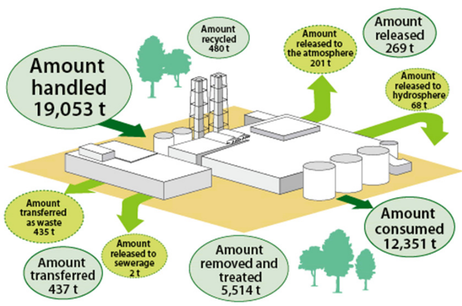
FACULTY OF PETROLEUM & RENEWABLE ENERGY ENGINEERING

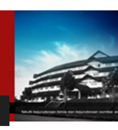
# CHAPTER 3.5 – 3.6

# Material Balances on Multiple-Unit Processes with Recycle and Bypass






## Course Learning Outcomes



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*At the end of this course students will be able to*

- define and draw a system and subsystem boundaries of a multi-unit process for which the material balance is to be made.
- perform the degree of freedom analysis for the overall system and each possible subsystem
- perform material balance calculations on a single unit process and multi-unit processes and for processes involving recycle, bypass or purging streams.

# Introduction to Multiple-Unit Processes



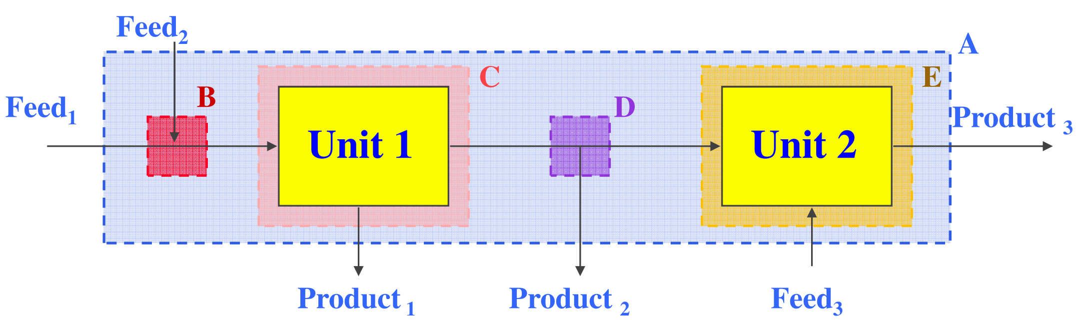
- Industrial processes rarely involve just one unit.
- Keeping track of material flows for overall processes
- Keeping track of material flow of all individual units
- Definition of system : arbitrary choice
- Recommended solving method

  Overall Balances → Balances on Subsystems



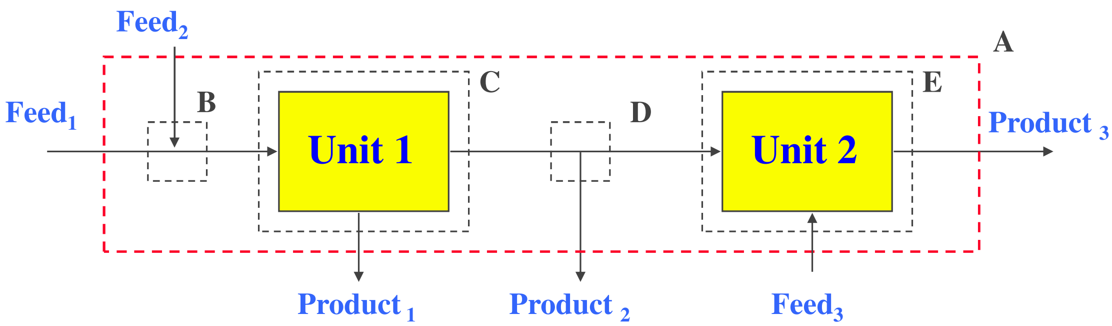
# Balances on Multiple Unit-Boundary






- Boundary system
  - System (overall balance) ……. Boundary A (3 inputs, 3 outputs)
  - Sub-system (balance on each process unit)
    - Stream mixer …… Boundary B (2 inputs, 1 output)
    - Unit 1 (e.g. reactor) ……Boundary C (1 input, 2 outputs)
    - Splitter …… Boundary D (1 input, 2 outputs)
    - Unit 2 (e.g. mixer) …… Boundary E (2 inputs = 1 output)

# Balances on Multiple Unit-One component




- **Number of independent balances = number of unit processes**
- For one component system
  - For every unit, 1 independent balance can be made.
    - Mixer/Splitter is considered as one unit process
  - For the above system we can only have 4 independent balances
    - Choose (4 from 5, *i.e.,* A, B, C, D, E). The remaining can be used as checking.



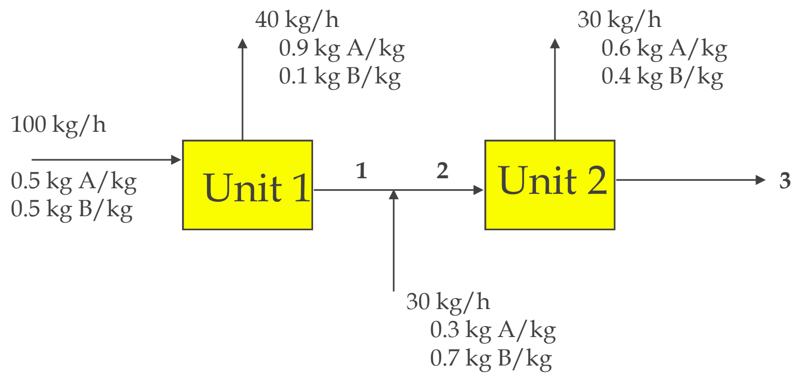


# Balances on Multiple Unit Processes

**Useful Information:**

- Do the overall material balance first for the whole system.
  - to determine unknown process feed and product stream variables
  - balances on various process subsystem may be used to determine interior stream variables
- In choosing subsystem, select the boundaries having intersect streams containing few unknown variables.
- The number of independent equations depends on the number of unreacted components in each subsystem.

# Two Units Distillation Column



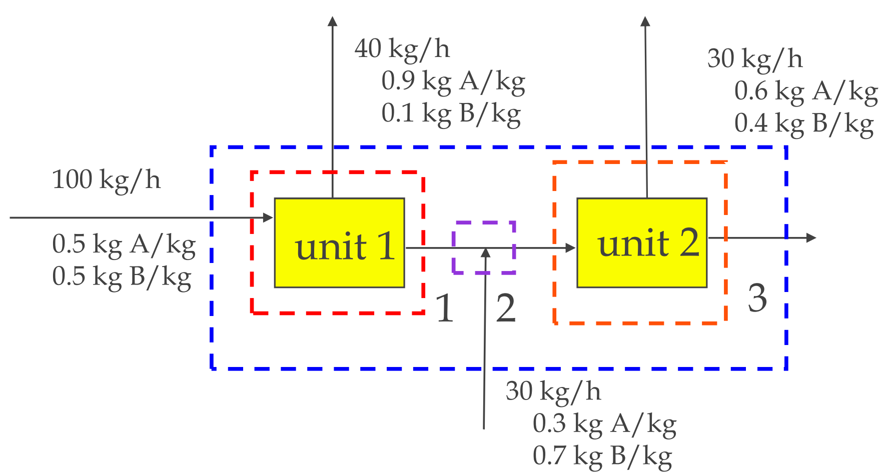

**Calculate the unknown flow rates and composition of streams 1, 2 and 3**

- Unknown flow rates and compositions.
- Boundaries





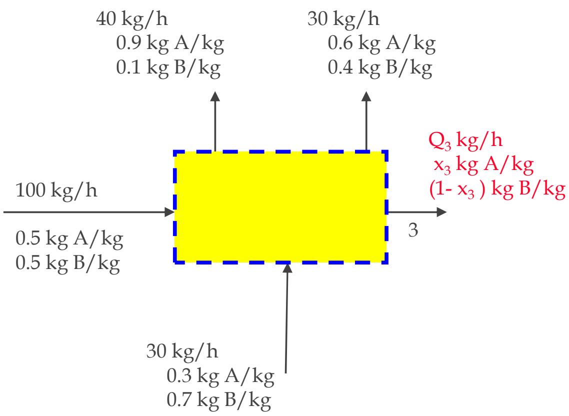
# Two Units Distillation Column - Boundaries



# Two Units Distillation Column

## *Overall material balance*





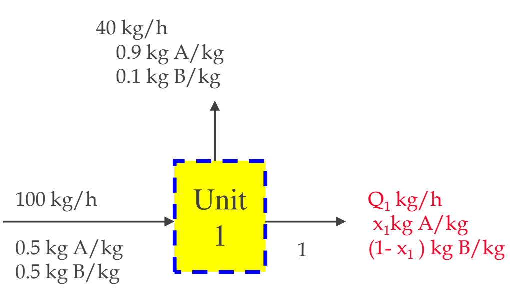

Basis : ?



# Two Units Distillation Column

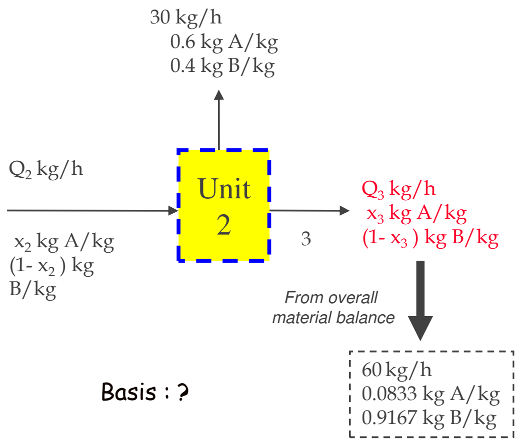
## *Material balance on Unit 1*






Basis : ?

# Two Units Distillation Column
## Material balance on Unit 2

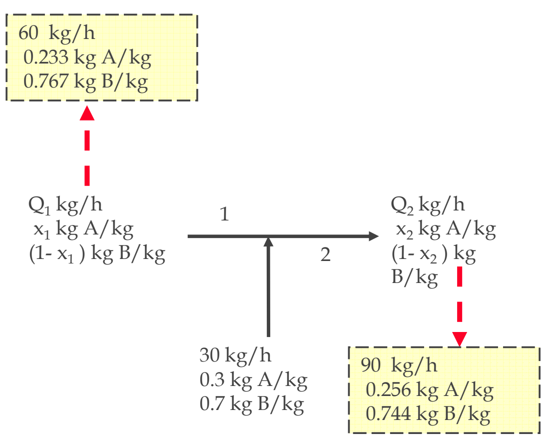



Basis : ?





# Two Units Distillation Column
## Material balance at stream junction




**Solution validation**

# Example 1 – Mixing/Evaporation Process (modified from question 3 of working session 2)

Strawberries contain about 15 wt% solids (assuming sugar) and 85 wt% water. To make 1 Ibm of strawberry jam, equal mass of crushed strawberries and sugar are mixed in a mixer. The mixture is then fed and subsequently heated in an evaporator to remove water until the product contains 25 wt% water.

a. Draw and label a flowchart of this process.
b. Classify the type of process involved and name the types of process equipment used.
c. Do the degree-of-freedom analysis to prove that the problem can be solved.
d. Calculate the mass (kg) of strawberries is required?
e. Calculate the percent mass of water is evaporated?.





# Solution – Process Flow Chart or Diagram

**(a) Draw and label a flowchart of this process.**

(b) Degree of freedom analysis





**Mixer**

**Evaporator**

# Example 2
## *(Desalination of Seawater)*

Seawater containing 3.50 wt% salt passes through a series of 5 evaporators. Roughly equal quantities of water are vaporized in each of the 5 units and are then condensed and combined to obtain a product stream of fresh water. The brine at the outlet of the last evaporator contains 5.00 wt% salt.

a) Draw a flowchart of the process and label all the streams entering and leaving the evaporators.
b) Calculate the fractional yield of fresh water from the process (kg $H_2O$ recovered / kg $H_2O$ in process feed)
c) Calculate the weight percent of salt in the solution leaving the fourth evaporator.
d) It is desired to achieve 9000 kg/h of fresh water from seawater using the same process. Calculate the mass flow rate of the seawater feed.





# Example 2
## *(Desalination of Seawater)*

How this problem is related to the principles of chemical engineering

**Process :** Evaporation
**Separating agent :** Heat
**Fundamental Knowledge:** Thermodynamics, Mass & heat balance / transfer
**Chem. Eng. Courses :** Mass & Energy Balances (SKF1113 & SKF2123) , Transport Process (SKF2313, Separation ProcessI (SKF3323)
**Equipment :** Multiple-unit evaporator

***Desalination of Seawater – the movie (multi-effect evaporator)***

a) **Draw a flowchart of the process and label all the streams entering and leaving the evaporators..**





b) **Calculate the fractional yield of fresh water from the process (kg $H_2O$ recovered / kg $H_2O$ in process feed)**

c) **Calculate the weight percent of salt in the solution leaving the fourth evaporator.**





## *(Using boundary 1)*

c) **Calculate the weight percent of salt in the solution leaving the fourth evaporator.**

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d) It is desired to achieve 9000 kg/h of fresh water from seawater using the same process. Calculate the mass flow rate of the seawater feed.

# Additional Example – Sugar Refinery

A simplified flow sheet for the manufacture of sugar is shown. Sugarcane is fed to a mill where a syrup is squeezed out, and the resulting "bagasse" (D) contains 80 wt% pulp and the remaining water and sugar. The syrup (*E* ) containing 13 wt% water, 14 wt% sugar and finely divided pieces of pulp is fed to a screen which removes all the pulp and a small amount of sugar to produce a clear syrup (*H* ) containing 15 wt% sugar. The evaporator makes a "heavy" syrup (K) containing 40 wt% sugar and the crystallizer produces 1000 kg/h of pure sugar crystals (M). (Note: In average, sugarcane contains 16 wt% sugar, 25 wt% water and the rest is pulp)

a. perform the degree of freedom analysis of the system and the process units
b. Find the water removed in the evaporator, kg/h
c. Find the mass fractions of the components in the waste stream *G*.
d. Find the rate of feed of sugarcane to the unit, kg/h
e. What percentage of sugar in feed is lost with the bagasse?
f. Is this an efficient operation? Explain why and why not.





# Process Flow Diagram / Chart

a. Degree of Freedom Analysis (DoF)





**Crystallizer**

**Mass balance around crystallizer**

**Mass balance around evaporator**

**Mass balance around screen**

**Mass balance around Mill**



Solution Additional working session – Sugar Refinery
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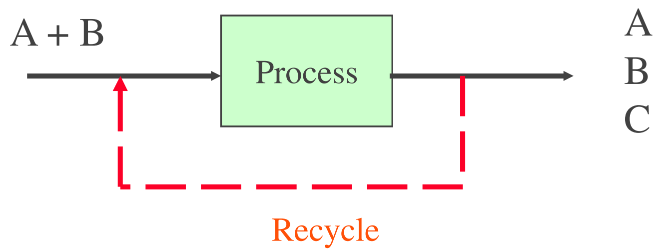
# Recycle

A + B → C




Recovering and reusing unconsumed reactants

Unused reactants (A, B)

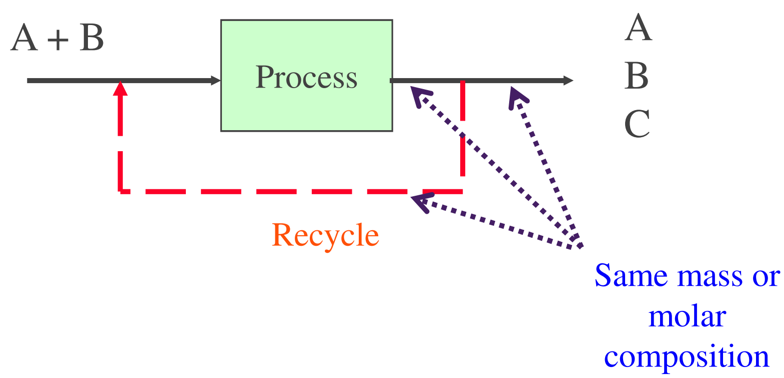




# Reasons for Recycle

- **Recovery of Catalyst**
  - ✓ Catalyst are usually expensive, and the processes generally include provision of recovering them with unconsumed reactant.
- **Dilution of Process Stream**
  - ✓ If the concentration of solids in the slurry is too high, the sluury is too difficult to handle.
- **Control of Process Variables**
  - ✓ Suppose the reaction is exothermic, the rate of heat generation can be reduced by lowering the reactant concentration by recycling a portion of the reactor effluent to the inlet.
- **Circulation of Process Fluid**
  - ✓ Most common example is the refrigeration cycle used in household refrigerators and air conditioners.

$$A + B \rightarrow C$$

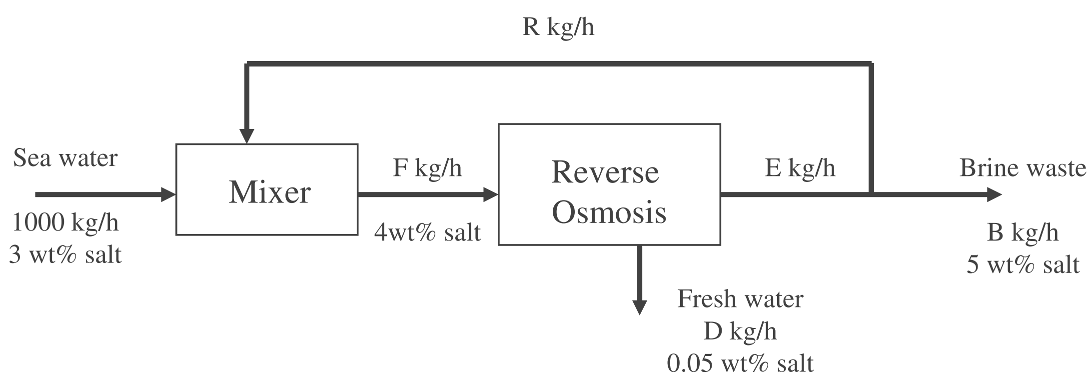




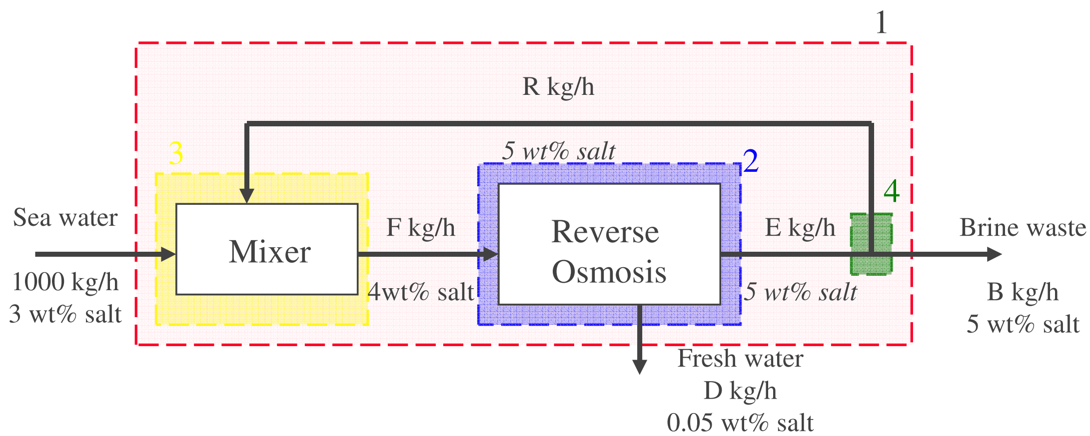



# Example 3 - Desalination of seawater

Fresh water can be produced from seawater using a reverse osmosis process as shown below.




Calculate the unknown mass flow rates and the value of R/E.




Basis : 1000 kg/hr seawater





**Mass balance on an overall system (loop 1)**

**Perform degree of freedom analysis**

# Solution

**Mass balance on reverse osmosis (loop 2)**

**Mass balance on mixer (loop 3)**





# Additional Example - Drying

In a wood drier, the hot air must contain at least 2 weight percent water to prevent the wood from drying too rapidly and splitting or warping. The original fresh air fed contains 1 weight percent water. Wood is dried from 20 weight percent water to 5 weight percent water. The wet air leaving the drier contains 4 weight percent water. Calculate the amount of wet air that must be returned to the drier if 2000 lbm/h of wet wood is dried.

# Solution





# Solution

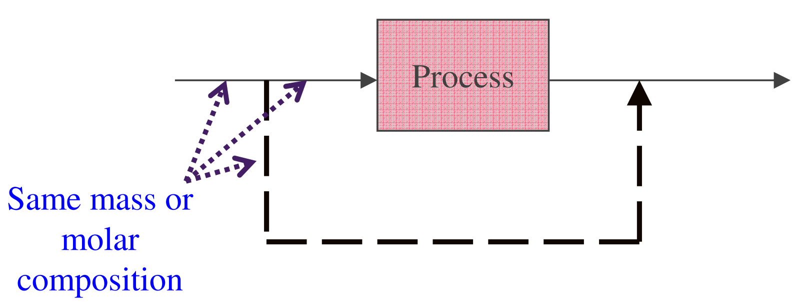
# Solution





# Bypass

- A fraction of the feed is diverted around the process unit and combined with the output stream.
- Controlling properties and compositions of product stream



# Example 4

In textile industry, it is desired to make caustic soda solution containing 24% NaOH by mass for a mercerization process. Due to the very high heat of dissolution of caustic soda in water, the solution is prepared as follows; First in a dissolution tank caustic soda of 50 wt% NaOH was prepared by mixing 100 kg of solid NaOH with water. It was then fed to the dilution tank where a fraction of feed water is added to produce the desired solution.

a) Calculate the amount of water required
b) Calculate the amount of desired solution produced.
c) Calculate the amount of 50 wt% NaOH solution produced.
d) Calculate the amount of feed water that is bypassed to the dilution tank.
e) Calculate the ratio of water that is bypassed to the dilution tank to that is fed to the process.





# Solution

Draw a process flowchart

# Solution

Select boundaries and perform degree of freedom analysis





# Solution