	806763	2694.6
4	3.8	14.44	1116.3	1246126	4241.94
5	5.3	28.09	1308.7	1712695	6936.11
TOTAL	15.1	56.35	4642.2	4655464	15931.15

Now that we have this data we can plug it into our linear regression equation:

$$m^* = \frac{n * \Sigma(\hat{x}_k * \hat{y}_k) - \Sigma(\hat{x}_k) * \Sigma(\hat{y}_k)}{n * \Sigma(\hat{x}_k{}^2) - (\Sigma(\hat{x}_k))^2}$$

$$= \frac{5 * 15931.13 - 15.1 * 4642.2}{5 * 56.35 - (15.1)^2}$$

$$= 177.9\ \frac{yard}{min}$$

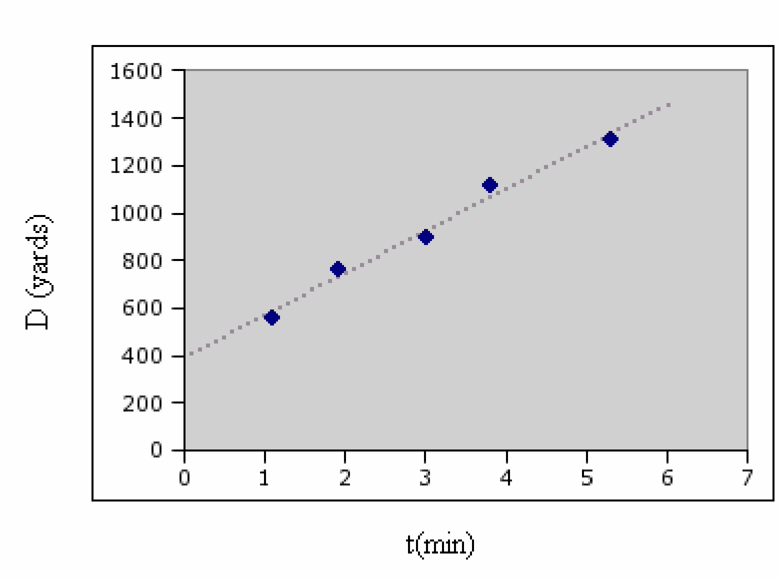
So $$b = \frac{\Sigma(\hat{y}_k) - m^* * \Sigma(\hat{x}_k)}{n}$$

$$= \frac{4642.2 - 177.9 * 15.1}{5} = 391.2 \text{ yards}$$

Hence the equation for the line of best fit is:

$$\boxed{D = 177.9 * t + 391.2}$$

The graph of this plotted against the data looks like this:



[edit] How to tell how good your regression is

In the previous example, we visually determined if it would be reasonable to perform a linear fit, but it is certainly possible to have a less clear-cut case! If there is some slight curve to the data, is it still "close enough" to be useful? Though it will always come down to your own judgment after seeing the fit line graph against the data, there is a mathematical tool to help you called a **correlation coefficient**, r, which can be defined in several different ways. One of them is as follows [1]:

$$\boxed{r = \frac{n * \Sigma(\hat{x}_k * \hat{y}_k) - \Sigma(\hat{x}_k) * \Sigma(\hat{y}_k)}{\sqrt{n * \Sigma(\hat{x}_k^2) - (\Sigma\hat{x}_k)^2} * \sqrt{n * \Sigma(\hat{y}_k^2) - (\Sigma\hat{y}_k)^2}}}$$

It can be shown that this value always lies between -1 and 1. The closer it is to 1 (or -1), the more reasonable the linear fit. In general, the more data points you have, the smaller r needs to be before it's a good fit, but a good rule of thumb is to look for high (higher than

0.85 or 0.9) values and then graph to see if the graph makes sense. Sometimes it will, sometimes it won't, the method is not foolproof.

In the above example we have:

$$r = \frac{5 * 15931.13 - 15.1 * 4642.2}{\sqrt{5 * 56.35 - (15.1)^2} * \sqrt{5 * 4655464 - (4642.2)^2}}$$

$$r = 0.992$$

Hence the data correlates very well with a linear model.

[edit] Linearization

[edit] In general

Whenever you have to fit a parameter or multiple parameters to data, it is a good idea to try to **linearize** the function first, because linear regression is much less intensive and more accurate than nonlinear regression. The goal with any linearization is to reduce the function to the form:

$$Variable\ 1 = constant + constant * \text{ Variable 2}$$

The difference between this and "standard" linear regression is that Variable 1 and Variable 2 can be *any functions* of x and y, as long as they are not combined in any way (i.e. you can't have $ln(x+y)$as one variable). The technique can be extended to more than two variables using a method called w:multiple linear regression but as that's more difficult to perform, this section will focus on two-dimensional regression.

[edit] Power Law

To see some of the power of linearization, let's suppose that we have two variables, x and y, related by a power law:

$$y = A * x^b$$

where A and b are constants. If we have data connecting changes in y to changes in x, we would like to know the values of a and b. This is difficult to do if the equation is in its current form but we can change it into a linear-type function!

The trick here is we need to get rid of the exponent b, so in order to do that we take the natural log of both sides:

$$ln \text{ y} = ln \text{ (A*x}^b\text{)}$$

Using laws of logarithms we can simplify the right-hand side to obtain the following:

$$y = A * x^b < - > ln\ \mathrm{y} = ln\ \mathrm{A} + b * ln\ \mathrm{x}$$

The beauty of this equation is that it is, in a sense, linear. **If we graph ln(y) vs. ln(x) obtain a straight line with slope b and y-intercept ln(A)**.

[edit] Exponentials

Another common use of linearization is with exponentials, where x and y are related by an expression of the form:

$$y = A * b^x$$

This works for any base but the most common base encountered in practice is Euler's constant, e. Again, we take the natural log of both sides, in order to get rid of the exponent:

$$y = A * b^x < - > ln\ \mathrm{y} = \ln A + x * \ln b$$

This time, **Graph ln y vs. x to obtain a line with slope ln(b) and y-intercept ln(A)**.

[edit] References

[1]: Smith, Karl J. The Nature of Mathematics. Pacific Grove, California: Brooks/Cole Publishing company, 63, p. 683Introduction to Chemical Engineering Processes/Numerical Root Finding Methods

[edit] Appendix 2: Problem Solving using Computers

[edit] Introduction to Spreadsheets

This tutorial probably works with other spreadsheets (such as w:open office) with minor modifications.

A **spreadsheet** such as Excel is a program that lets you analyze moderately large amounts of data by placing each data point in a **cell** and then performing the same operation on groups of cells at once. One of the nice things about spreadsheets is that data input and manipulation is relatively intuitive and hence easier than doing the same tasks in a programming language like MATLAB (discussed next). This section shows how to do some of these manipulations so that you don't have to by hand.

[edit] Inputting and Manipulating Data

The first step in any spreadsheet analysis is to input the raw data you want to analyze. It is most effective if you put it in columns, with one column for each variable. It lets you see more data at once, and it also is less limited because the maximum number of rows is much larger than the maximum number of columns.

It is good practice to use the first row for the names of the variables, and the remaining for the data points. Make sure you include units.

	A	B
1	t(min)	D (yards)
2	1.1	559.5
3	1.9	759.5
4	3.0	898.2
5	3.8	1116.3
6	5.3	1308.7

[edit] Performing Operations on Groups of Cells

[edit] Statistics on Data Sets

[edit] Graphing Data

In Excel, there are a variety of ways to graph the data you have inserted, such as bar graphs, pie charts, and many others. The most commonly-used in my experience is the **scatterplot**, which is the name Excel uses for the typical x-y "line graph" plot that you probably think of first when you think of a graph.

[edit] Scatterplots

Scatterplots can be made relating any one independent variable to any number of dependent variables, though if you try to graph too many it will get crowded and hard to read. Excel will automatically give each different dependent variable a different color and a different shape, so that you can distinguish between them. You can also name each "series" of data differently and Excel will automatically set up a legend for you.

This is how to make a scatterplot:

1. Put the data into columns just like it was given in the problem statement.
2. Now we need to set up the graph. Go to: $Insert \rightarrow Chart$.
3. Select "XY (scatter)" and click "next".
4. Click the "series" tab (on top). If there are any series present, remove them with the remove button (since it usually guesses wrong what you want to graph).

Now we can add a series for each dependent variable we want to graph as follows:

1. Click "add".
2. Next to "X values" click the funky arrow symbol to the right of the text box. A small box will pop up.
3. Click on the first value for the *independent variable* and drag the mouse down to the last value. Click the funky symbol again to bring you back to the main window.
4. Do the same thing with the "Y values" but this time you want to select the values of the *dependent variable*.
5. Click next, and give the graph a title and labels if you want. Then click next and "finish" to generate your graph.

[edit] Performing Regressions of the Data from a Scatterplot

Once you have a scatterplot of your data, you can do one of several types of regression: logarithmic, exponential, polynomial (up to 6th degree), linear, or moving-average. Excel will plot the regression curve against your data automatically, and (except for moving average) you can tell it to give you an equation for the curve. To do this:

1. Right click on one of the data points (it doesn't matter which). Click "add trendline..."
2. A new window will come up, asking you for the type of regression. Choose the type of regression you want to use.
3. Click on the "options" tab, and check the "Display Equation on Chart" box (and, if you want, the "Display R-squared value on Chart" box). Click OK.

If you chose a "linear" regression with the sample data above, the equation and R^2 value appear on the graph as $y = 177.87x + 391.28, R^2 = 0.9843$. Note Excel displays

R^2 rather than R (so that we don't need to worry about negative vs. positive values); if you want R just take the square root, which is 0.9921 as we calculated in the section on linear regressions.

[edit] Introduction to MATLAB

[edit] Inserting and Manipulating Data

[edit] Importing Data from Excel

[edit] Performing Operations on Entire Data Sets

[edit] Graphing of Data

[edit] Regressions

MATLAB is able to do regressions up to very large polynomial orders, using the "polyfit" function. The syntax for this function is:

```
polyfit(XDATA, YDATA, Order)
```

The x data and y data must be in the form of *arrays*, which for the purposes of this application are simply comma-separated lists separated by brackets. For example, suppose you want to perform the same linear regression that had been performed in the "linear regression" section. The first step is to define the two variables:

```
>> XDATA = [1.1,1.9,3.0,3.8,5.3];
>> YDATA = [559.5,759.4,898.2,1116.3,1308.7];
```

Then just call polyfit with order '1' since we want a linear regression.

```
>> polyfit(XDATA, YDATA, 1)
ans = 1.0e+002 *
  1.77876628209900   3.91232582806103
```

The way to interpret this answer is that the first number is the slope of the line (1.778*10^2) and the second is the y-intercept (3.912*10^2).

[edit] Appendix 3: Notation

[edit] A Note on Notation

[edit] Base Notation (in alphabetical order)

$[i]_n$: Molarity of species i in stream n
A: Area
m: mass
MW: Molecular Weight (Molar Mass)
n: moles
N: Number of components
x: Mass fraction
y: Mole fraction
v: velocity
V: Volume

[edit] Greek

ρ: Density
Σ: Sum

[edit] Subscripts

If a particular component (rather than an arbitrary one) is considered, a specific letter is assigned to it:

- [A] is the molarity of A
- $x_A$is the mass fraction of A

Similarly, referring to a specific stream (rather than any old stream you want), each is given a different number.

- $\dot{n}_1$is the molar flowrate in stream 1.
- $\dot{n}_{A1}$is the molar flow rate of component A in stream 1.

Special subscripts:

If A is some value denoting a property of an *arbitrary* component stream, the letter i signifies the arbitrary *component* and the letter n signifies an arbitrary *stream*, i.e.

- $A_n$is a property of *stream* n. Note $\dot{n}_n$is the molar flow rate of stream n.
- $A_i$is a property of *component* i.

The subscript "gen" signifies generation of something inside the system.

The subscripts "in" and "out" signify flows into and out of the system.

[edit] Embellishments

If A is some value denoting a property then:

$\bar{A}_n$denotes the *average* property in stream n

$\dot{A}_n$denotes a *total flow rate* in steam n

$\dot{A}_{in}$denotes the flow rate of component i in stream n.

$\hat{A}$indicates a data point in a set.

[edit] Units Section/Dimensional Analysis

In the units section, the generic variables L, t, m, s, and A are used to demonstrate dimensional analysis. In order to avoid confusing dimensions with units (for example the unit m, meters, is a unit of length, not mass), if this notation is to be used, use the *unit equivalence* character $\doteq$rather than a standard equal sign.

[edit] Appendix 4: Further Reading

Chapra, S. and Canale, R. 2002. *Numerical Methods for Engineers*, 4th ed. New York: McGraw-Hill.

Felder, R.M. and Rousseau, R.W. 2000. *Elementary Principles of Chemical Processes*, 3rd ed. New York: John Wiley & Sons.

Masterton, W. and Hurley, C. 2001. *Chemistry Principles and Reactions*, 4th ed. New York: Harcourt.

Perry, R.H. and Green, D. 1984. *Perry's Chemical Engineers Handbook*, 6th ed. New York: McGraw-Hill.

Windholz *et al*. 1976. *The Merck Index*, 9th ed. New Jersey: Merck.

[edit] Appendix 5: External Links

Unit conversion table (Wikipedia)

Enthalpies of Formation (Wikipedia)

| Online Saturated Steam Calculator (UConn A&E Services) - NOTE: This site ONLY works for saturated steam, not superheated steam or sub-cooled water

| Periodic Table (Los Alamos National Laboratory)

- Physical properties tables

[edit] Appendix 6: License

Version 1.2, November 2002

```
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