CE407 SEPARATIONS

Lecture 11

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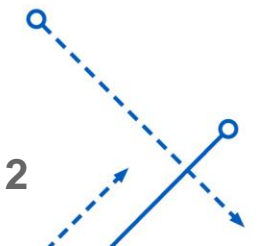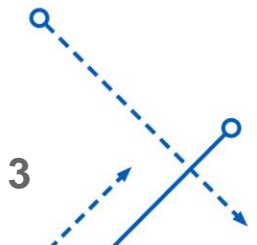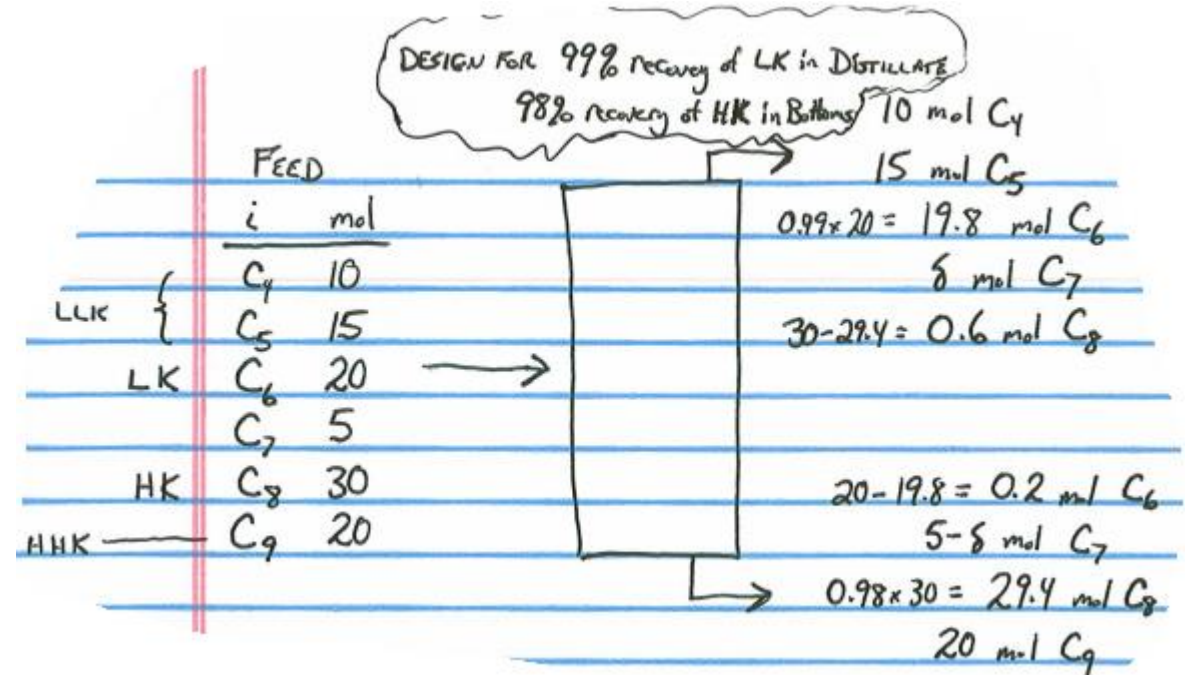
Multi-Component Distillation McSH pp 742-759

- Separating mixtures of three or more components through a series of distillation columns

- Key Components
  - You have multiple components and design each column such that the separation is based on two key components

- Light Key
  - This component primarily goes to distillate, although an appreciable amount will go to bottoms

- Heavy Key
  - This component primarily goes to bottoms, although an appreciable amount will go to distillate

- Distributed Components
  - Components which are sent to both Distillate and Bottoms in large amounts

- Non-Distributed Components
  - Components which have a mole fraction of 10^{-6} or lower in ONE of the two streams

Multi-Component Distillation

- Purpose of this column is to achieve a cut between the Light Key (LK) and the Heavy Key (HK)

- Material that is equal to or more volatile (lighter) than LK goes primarily to distillate

- Material that is equal to or less volatile (heavier) than HK goes primarily to bottoms

- Note that material that is between LK and HK in volatility is distributed between the Distillate and Bottoms   More on that later…

- **Heavy and Light Keys should be selected from components present as a larger mole fraction of the feed.**

DESIGN FOR 99% recovery of LK in DISTILLATE
98% recovery of HK in Bottoms

FEED

i	mol
C_4	10
C_5	15
C_6	20
C_7	5
C_8	30
C_9	20

LLK { C_4, C_5
LK C_6
HK C_8
HHK C_9

10 mol C_4
15 mol C_5
$0.99 \times 20 = 19.8$ mol C_6
8 mol C_7
$30 - 29.4 = 0.6$ mol C_8

$20 - 19.8 = 0.2$ mol C_6
$5 - 8$ mol C_7
$0.98 \times 30 = 29.4$ mol C_8
20 mol C_9

Multi-Component Distillation

- If the column can reduce LK to a few mole % in bottoms than the LLK components are basically ABSENT from the bottoms

- Similarly HHK components are basically absent in Distillate

- Components whose volatility is in between LK and HK will present in significant amounts in both Distillate and Bottoms
  - In this example we show **δ** moles of C6 in distillate and therefore 5- **δ** moles (the difference between the # of C6 moles fed and the # in the distillate) as being in the bottoms

- In fact HHK mole fractions in Distillate and LLK mole fractions in Bottoms are not truly Zero
  - But they are REALLY, REALLY, REALLY close to zero
  - Zero is an excellent 1st approximation
  - See notes "L11 Example Problems" on Course Website for demonstration of the robustness of this assumption

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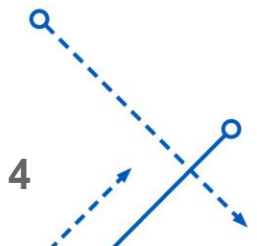
Column Sequencing

- Ternary Example – Direct Split

- Arrow for feed is drawn to indicate where we are splitting the stream

- Smaller letter indicates normal impurities (a few mole %)

- Letters in (parentheses) indicate trace amounts

- 1st column gives component A to a specified purity in distillate, it does not separate B from C

- 2nd column needed to separate B and C

- Now you have streams of specified purity for each component
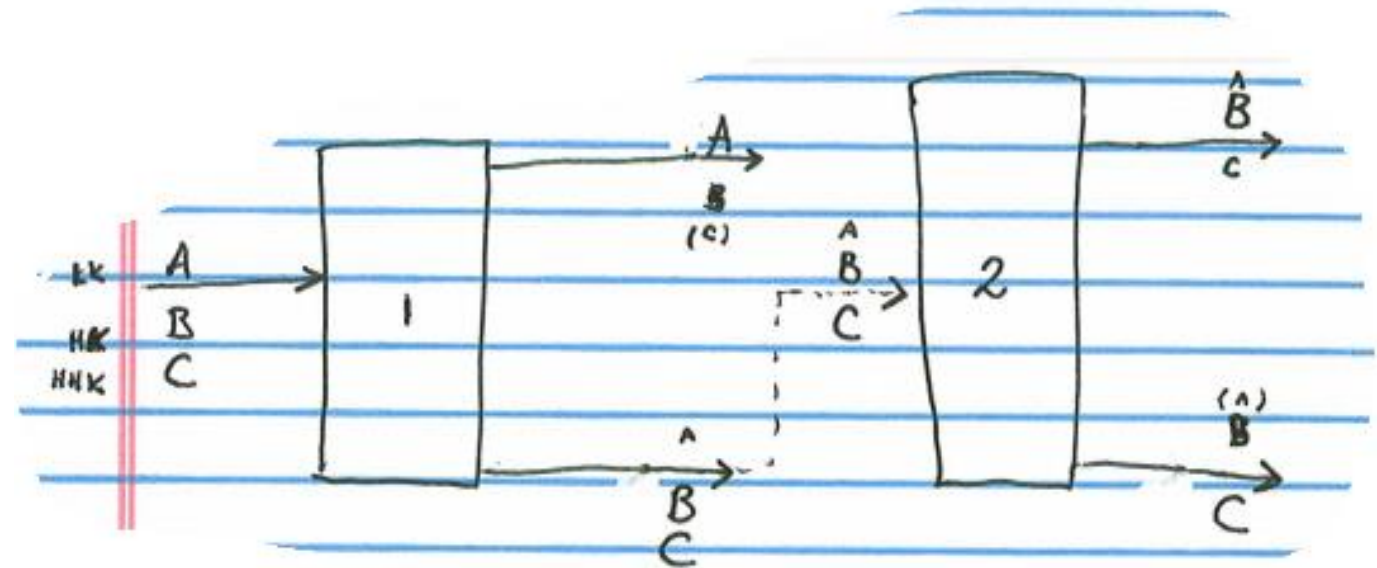
If you have N components you need N-1 columns to get each component to a specified purity

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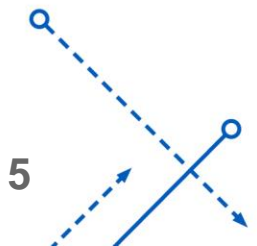
Alternate Ternary Sequence

- Indirect Split

- A and B are separated from C in 1st column

- You still end with streams that have each of the components to specified purities

- As the number of components increases the number of choices for sequences increases dramatically

- See notes "Multi-Component Column Sequencing Example" on Course Website
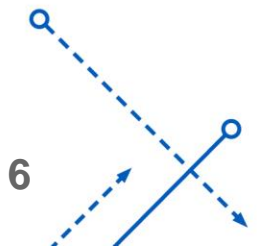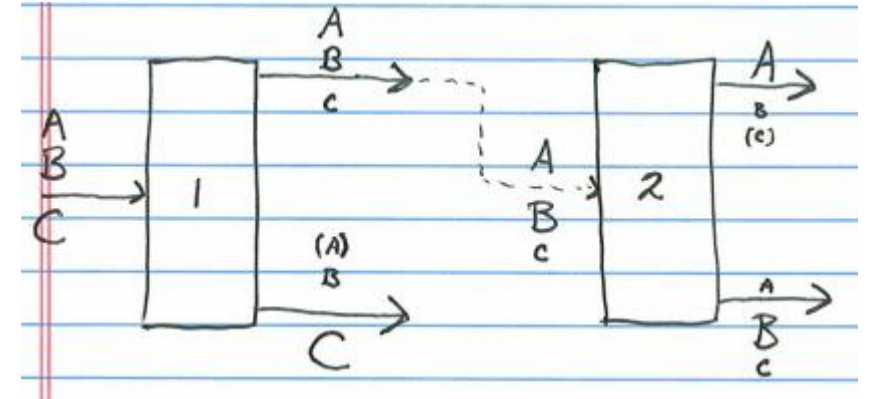
Analytical Methods for Multi-Component Fractionation

- Assumptions:
  - Constant Molar Flows

  - Constant Relative Volatilities, $\alpha_{ij} = \dfrac{y_i/x_i}{y_j/x_j}$

- **N$_{min}$** = minimum # of stages, corresponding to Total Reflux – same derivation as eq 21.45 for binary

$$N_{min} + 1 = \frac{ln\left[\dfrac{x_{iD}/x_{iB}}{x_{jD}/x_{jB}}\right]}{ln\,\overline{\alpha_{ij}}}$$

Fenske Equation eq 22.13

- x_{iD} is the mole fraction of component **i** in the Distillate

- x_{iB} is the mole fraction of component **i** in the Bottoms

- x_{jD} is the mole fraction of component **j** in the Distillate

- x_{jB} is the mole fraction of component **j** in the Bottoms
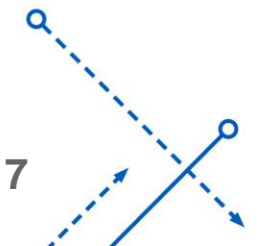
Analytical Methods for Multi-Component Fractionation

$$N_{min} + 1 = \frac{ln\left[\dfrac{x_{iD}/x_{iB}}{x_{jD}/x_{jB}}\right]}{ln\,\overline{\alpha_{ij}}}$$

- $\overline{\alpha_{ij}}$ is an average value of α_{ij} at Distillate, Feed, and Bottom temperatures (if α_{ij} is not exactly constant)

$$\overline{\alpha_{ij}} = \sqrt[3]{\alpha_{ij_D}\,\alpha_{ij_F}\,\alpha_{ij_B}}$$

- Note that we can multiply both the numerator and denominator in the upper logarithm by D/B

$$\boxed{N_{min} + 1 = \frac{ln\left[\dfrac{Dx_{iD}/Bx_{iB}}{Dx_{jD}/Bx_{jB}}\right]}{ln\,\overline{\alpha_{ij}}}}$$

- Why did we do that? Now the Fenske equation is in terms of molar flows, rather than mole fractions and that can make it easier to work with in some cases

Analytical Methods for Multi-Component Fractionation

- When calculating N_{min} **i = LK**, light key and **j = HK**, heavy key

- When you have determined N_{min} you can use that value in the Fenske equation with one of the distributed components set equal to **i** and leave **j** as the **HK**. This will allow you to calculate **δ** and determine the mole fractions of that distributed component

- Common conventions when stating α_{ij} is to have **j = HK**. Then α_{ij} is always relative to the heavy key

  - $\alpha_{ij} > 1$ for components lighter than **HK**

  - $\alpha_{ij} = 1$ for the **HK**

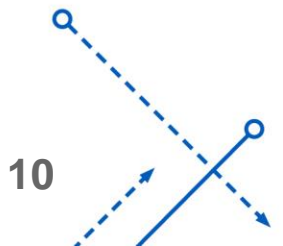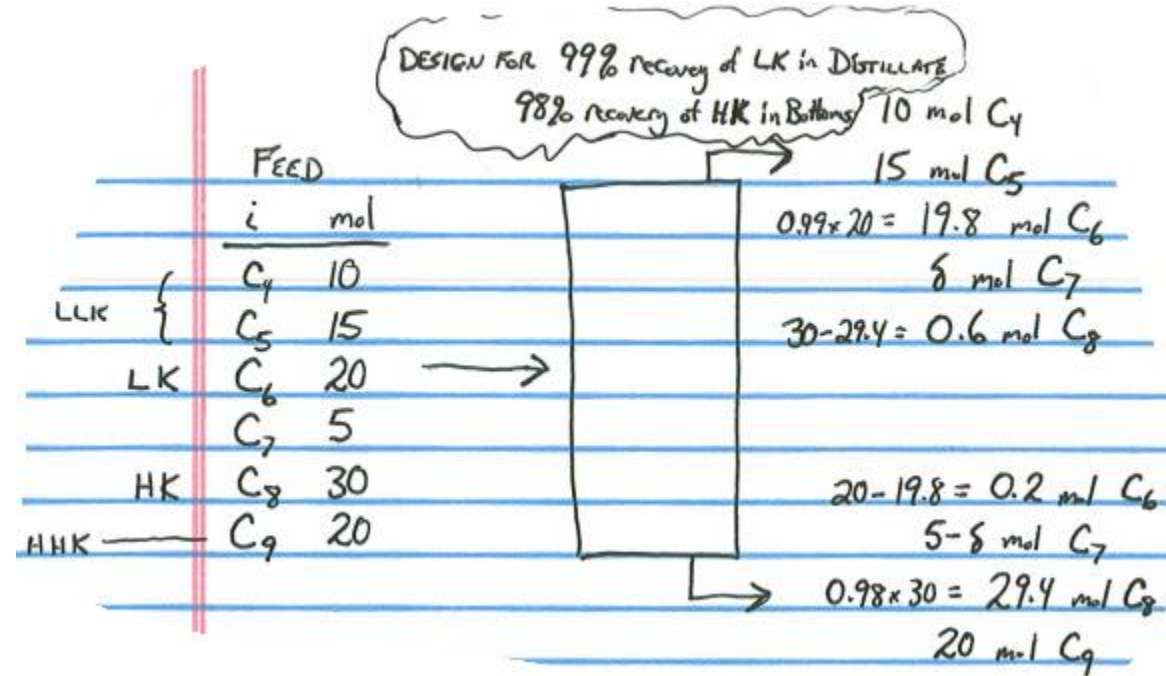 - $\alpha_{ij} < 1$ for components heavier than **HK**
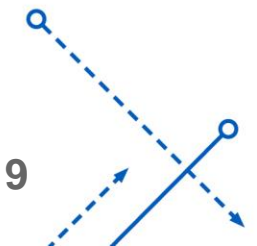
Distributed component, solve for δ

- Volatility data

i	$k_i = P^{sat}/P$	α_{ij}
nC$_4$	24	14.18
nC$_5$	11	6.47
nC$_6$	6	3.53
nC$_7$	3.2	1.88
nC$_8$	1.7	1.00
nC$_9$	0.85	0.50

DESIGN FOR 99% recovery of LK in DISTILLATE
98% recovery of HK in Bottoms

FEED

i	mol
C$_4$	10
C$_5$	15
C$_6$	20
C$_7$	5
C$_8$	30
C$_9$	20

LLK { C$_4$, C$_5$

LK   C$_6$

HK   C$_8$

HHK C$_9$

10 mol C$_4$
15 mol C$_5$
0.99 × 20 = 19.8 mol C$_6$
δ mol C$_7$
30 - 29.4 = 0.6 mol C$_8$

20 - 19.8 = 0.2 mol C$_6$
5 - δ mol C$_7$
0.98 × 30 = 29.4 mol C$_8$
20 mol C$_9$

- Calculate N$_{min}$ + 1 for LK/HK

- i = C$_6$, j = C$_8$

$$N_{min} + 1 = \frac{ln\left[\frac{Dx_{iD}/Bx_{iB}}{Dx_{jD}/Bx_{jB}}\right]}{ln\,\overline{\alpha_{ij}}} = \frac{ln\left[\frac{19.8/0.2}{0.6/29.4}\right]}{ln\,3.53} = 6.729$$

Distributed component, solve for δ

- Perform Fenske for i = C_7 and j = C_8

$$N_{min} + 1 = \frac{ln\left[\frac{Dx_{iD}/Bx_{iB}}{Dx_{jD}/Bx_{jB}}\right]}{ln\,\overline{\alpha_{ij}}} = \frac{ln\left[\frac{\delta/(5-\delta)}{0.6/29.4}\right]}{ln\,1.88} = 6.729$$

- Rearrange

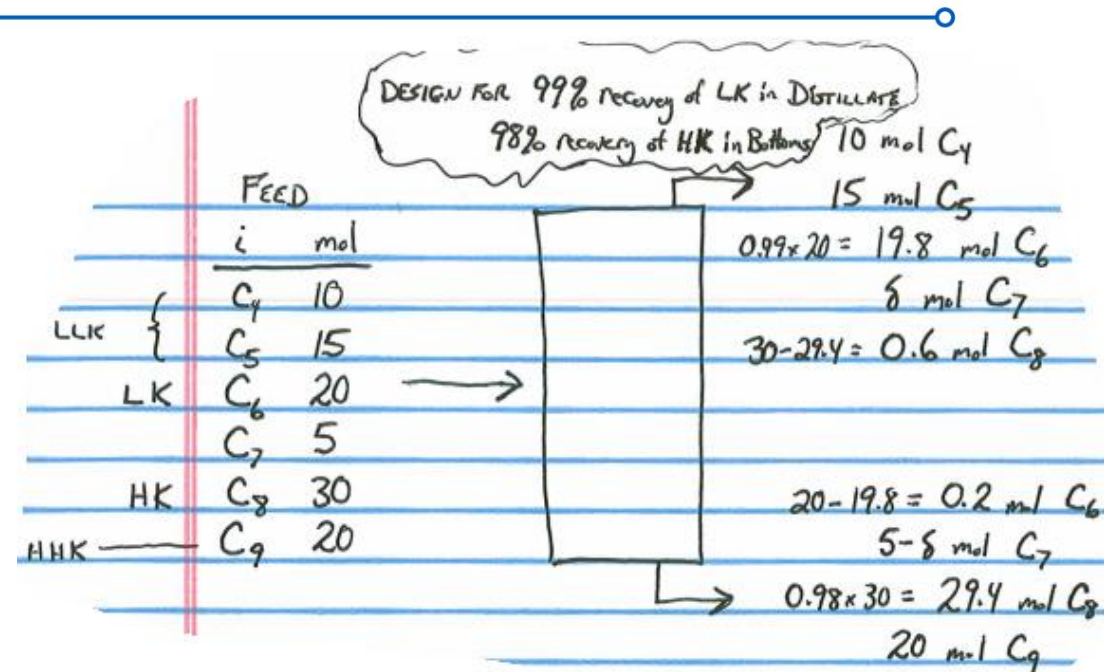$$6.729\,ln(1.88) = ln\left[\frac{\delta/(5-\delta)}{0.6/29.4}\right]$$

- Take exponential of both sides

$$1.88^{6.729} = \frac{\delta/(5-\delta)}{0.6/29.4} = \frac{\delta/(5-\delta)}{0.0204}$$

$$69.95 * 0.0204 = 1.427 = \delta/(5-\delta)$$

$$\delta = 2.94 \,,\, 5 - \delta = 2.06$$

- 2.94 moles of C_7 in Distillate and 2.06 moles of C_7 in Bottoms

DESIGN FOR 99% recovery of LK in DISTILLATE
98% recovery of HK in Bottoms

FEED

	i	mol
LLK {	C_4	10
	C_5	15
LK	C_6	20
	C_7	5
HK	C_8	30
HHK	C_9	20

10 mol C_4
15 mol C_5
0.99×20 = 19.8 mol C_6
δ mol C_7
30-29.4 = 0.6 mol C_8

20-19.8 = 0.2 mol C_6
5-δ mol C_7
0.98×30 = 29.4 mol C_8
20 mol C_9

Minimum Reflux Ratio – Underwood's Method McSH pp 749-752

- Applies to cases where LK and HK are adjacent (no components with intermediate volatility). Let's jump to the method and avoid the derivation

- Eq 22.29
$$1 - q = \sum_i \frac{\alpha_i x_{i,F}}{\alpha_i - \varphi}$$
sum i is over ALL components

  - You have values for everything except φ, but you have to solve for φ iteratively
  - There will be multiple solutions for φ. The correct one is between $\alpha_{HK} = 1$ and α_{LK}

- Eq 22.30
$$\frac{V_{min}}{D} = R_{min} + 1 = \sum_i \frac{\alpha_i x_{i,D}}{\alpha_i - \varphi}$$
sum i is over only components in distillate

- Where:
  - **q** = feed quality
  - $\alpha_i = \alpha_{i,HK}$ the volatility of component i relative to the heavy key
  - $x_{i,F}$ is the mole fraction of component i in the feed
  - $x_{i,D}$ is the mole fraction of component i in the Distillate
  - What is φ? Don't worry about that. We will use Eq 22.29 to find it and then use it in eq 22.30 to solve for minimum Reflux Ratio, R_{min}

Required Number of stages for a Given Value of R

- ## Gilliland Correlation

- Figure 22.5, pp 757 – Note Textbook in this section uses a definition of N that includes the Reboiler. I have modified the label on the graph to use N', where N' = N + 1. This maintains our definition of N as the number of trays in the column

- **Steps:**

- Use Fenske equation to calculate **N$_{min}$**

  - **N'$_{min}$ = N$_{min}$ + 1**

- Use Underwood's Method to calculate **R$_{min}$**

- Choose a value of R and calculate $\dfrac{R - R_{min}}{R+1}$

- Read $\dfrac{N' - N'_{min}}{N'+1}$ off of the graph

- Solve for N' **N = N' - 1**   Report as N stages + Reboiler

- See notes "Multicomponent Distillation Shortcut Examples"

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