Lecture 3
Multiple flash drums and distillation column

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Intended Learning Outcomes:

1. Understand limitation of the single-stage flash column
2. Analyze the key components of the distillation column.
3. Write and solve external mass and energy balances for binary distillation column.
4. Write and solve operating equation for the rectifying and stripping sections.
5. Calculate the number of stages using the graphical (McCabe-Thiele) approach.

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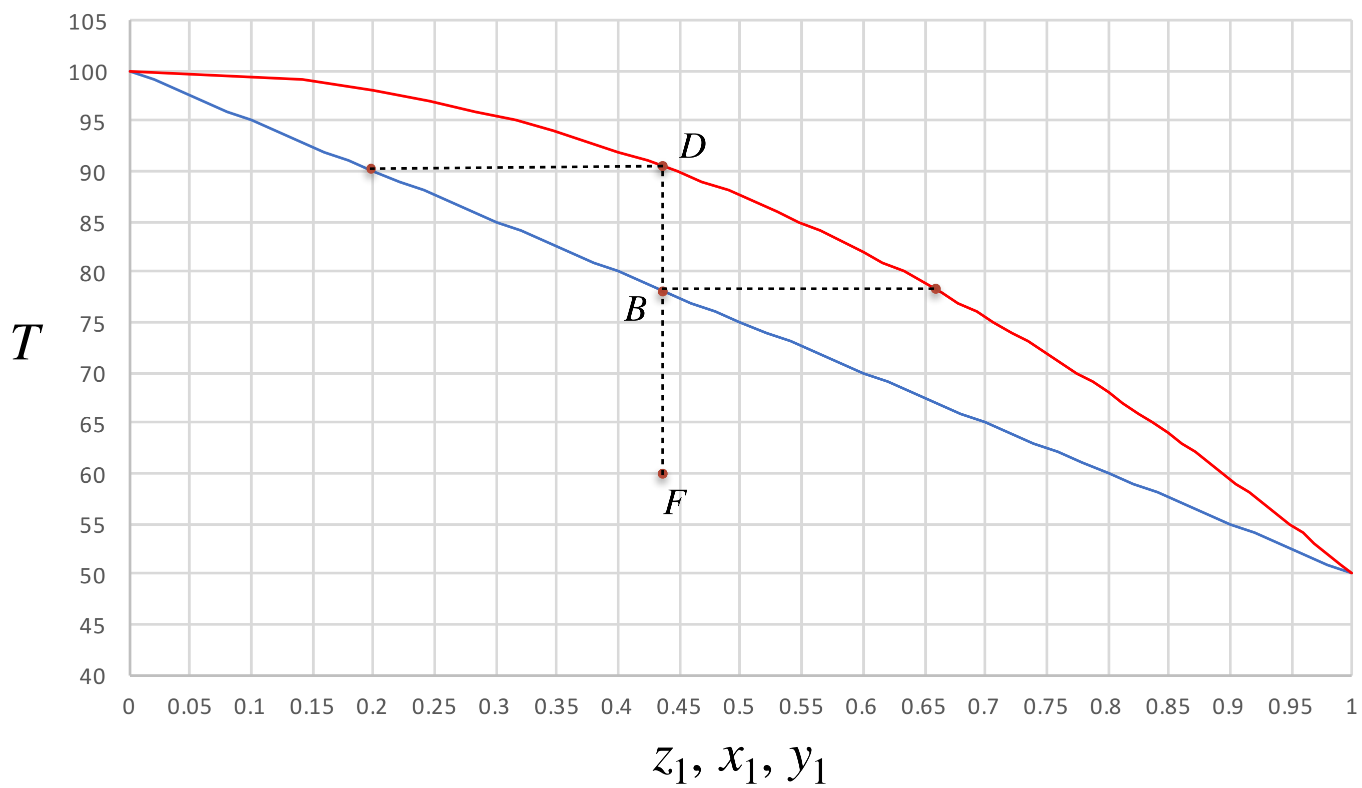
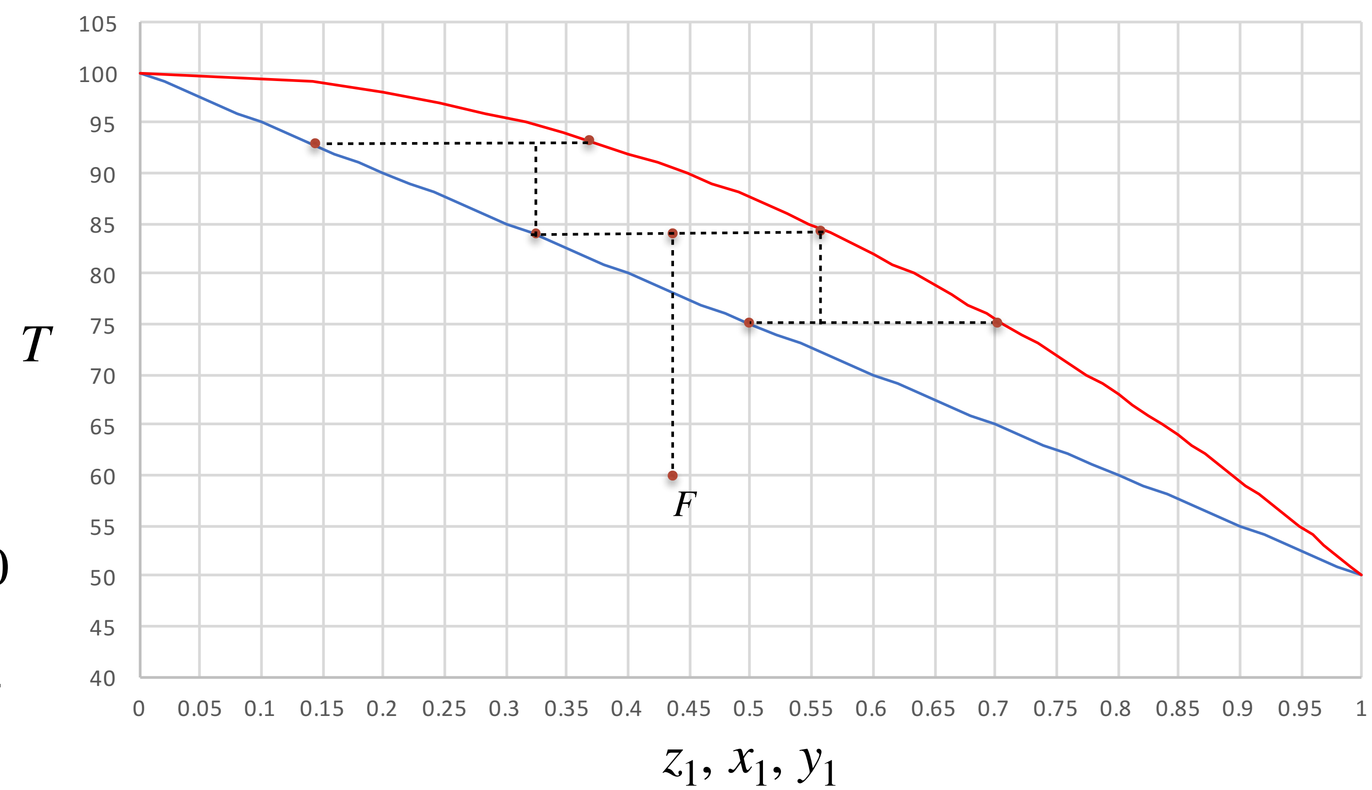
Multiple flash column



Maximum y_1 = 0.66

Minimum x_1 = 0.2



Maximum y_1 = 0.70

Minimum x_1 = 0.14

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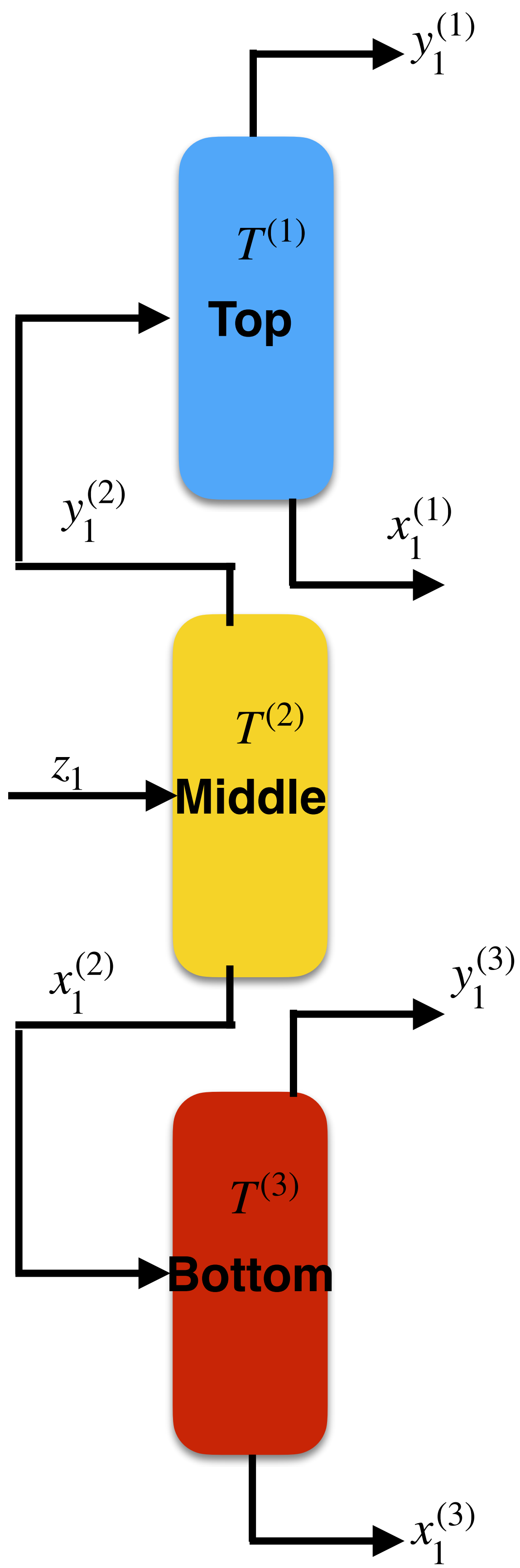
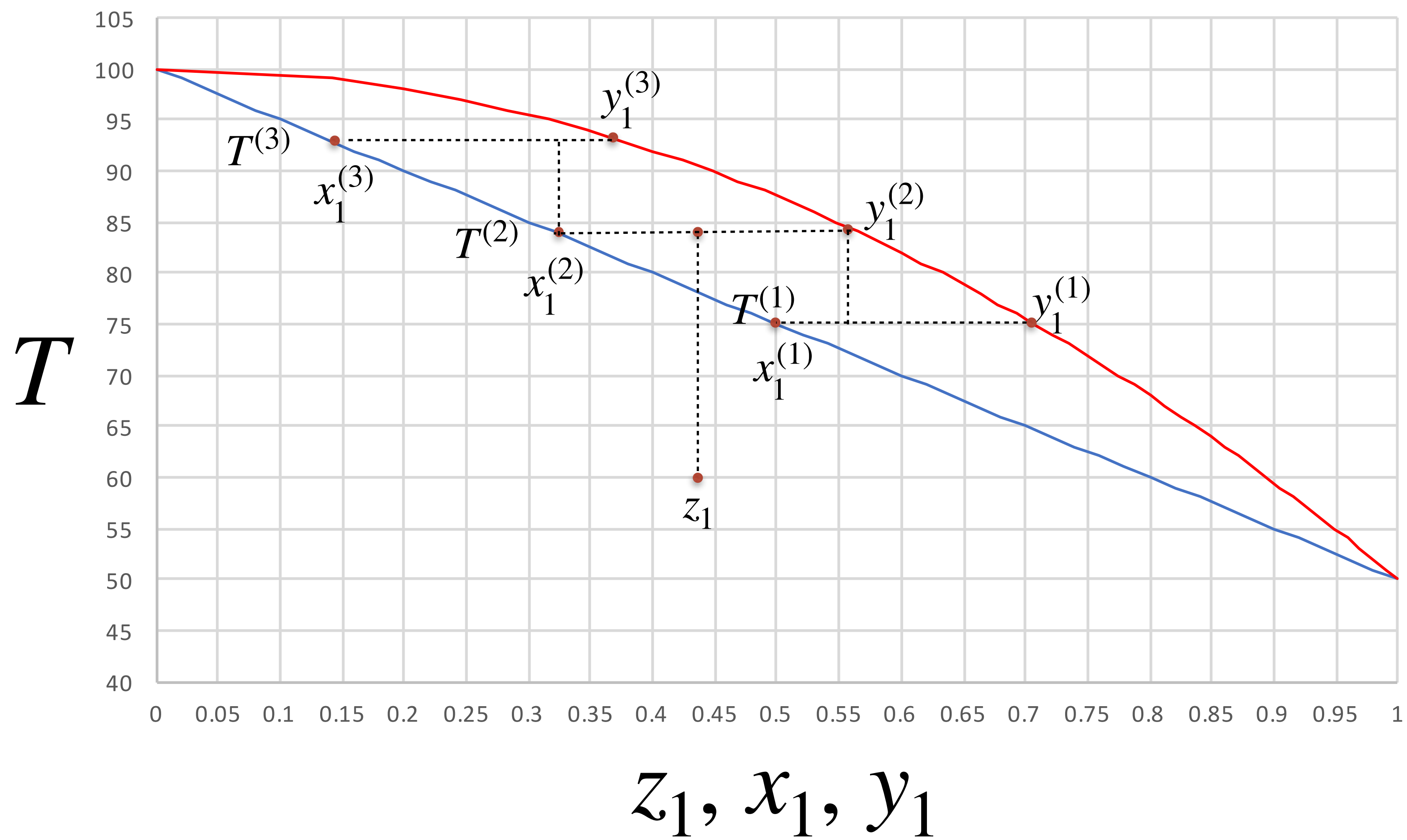
Can you assign concentrations for each stream





Which flash drum is operating at the highest temperature?

A) Middle

B) Top

C) Bottom

D) Not enough info

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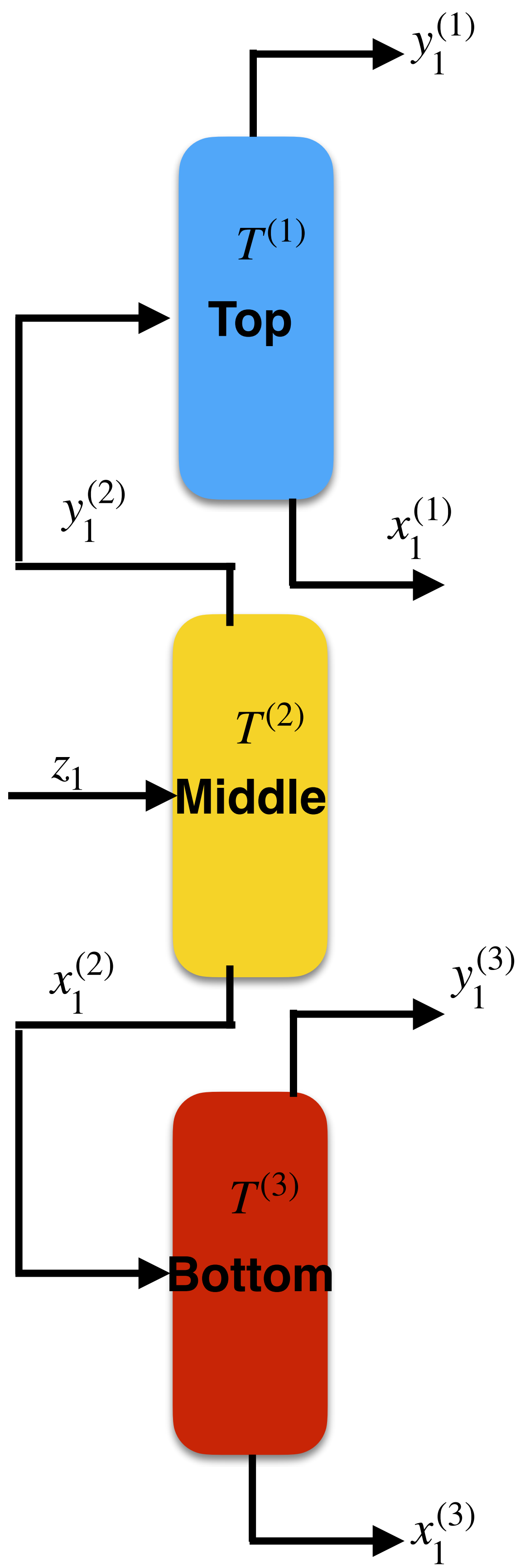
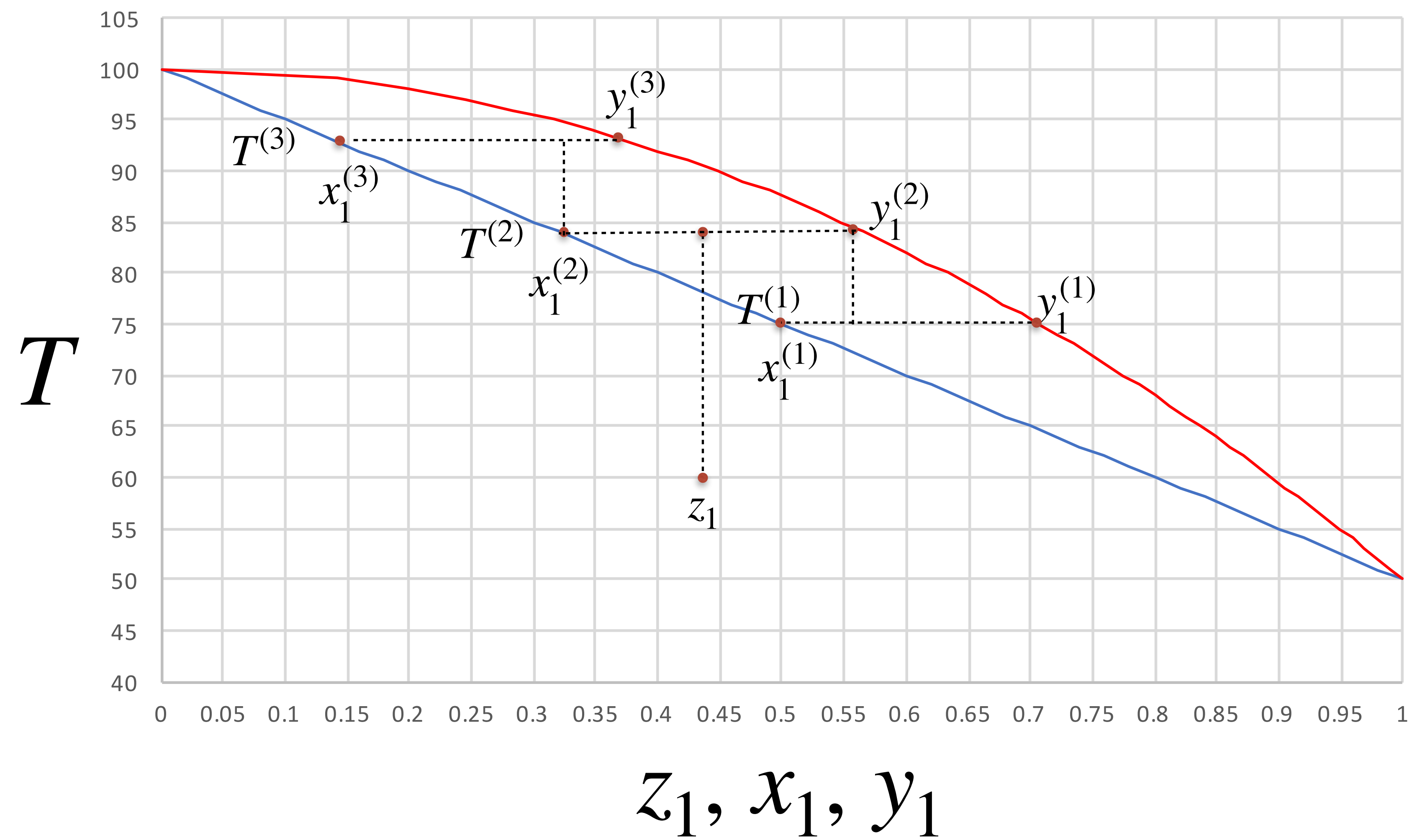
Can you assign concentrations for each stream





1. Where do we have the highest purity component 1?
2. Where do we have the highest purity component 2?

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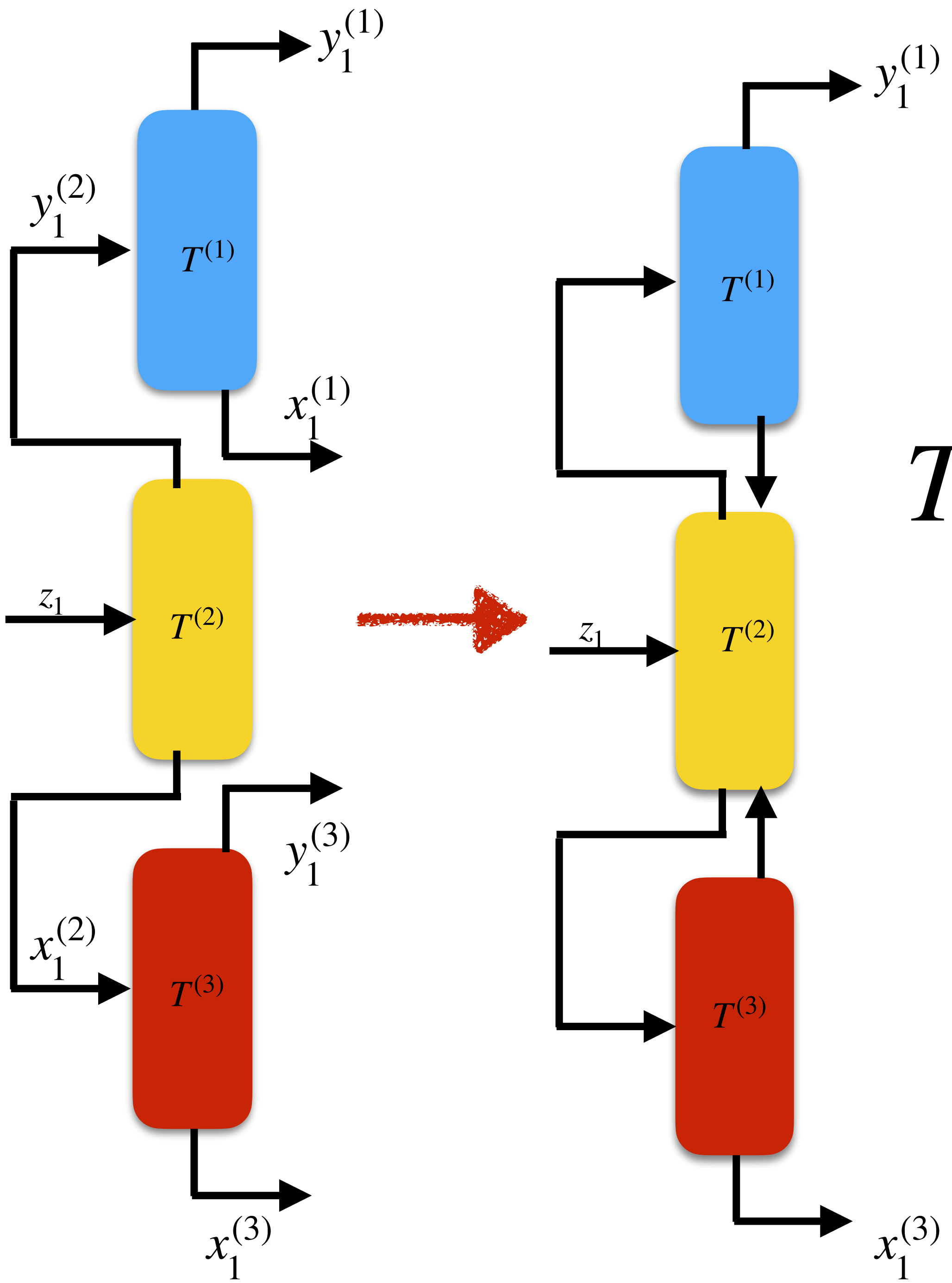
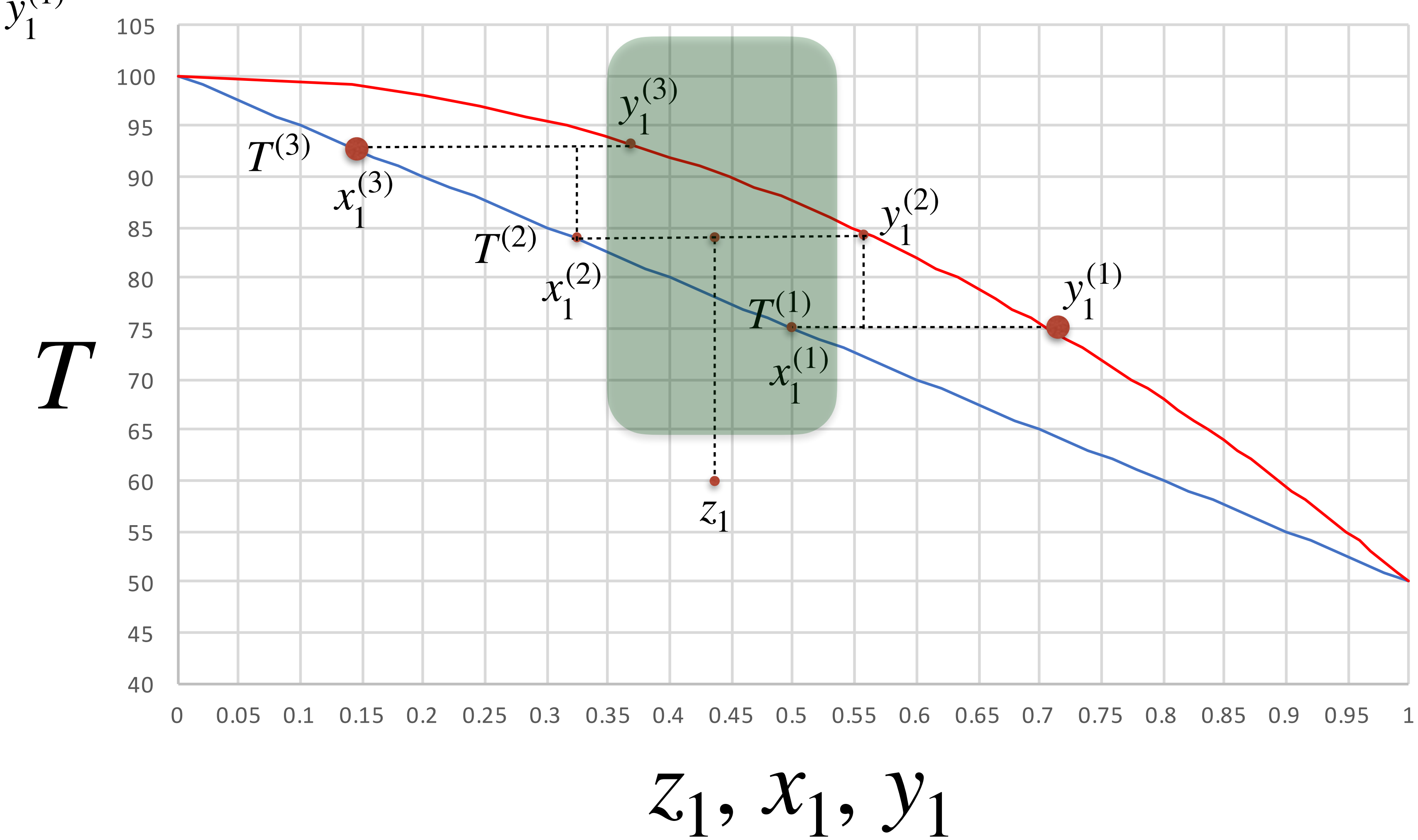
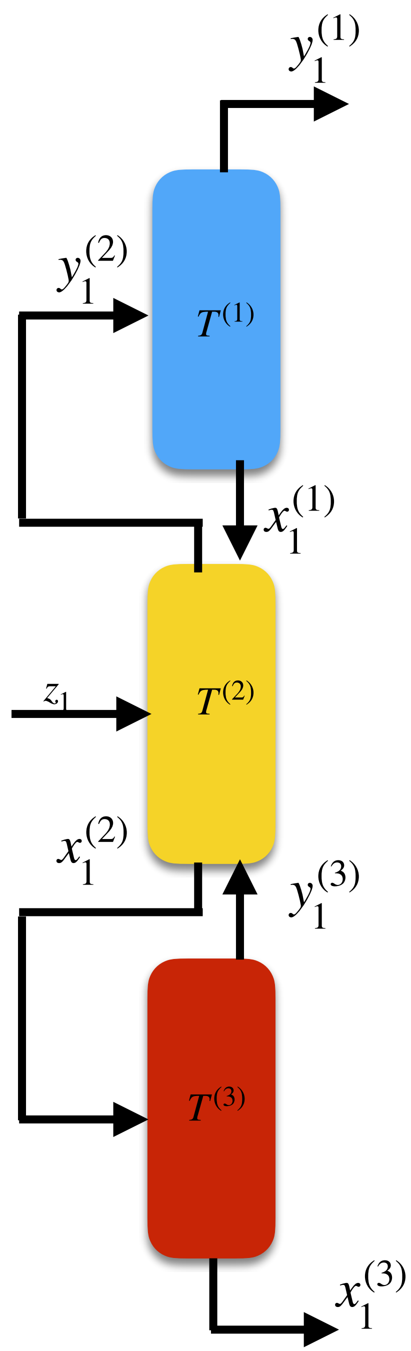
Can you suggest further improvements??

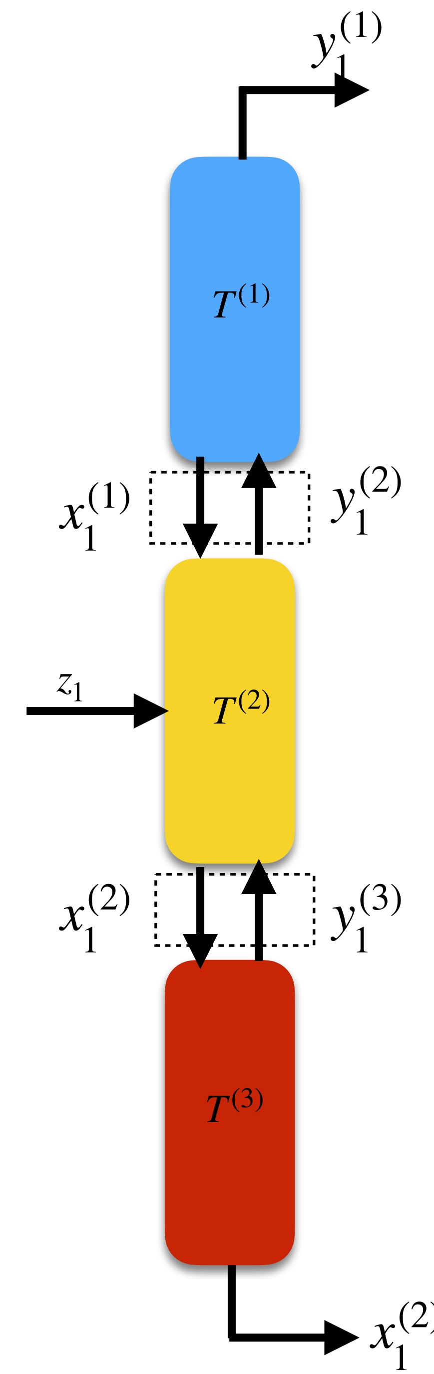




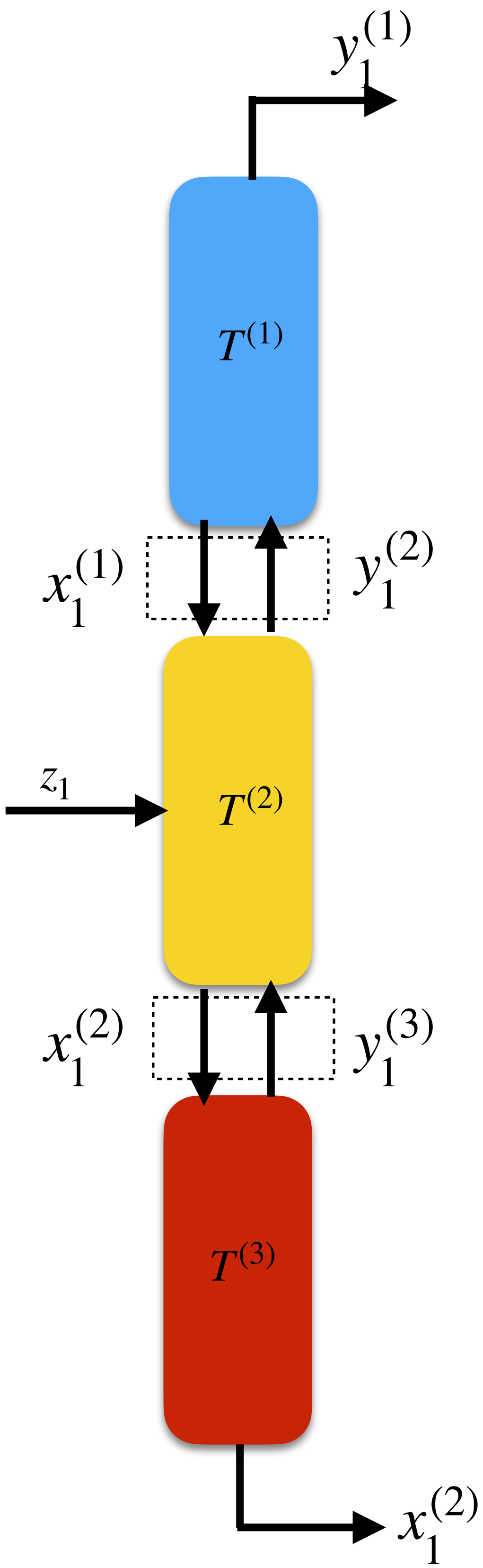
Further improvements: heat and mass exchange between liquid and vapor streams

$T^{(3)} > T^{(2)} > T^{(1)}$

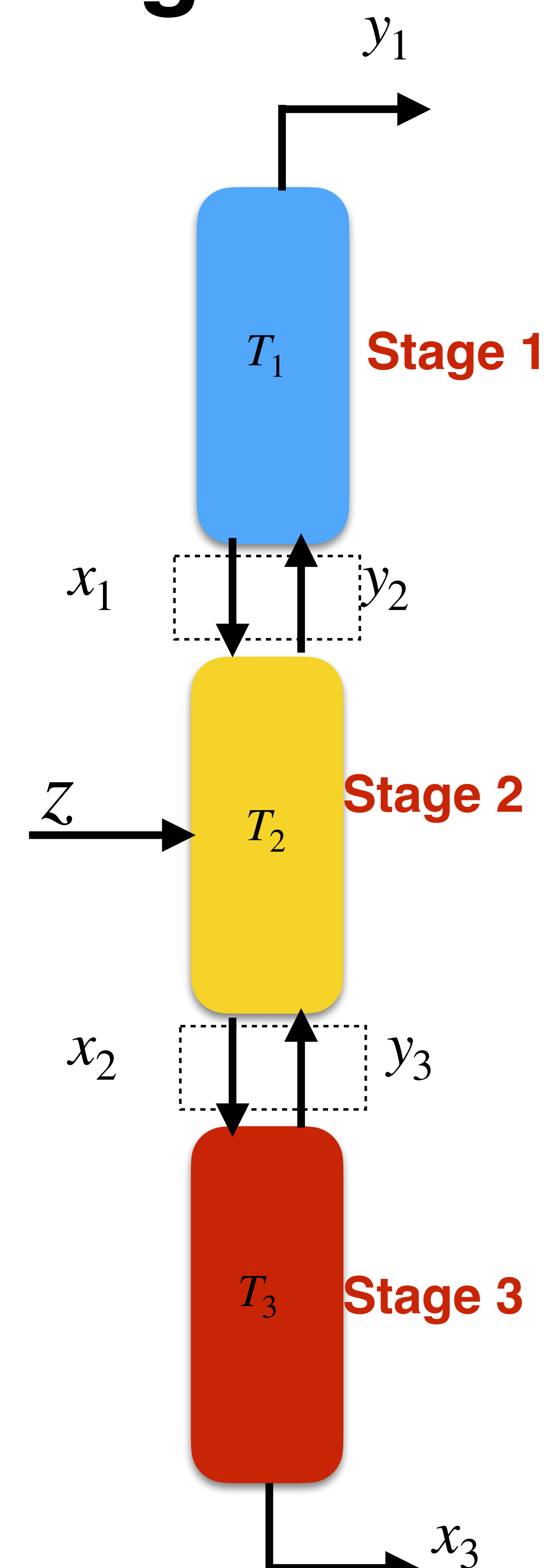




Major nomenclature change for multistage processes



Stage # becomes more important
We only refer to most volatile component for binary case



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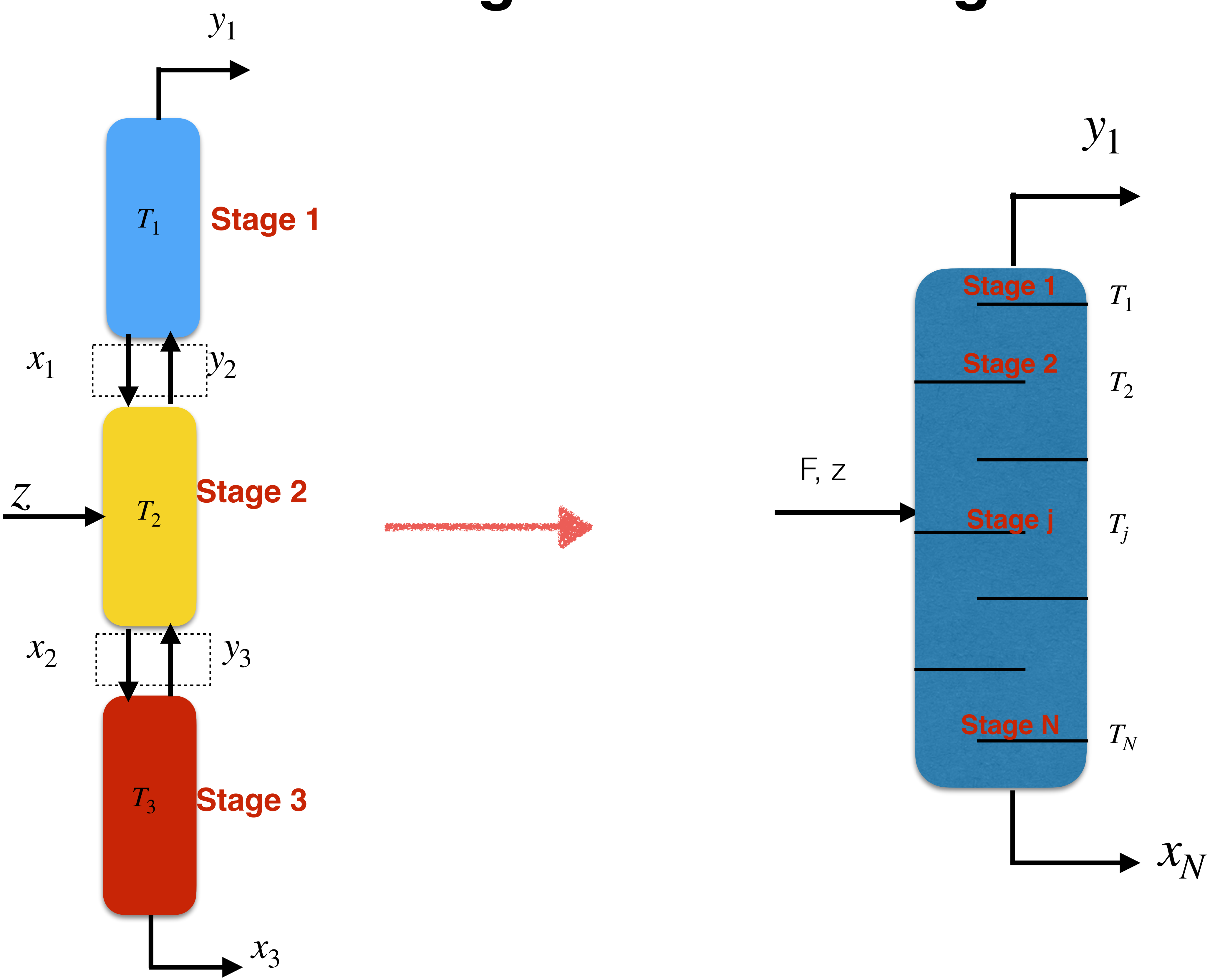
Single column design



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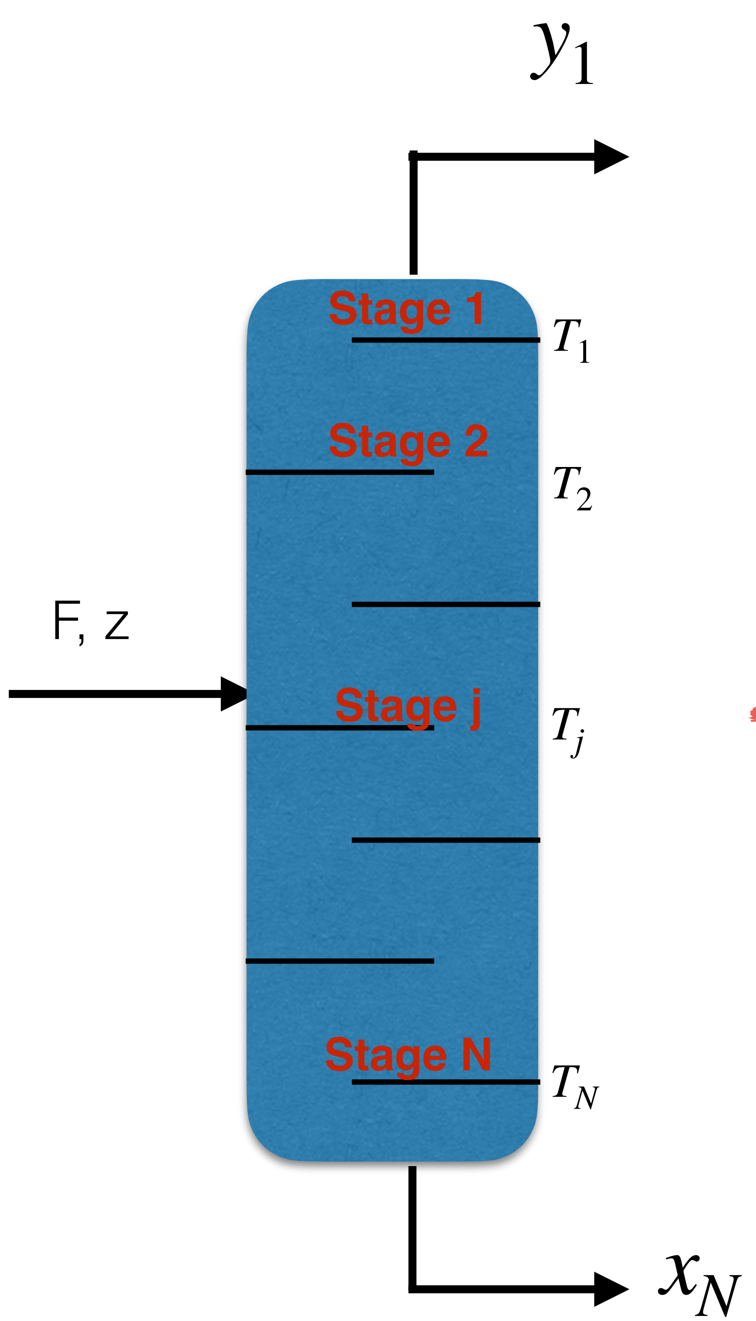
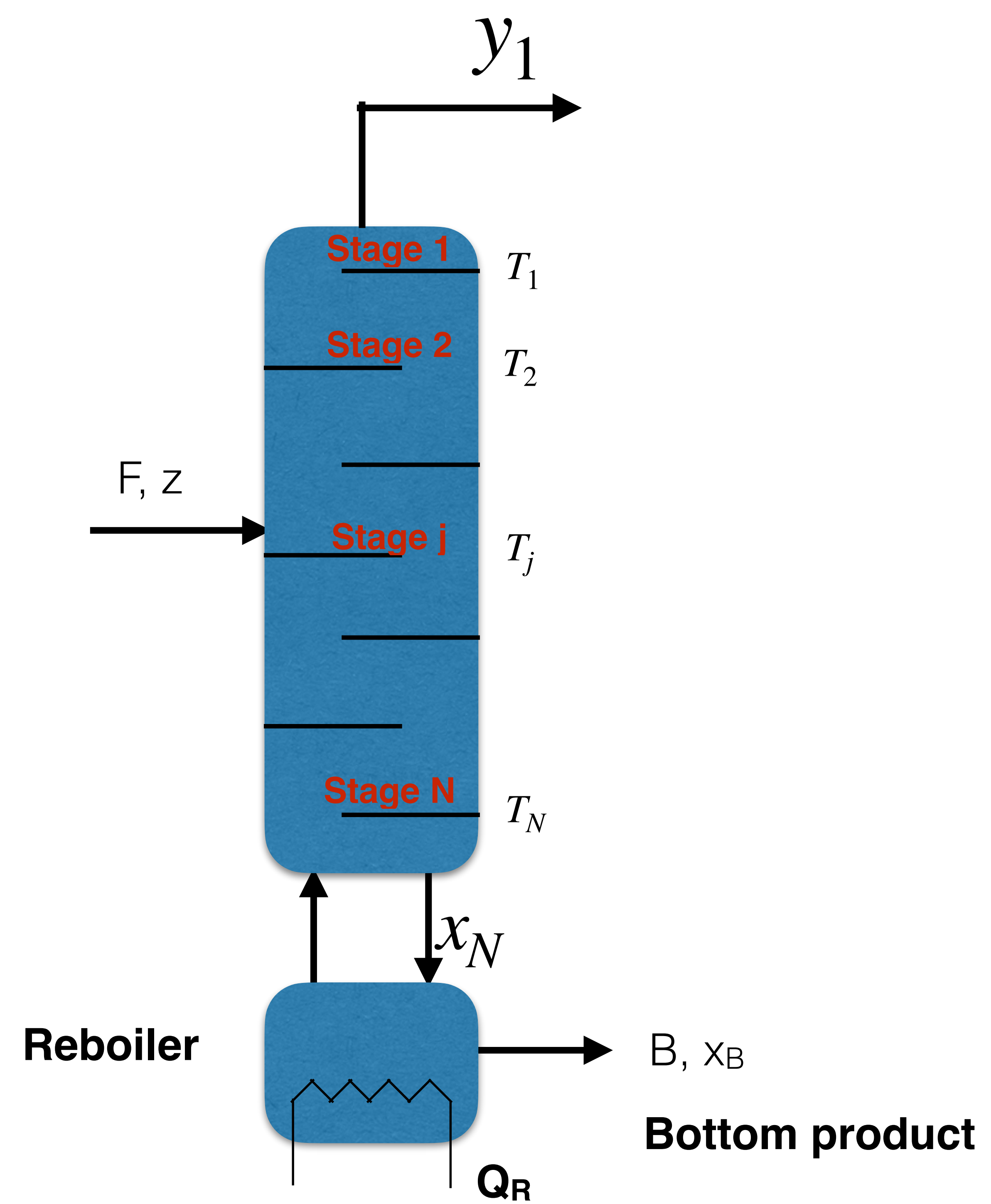
Heat management (maintaining temperature)





Some of liquid at bottom, x_N, is heated using a reboiler and sent back to column

We have to heat stages using some heating arrangement

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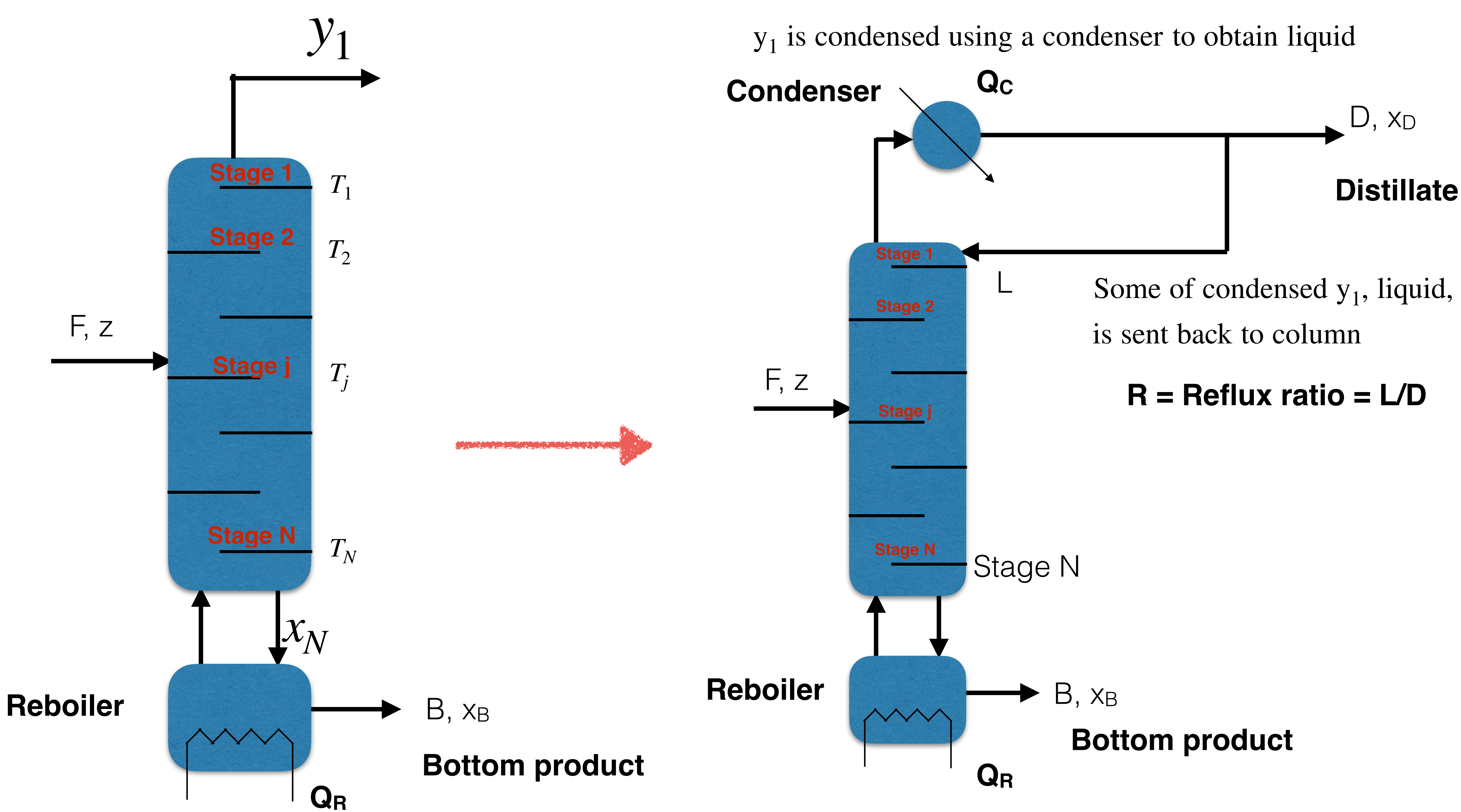
Liquid products are desired



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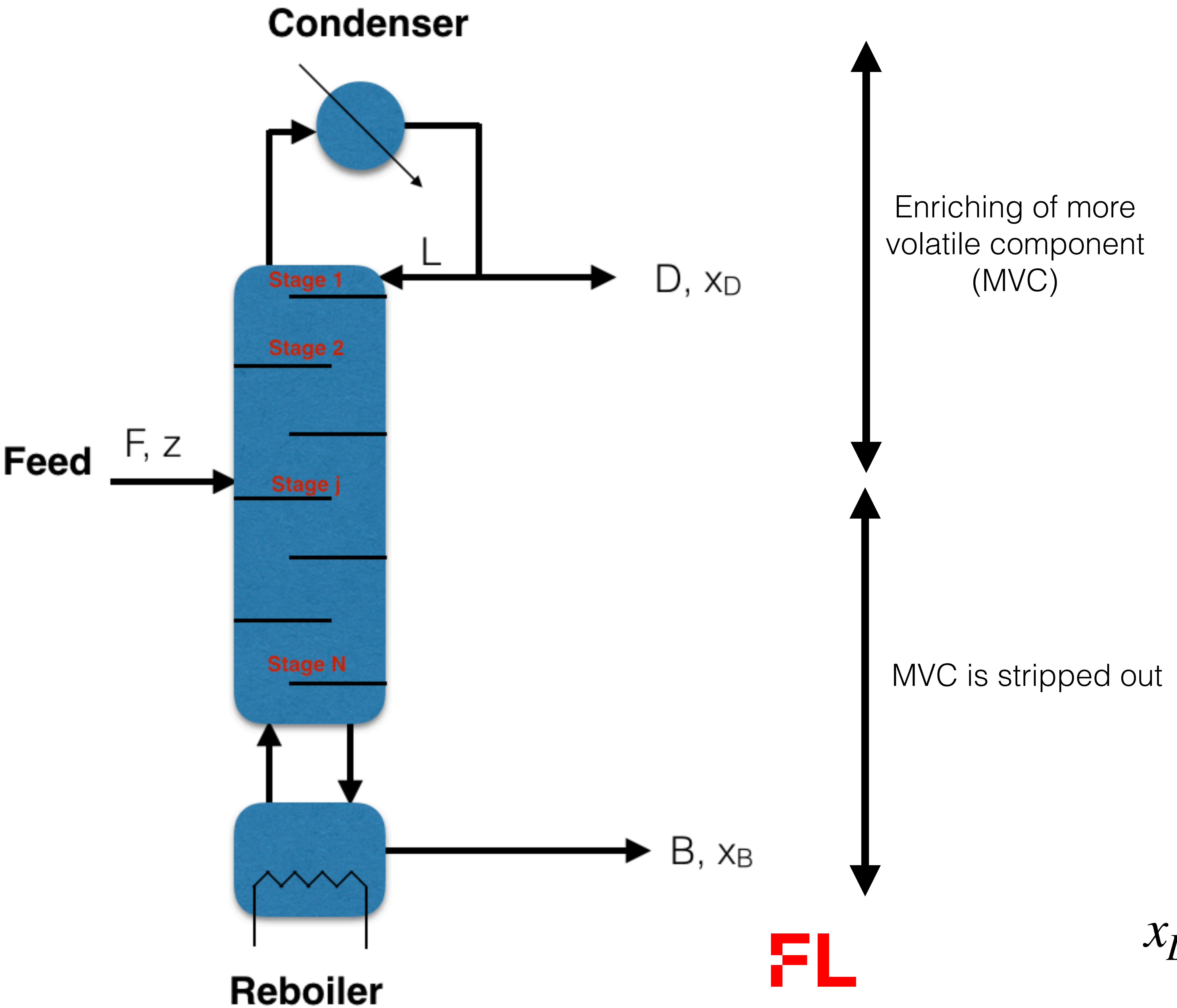
Analysis in two sections



Enriching or Rectifying section

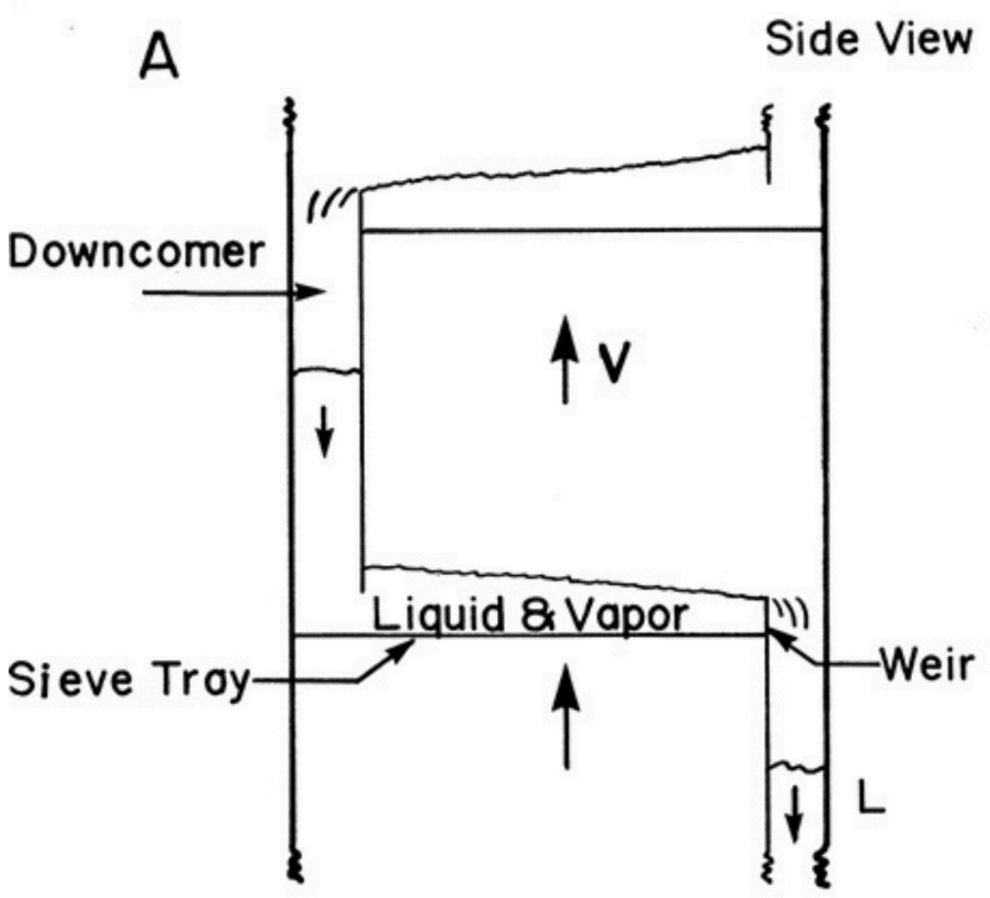
Stripping section

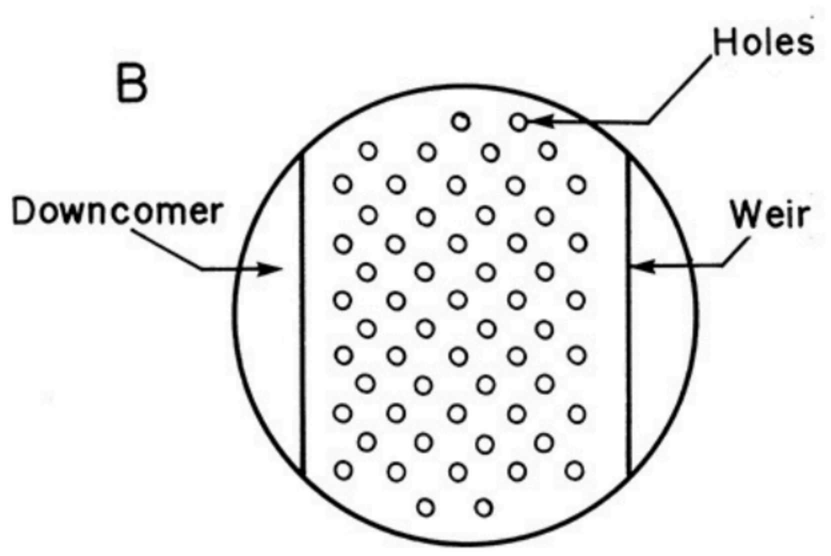
$$x_D > z > x_B$$

Operation at each plate

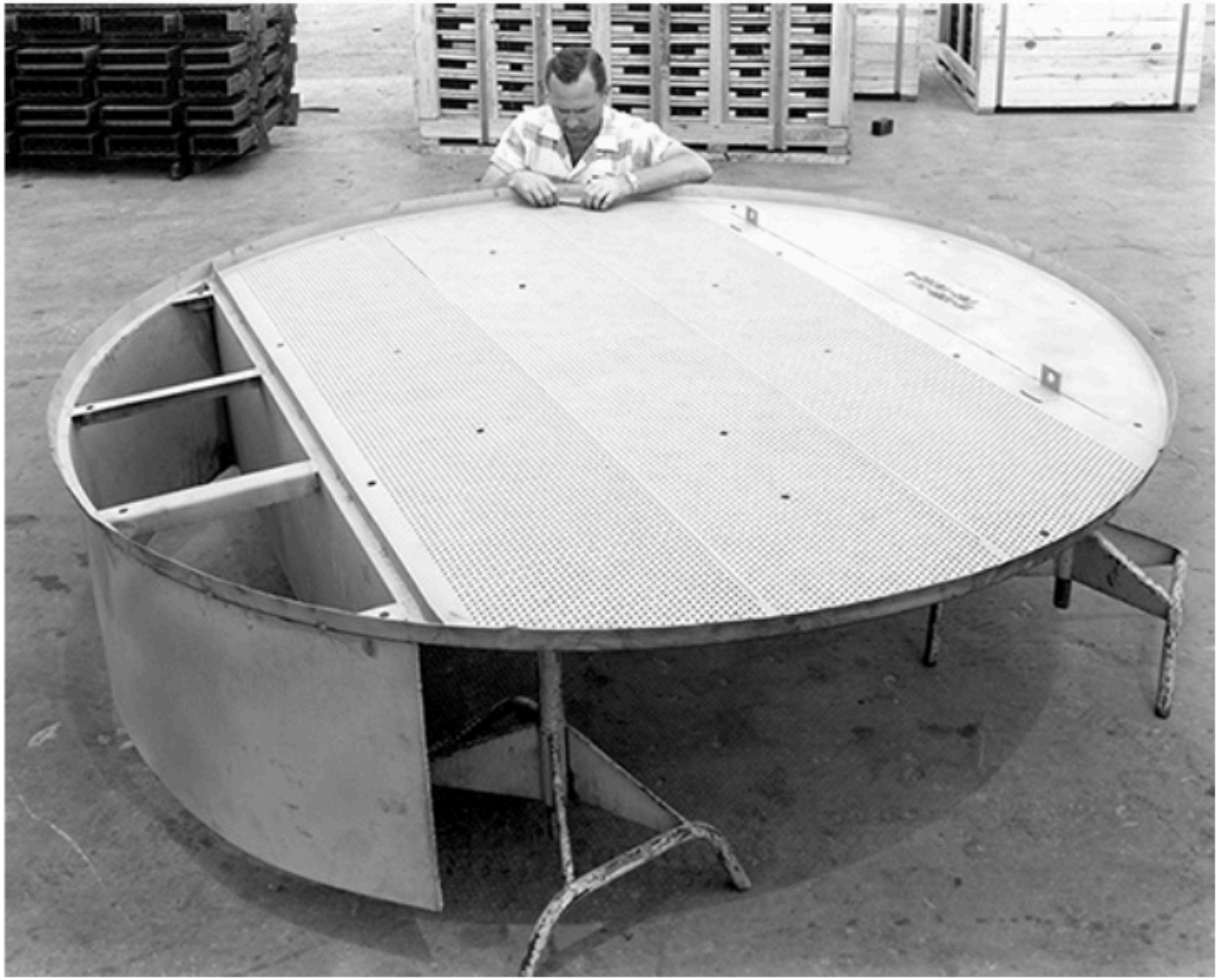
Trays (also known as plates or stages): Where liquid-vapor contact occurs.

Simplest tray: Sieve tray





Sieve tray



Valve tray to control gas flow rate

Holes are fitted with caps which can move up or down depending on the pressure of vapor and liquid

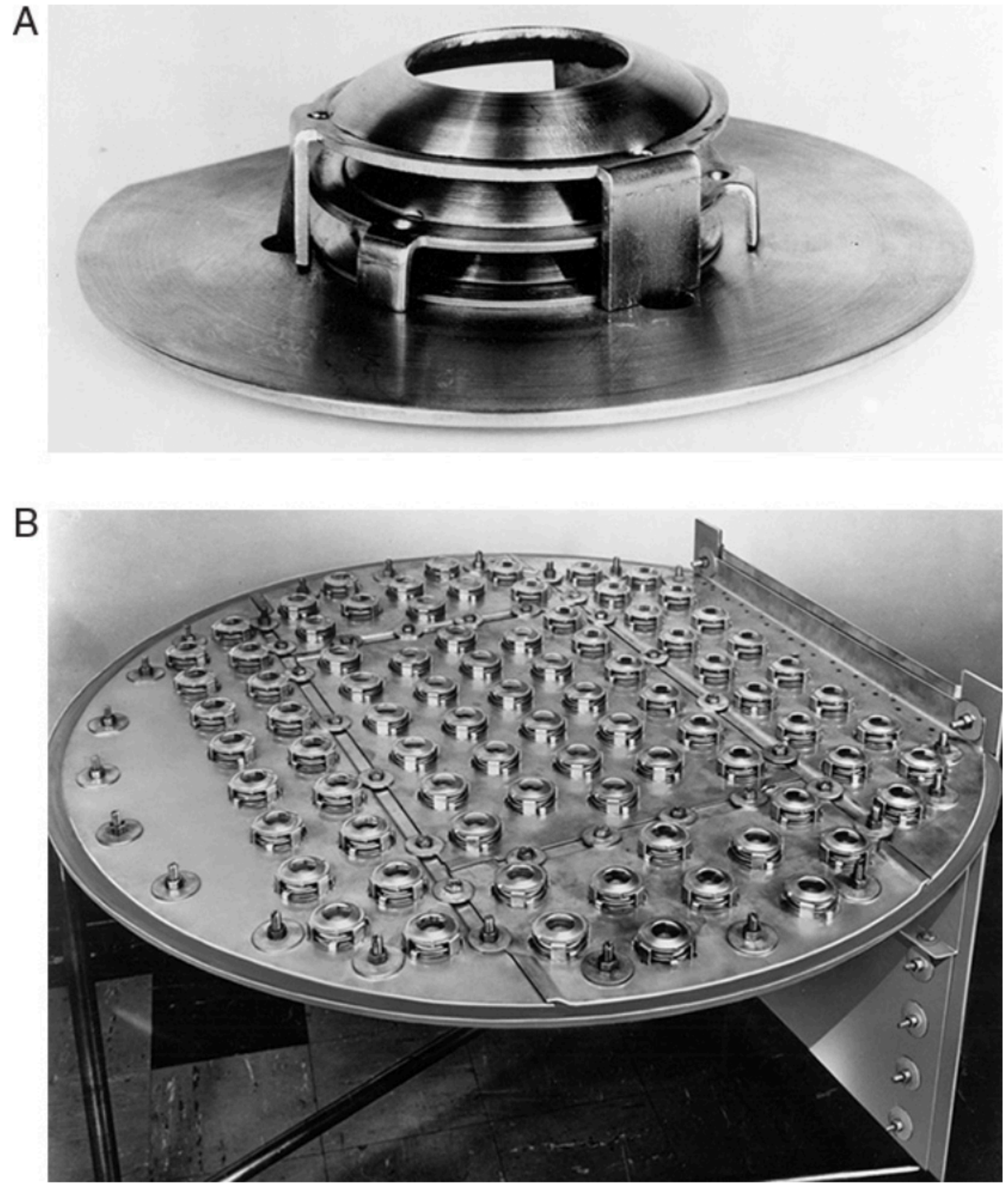


FIGURE 10-1. *(A) Valve assembly for Glitsch A-1 valve, and (B) small Gitsch A-1 ballast tray; courtesy of Glitsch, Inc., Dallas, Texas*

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A few facts about distillation

1. Distillation is derived from Latin word *destillare*, which means “dripping”.

2. The term rectification is derived from the latin word, *rectefacere*, which means “to improve”.

3. Distillation dates back to at least 1st century A.D.

4. By 11th century, distillation was used in Italy to make alcoholic beverages in the batch mode.

5. By 16th century, it was known that separation can be improved by multiple stages, in Rectificatorium.

6. Distillation consumes 25% of the energy in all chemical industry (50% energy related to separation process).

7. Distillation can be extremely energy-intensive when $\alpha_{12} < 1.5$ (example, close boiling chemicals such as propane/propylene, xylene isomers with α_{12} close to 1.1)

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Mass balances

$F = D + B$ **Eq. 1**

$Fz = Dx_D + Bx_B$ **Eq. 2**

Usually F, z, x_B, x_D, and R $\left(R = \frac{L}{D}\right)$ are given

Calculate D, B, L

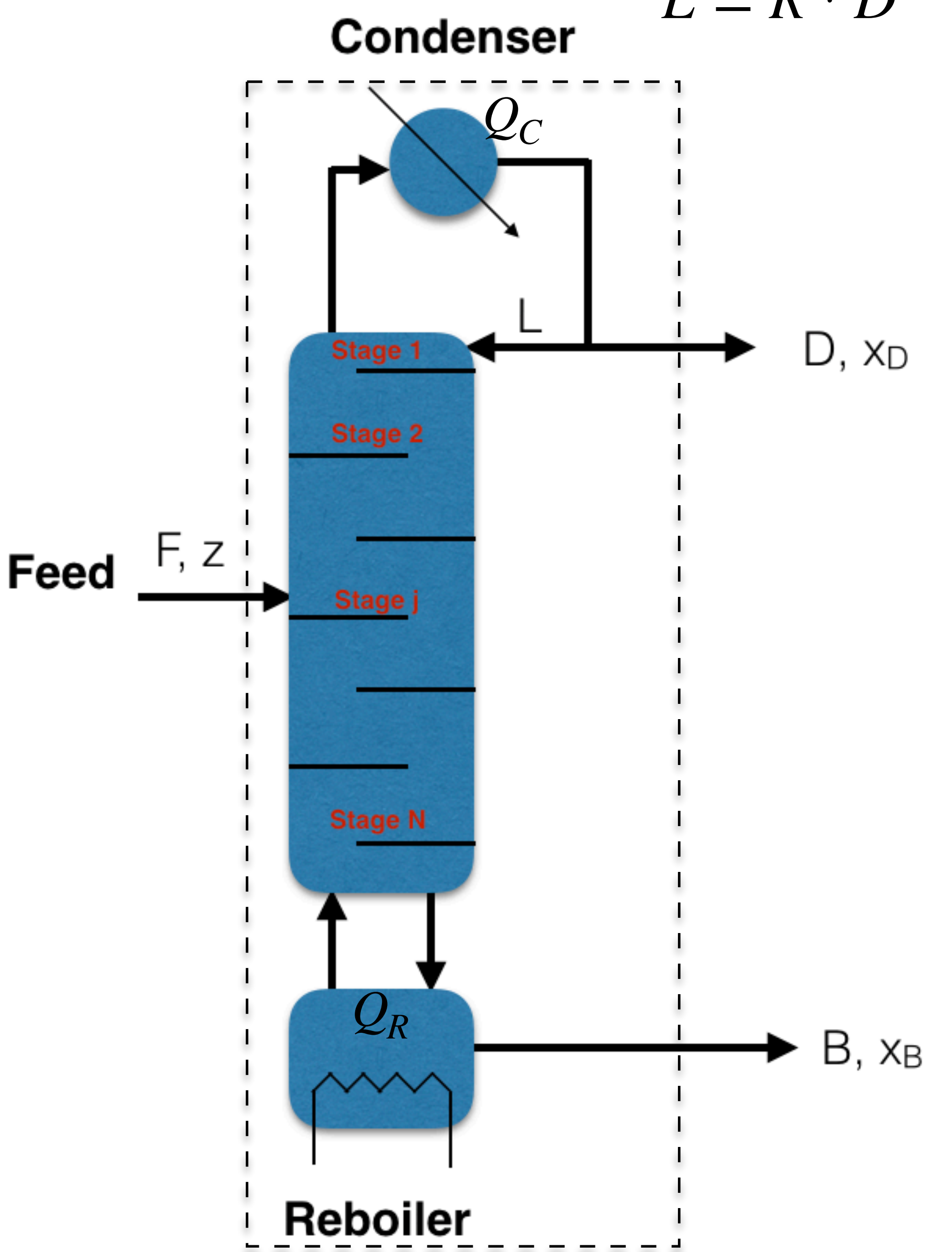
$$D = F\frac{z - x_B}{x_D - x_B}$$

$$B = F\frac{x_D - z}{x_D - x_B}$$

Do you see a similarly to lever rule ??

R = Reflux ratio = L/D

$L = R * D$



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Overall energy balance

$$Fh_F + Q_R + Q_C = Dh_D + Bh_B$$

We need one more equation

Q_C is heat taken out for condensing V_1 to liquid (D+L)

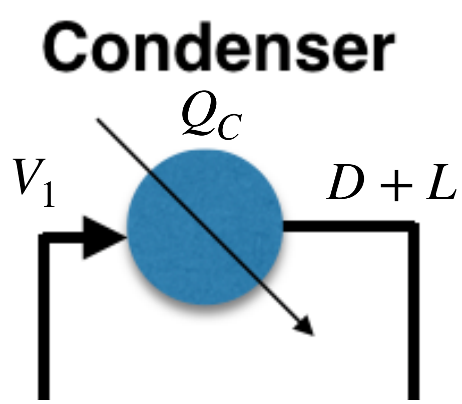
$$V_1 h_{V_1} + Q_C = (D+L)h_D$$

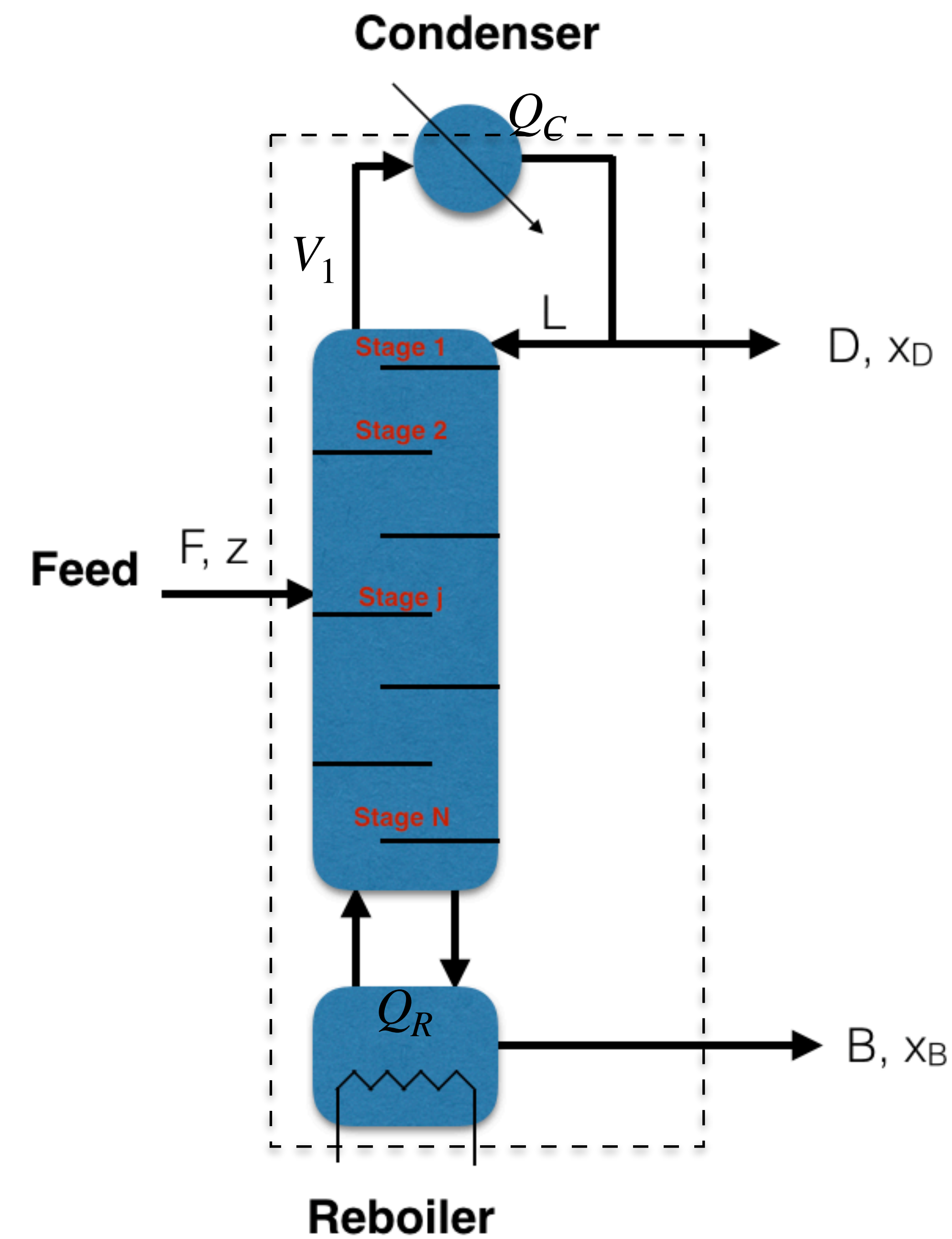
$$V_1 h_{V_1} = (D+L)h_D - Q_C$$

$$V_1 = D + L$$

$$\Rightarrow Q_C = -(D+L)\left(h_{V_1} - h_D\right)$$

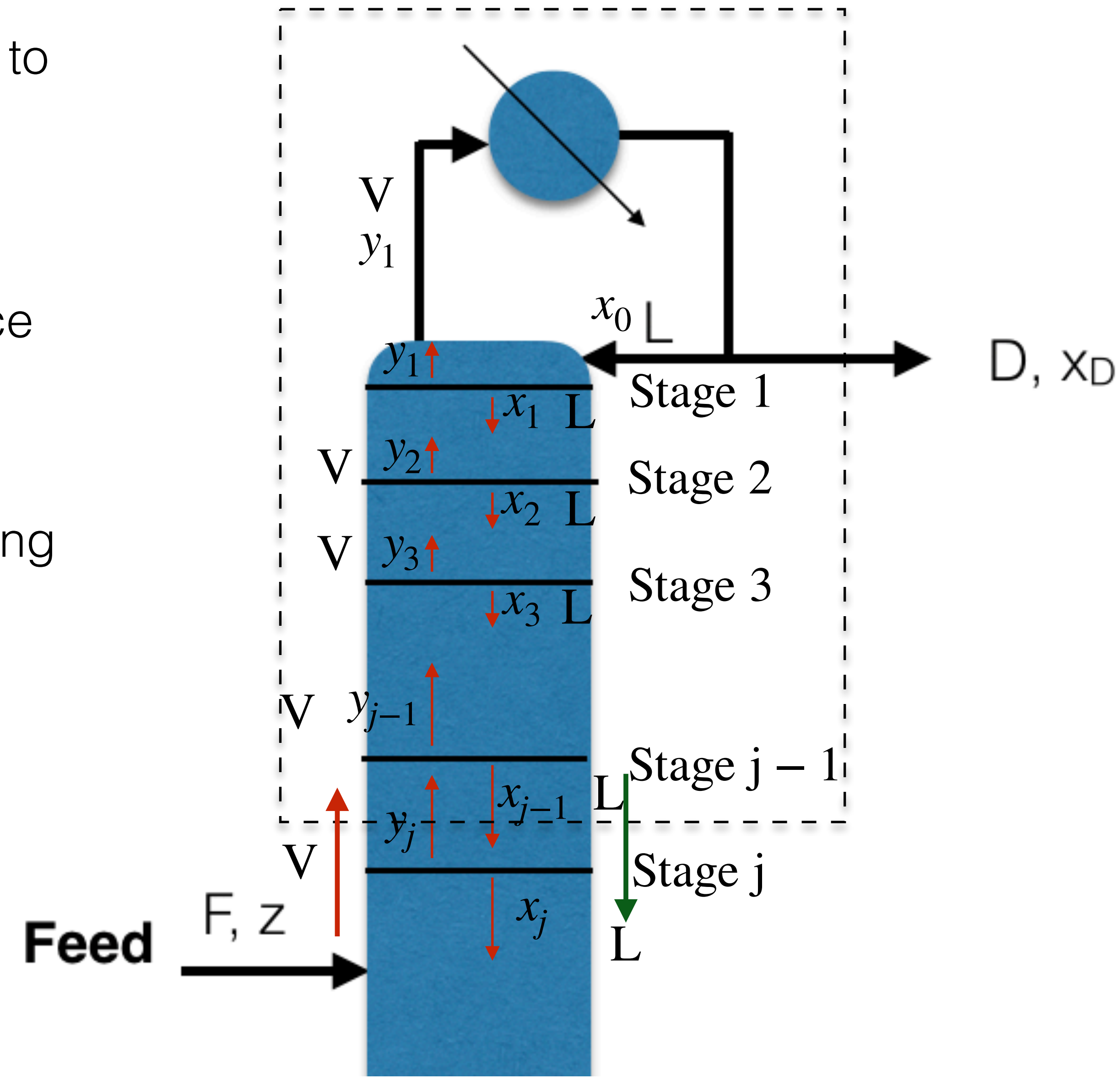
Latent heat of vaporization





Stage by stage balance: rectifying section

1. Constant Molar Flow Assumption: Liquid and vapor flow rates above the feed do not change from stage to stage (assume similar molar volume).
2. Column pressure is uniform.
3. Column is well insulated and no heat loss takes place from column.
4. Each stage is an equilibrium stage: streams leaving the column are in equilibrium (note that stream arriving in the column are not in equilibrium)



Phase equilibria

$$y_1 = k_1 x_1 \qquad k_1 = f(T_1, P)$$

$$y_2 = k_2 x_2 \qquad k_2 = f(T_2, P)$$

$$y_j = k_j x_j \qquad k_3 = f(T_3, P)$$

Equilibrium line

Overall mass balance

In = out

steady-state operation (no accumulation)

$$V y_j = L x_{j-1} + D x_D$$

Operating line

$$y_j = \frac{L}{V} x_{j-1} + \frac{D}{V} x_D$$

Stage by stage balance: rectifying section

$$y_j = \frac{L}{V}x_{j-1} + \frac{D}{V}x_D$$

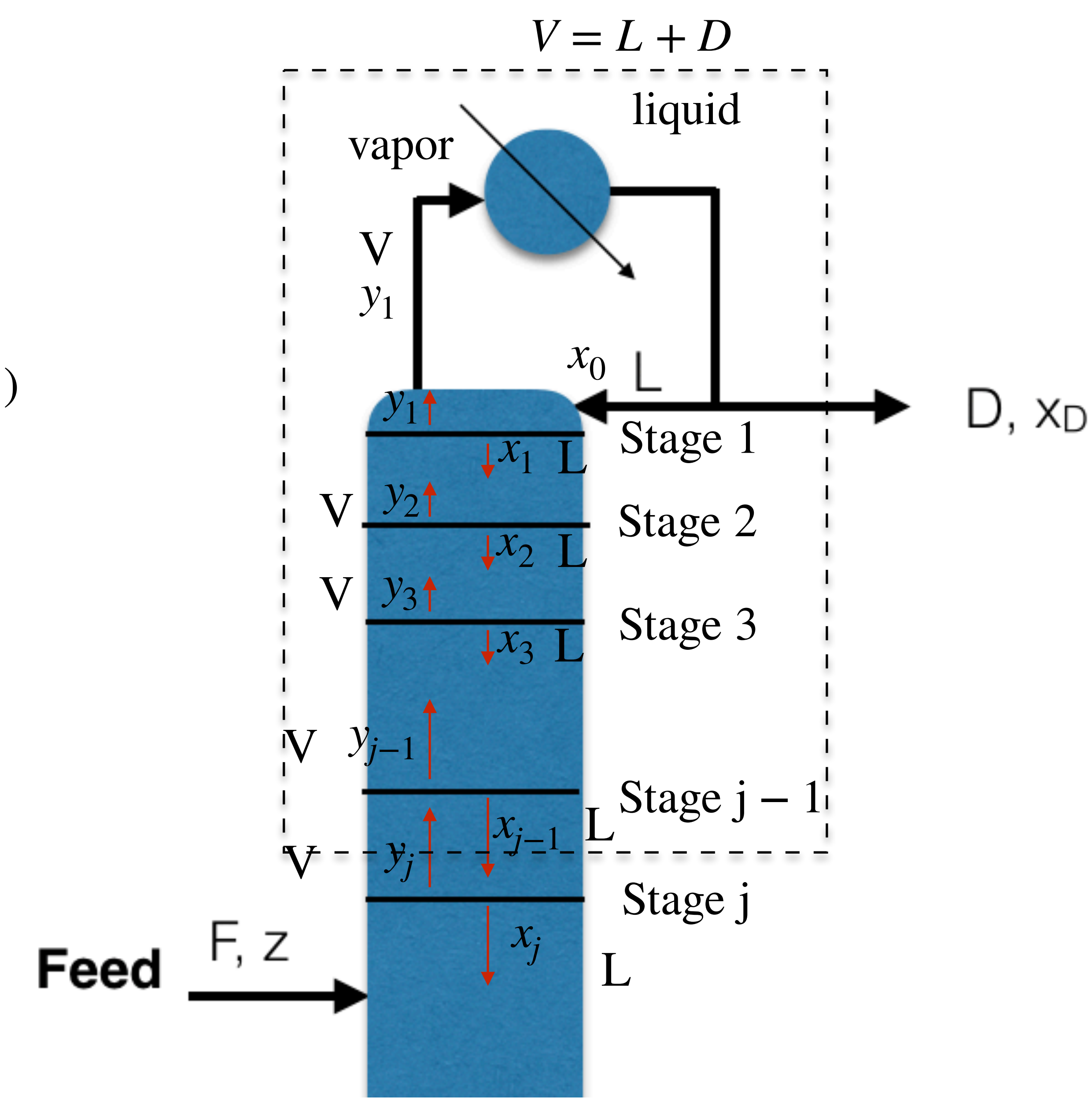
$$R = \frac{L}{D} \qquad \Rightarrow L = RD$$

$$V = L + D \qquad \Rightarrow V = DR + D = D(R+1)$$

$$\Rightarrow y_j = \frac{RD}{D(R+1)}x_{j-1} + \frac{D}{D(R+1)}x_D$$

$$\Rightarrow y_j = \frac{R}{(R+1)}x_{j-1} + \frac{1}{(R+1)}x_D$$

Operating line above the feed



$$y_1 = \frac{R}{(R+1)}x_0 + \frac{1}{(R+1)}x_D$$

$$y_2 = \frac{R}{(R+1)}x_1 + \frac{1}{(R+1)}x_D$$

Important note: point (x_D, x_D) lies on this line

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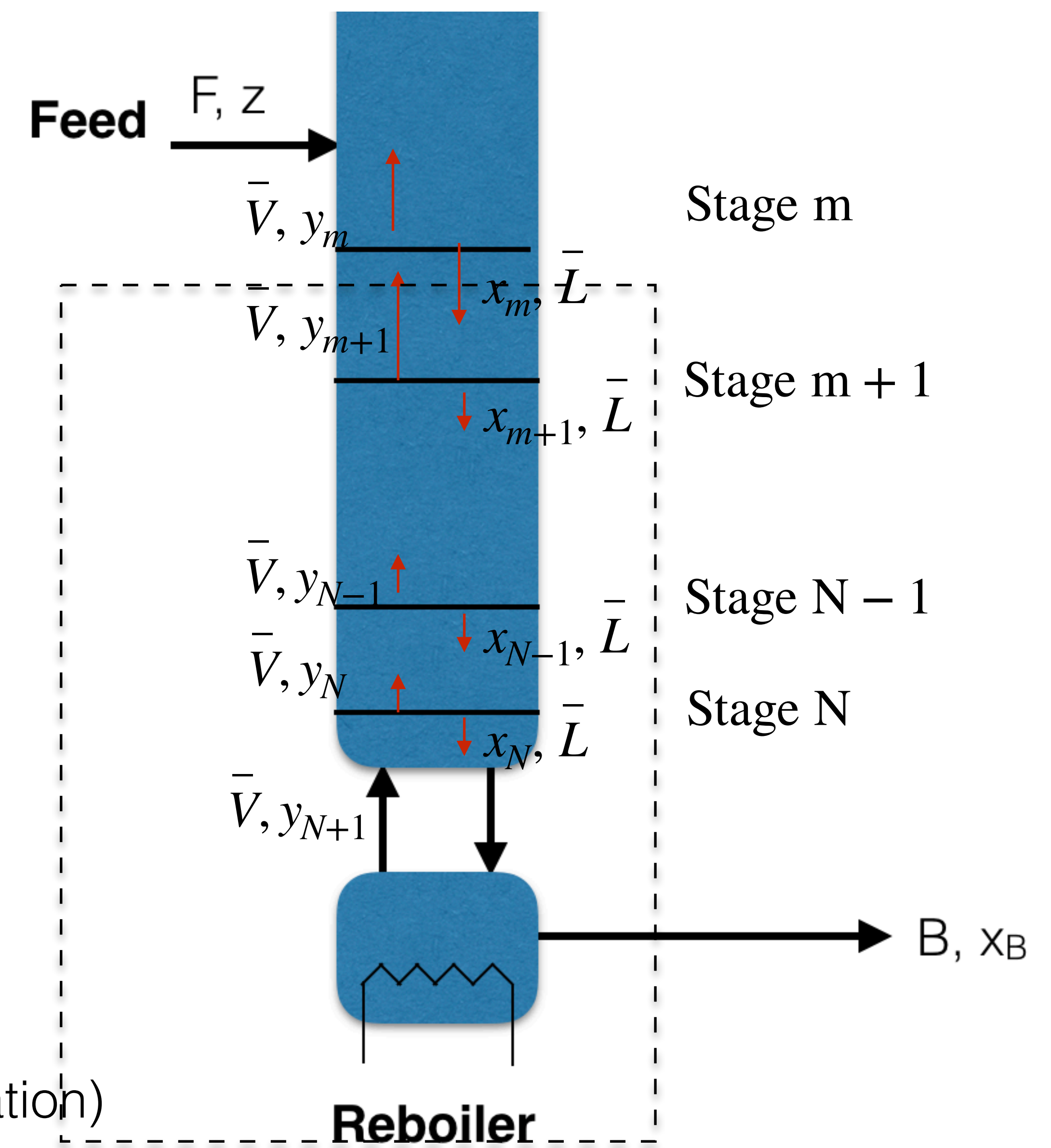
Stage by stage balance: stripping section

1. CMO assumption: Liquid and vapor flow rates below the feed do not change from stage to stage (assume similar molar volume).
2. Column pressure is uniform.
3. Column is well insulated and no heat loss takes place from column.
4. Each stage is an equilibrium stage: streams leaving the column are in equilibrium (note that stream arriving in the column are not in equilibrium)



$y_m = k_m x_m \qquad k_m = f(T_m, P)$ Equilibrium line

Overall mass balance

In = out steady-state operation (no accumulation)

$$\bar{L}x_m = \bar{V}y_{m+1} + Bx_B$$ Operating line

$$\bar{V}y_{m+1} = \bar{L}x_m - Bx_B$$

$$y_{m+1} = \frac{\bar{L}}{\bar{V}}x_m - \frac{B}{\bar{V}}x_B$$

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Stage by stage balance: stripping section

$$y_{m+1} = \frac{\bar{L}}{\bar{V}} x_m - \frac{B}{\bar{V}} x_B$$

Boilup ratio, $V_B = \frac{\bar{V}}{B}$ $\Rightarrow \bar{V} = BV_B$

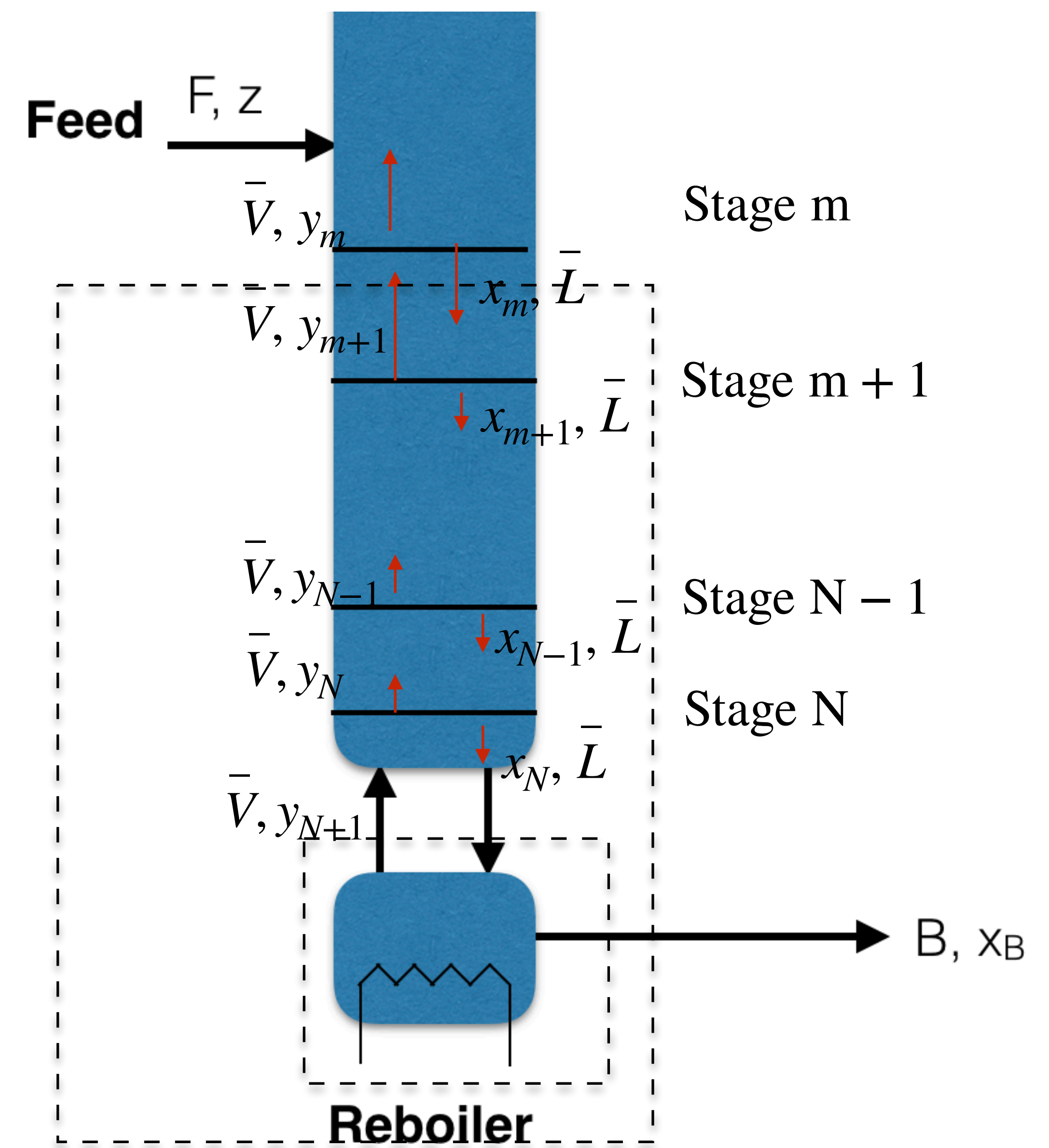
$$\bar{L} = \bar{V} + B \qquad \Rightarrow \bar{L} = BV_B + B = B(V_B + 1)$$

$$\Rightarrow y_{m+1} = \frac{B(V_B + 1)}{BV_B} x_m - \frac{B}{BV_B} x_B$$

$$\Rightarrow y_{m+1} = \frac{V_B + 1}{V_B} x_m - \frac{1}{V_B} x_B$$

$$y_{N+1} = \frac{V_B + 1}{V_B} x_N - \frac{1}{V_B} x_B$$

$$y_N = \frac{V_B + 1}{V_B} x_{N-1} - \frac{1}{V_B} x_B$$



Important note: point (x_B, x_B) lies on this line

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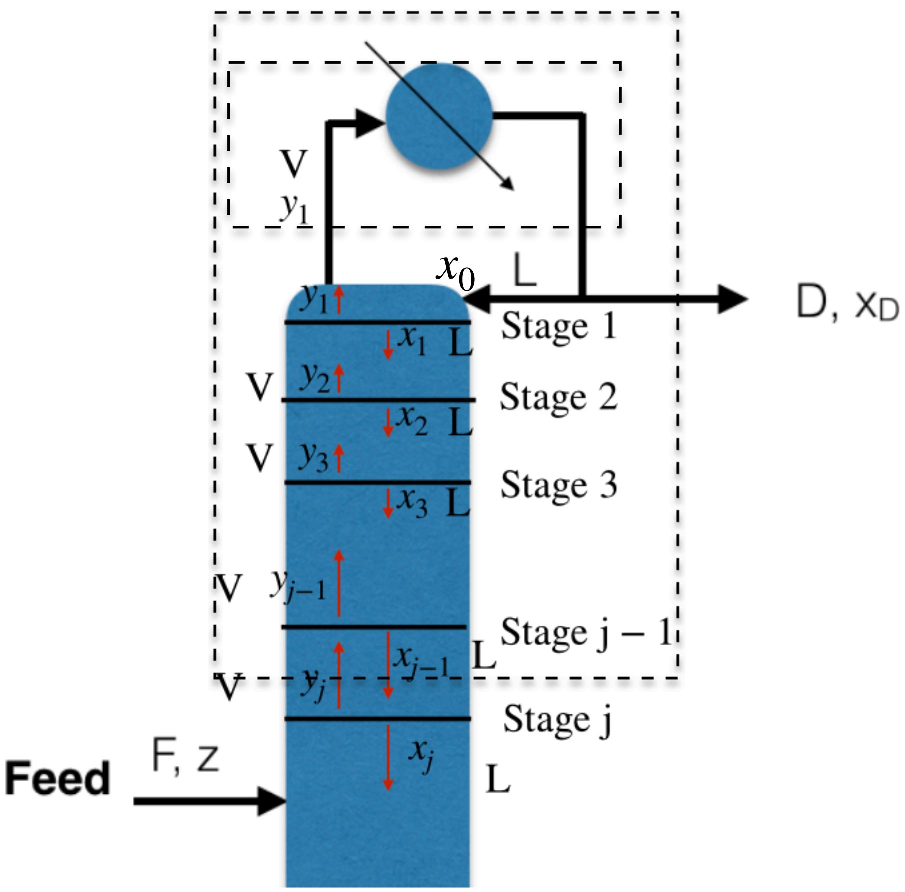
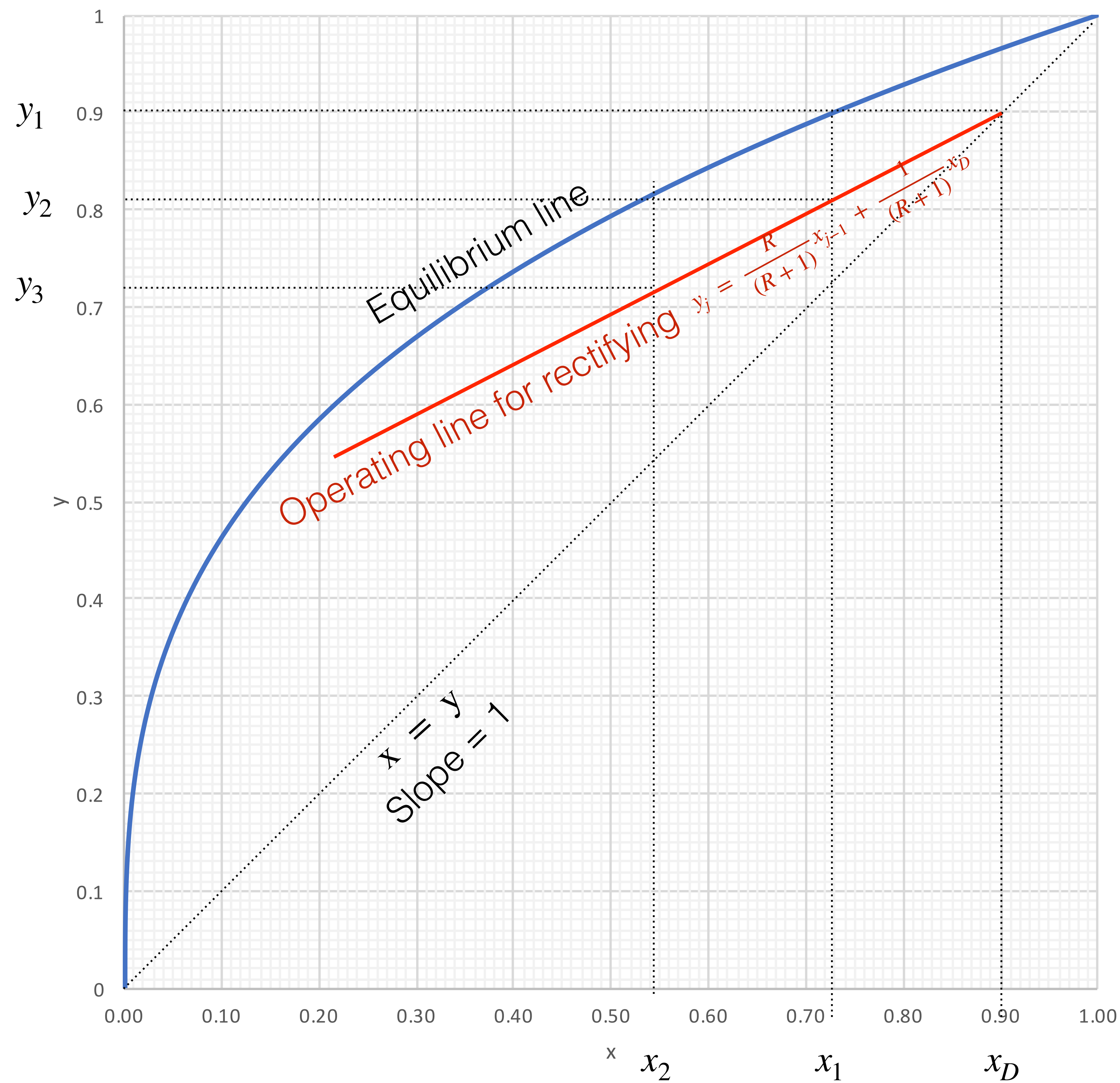
Graphical representation

$$V = L + D$$

$$Vy_1 = (L + D)x_0$$

$$Vy_1 = Vx_0$$





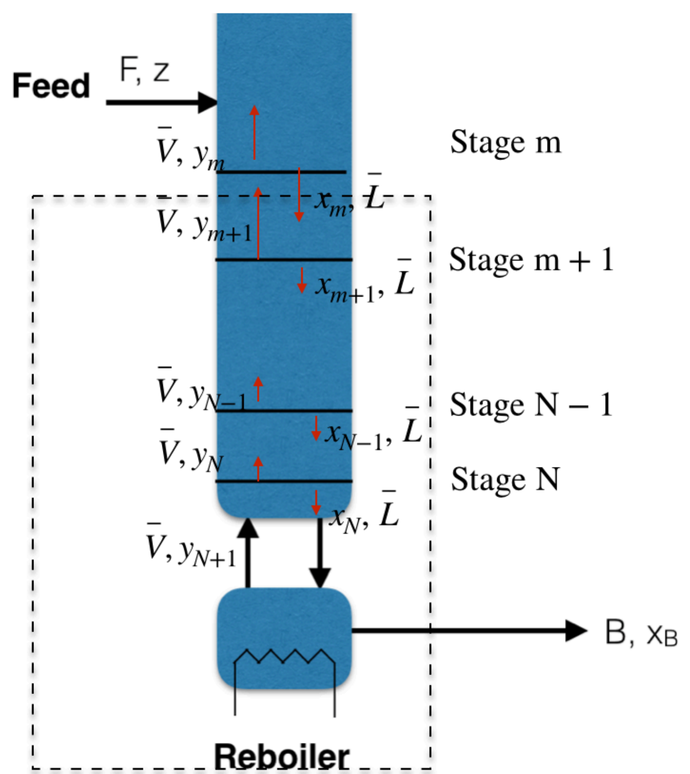
$x_0 = x_D = y_1$ at stage 1

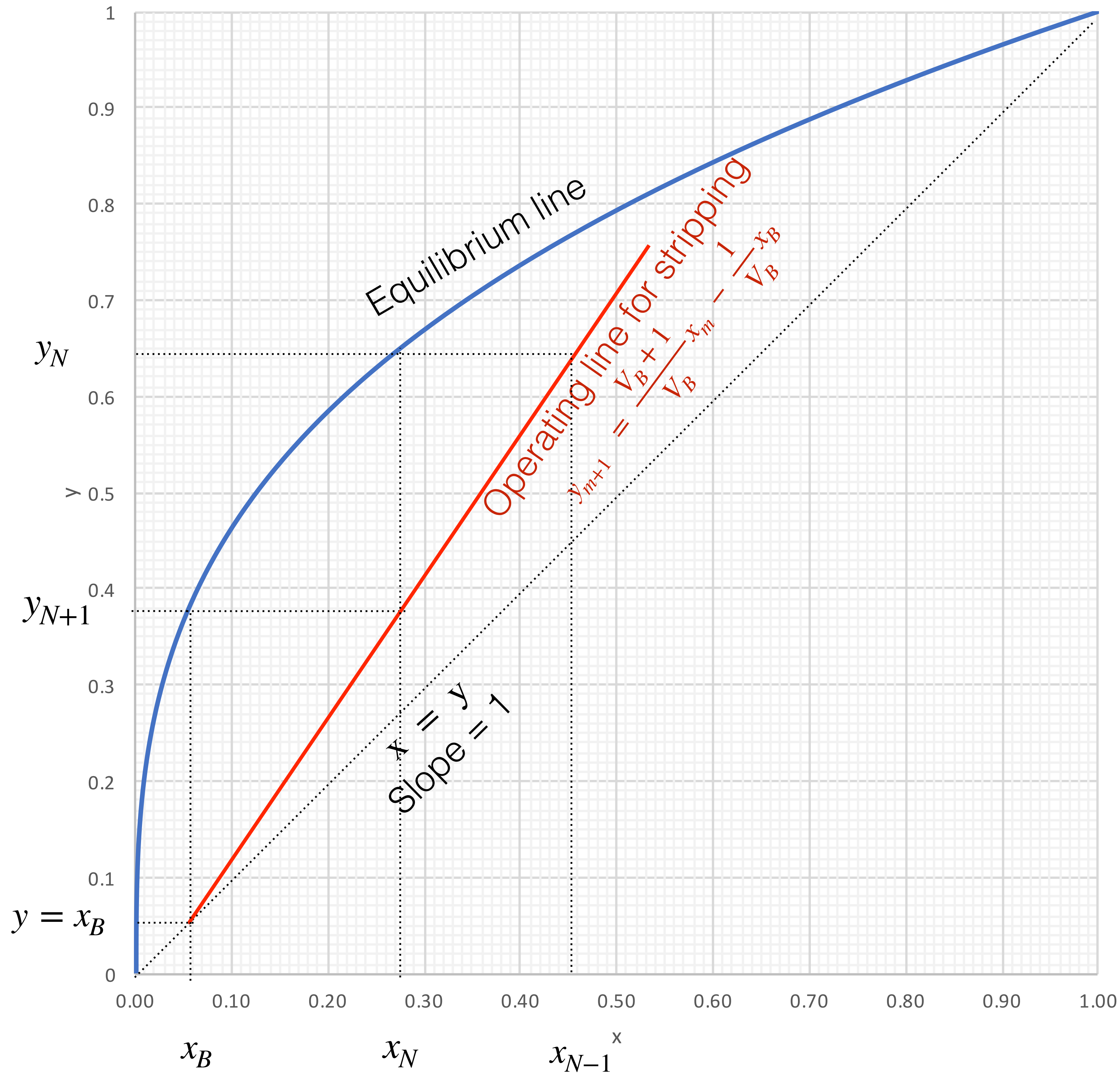
$$y_j = \frac{R}{(R+1)}x_{j-1} + \frac{1}{(R+1)}x_D$$

$$y_1 = \frac{R}{(R+1)}x_0 + \frac{1}{(R+1)}x_D$$

Slope = R/(R+1) < 1

Graphical representation





$$y_{N+1} = \frac{V_B+1}{V_B}x_N - \frac{1}{V_B}x_B$$

$$y_{m+1} = \frac{V_B+1}{V_B}x_m - \frac{1}{V_B}x_B$$

(x_B, x_B) falls on the operating line

Slope = $(V_B+1)/V_B > 1$

x_B and y_{N+1} are at equilibrium

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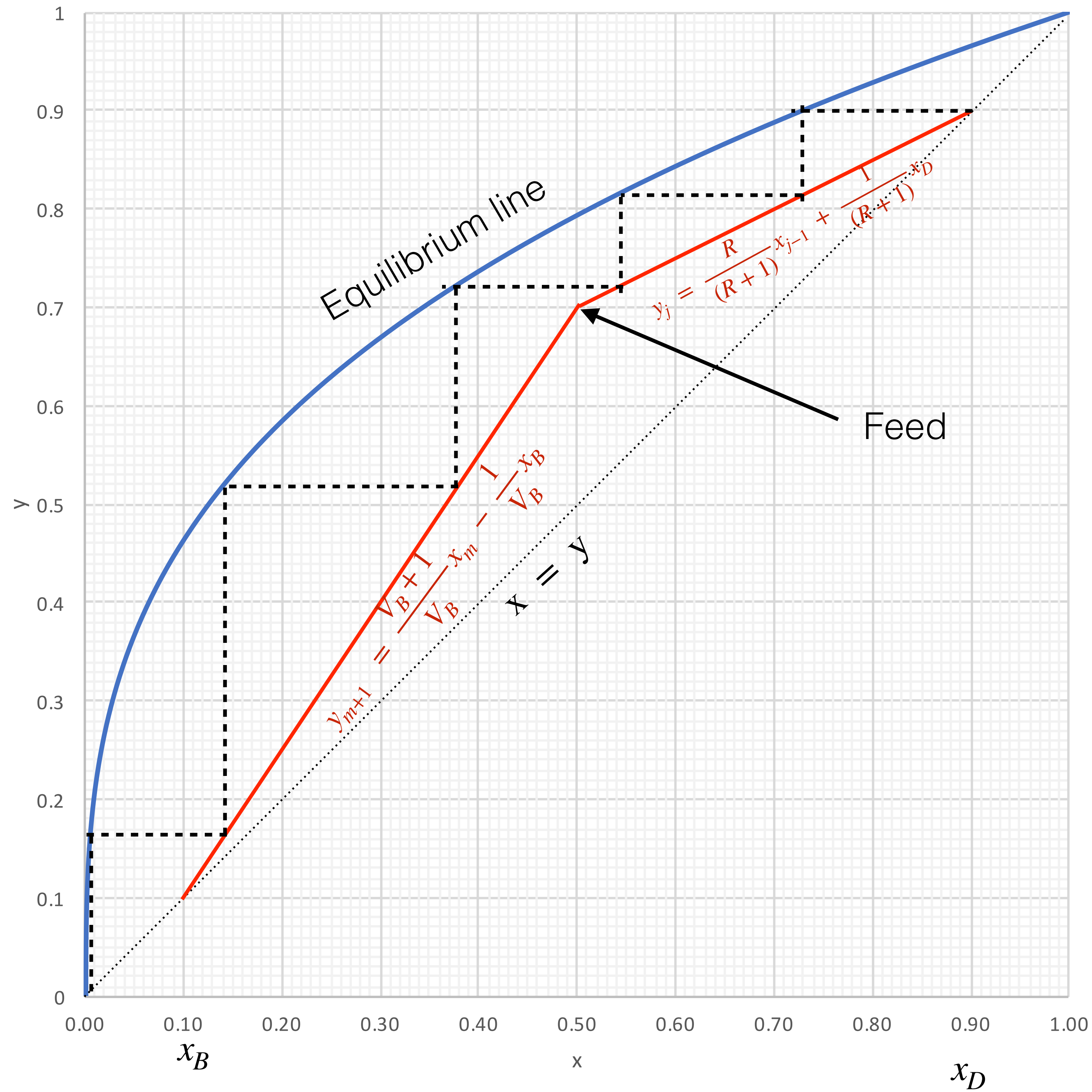
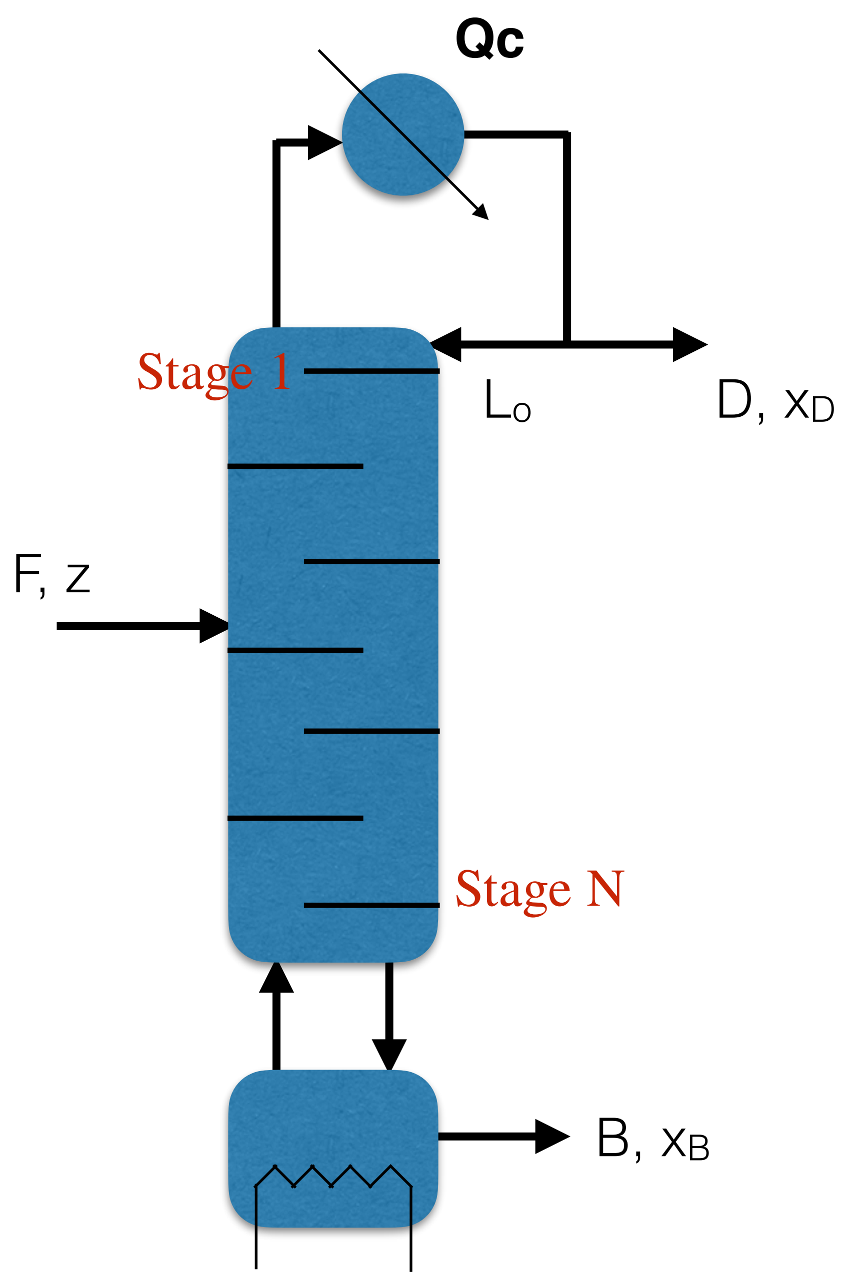
Counting number of equilibrium stages



Which one is NOT an equilibrium stage in the following configuration

A. Stage 1
B. Stage N
C. Reboiler
D. Total condenser



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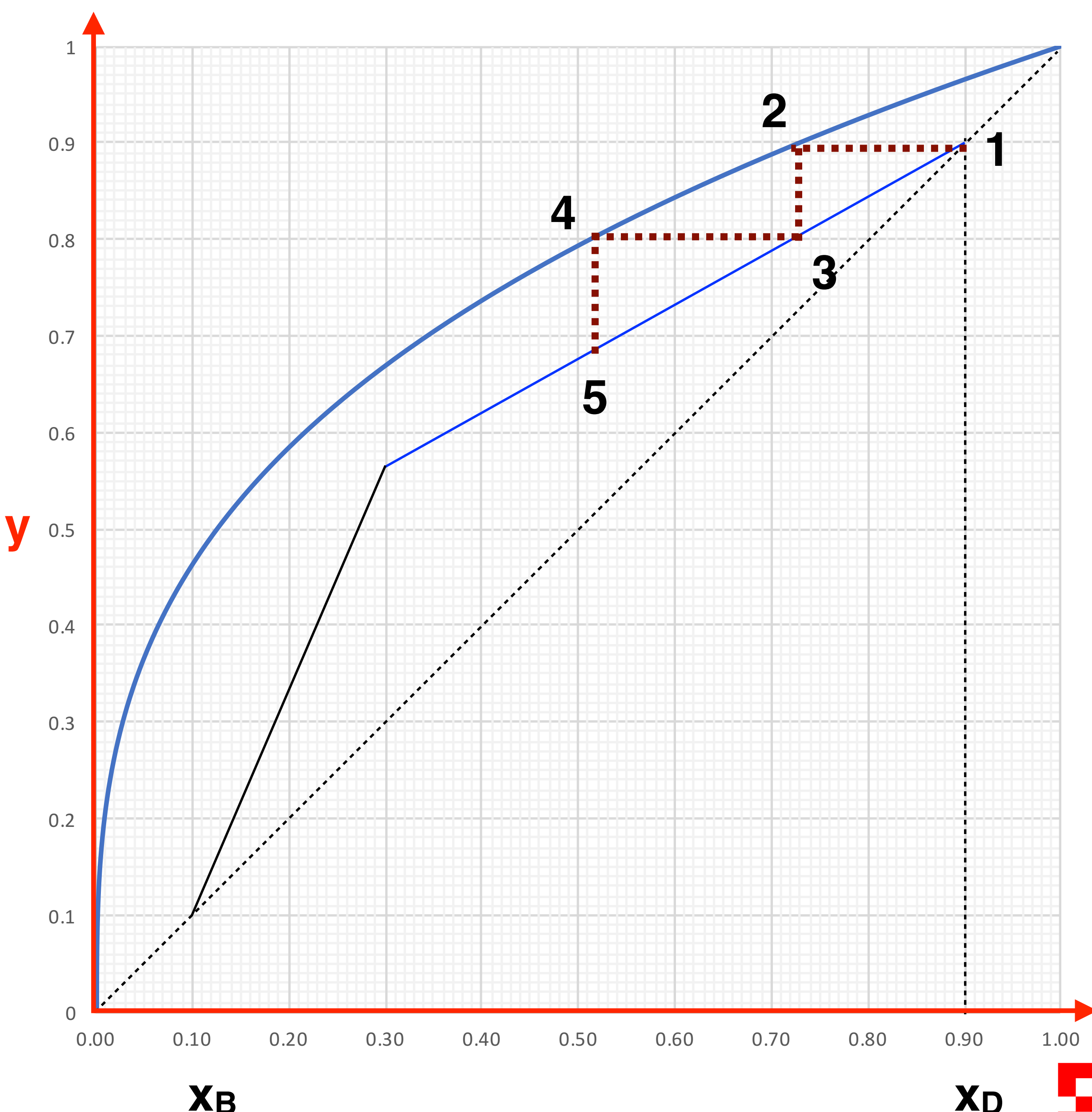
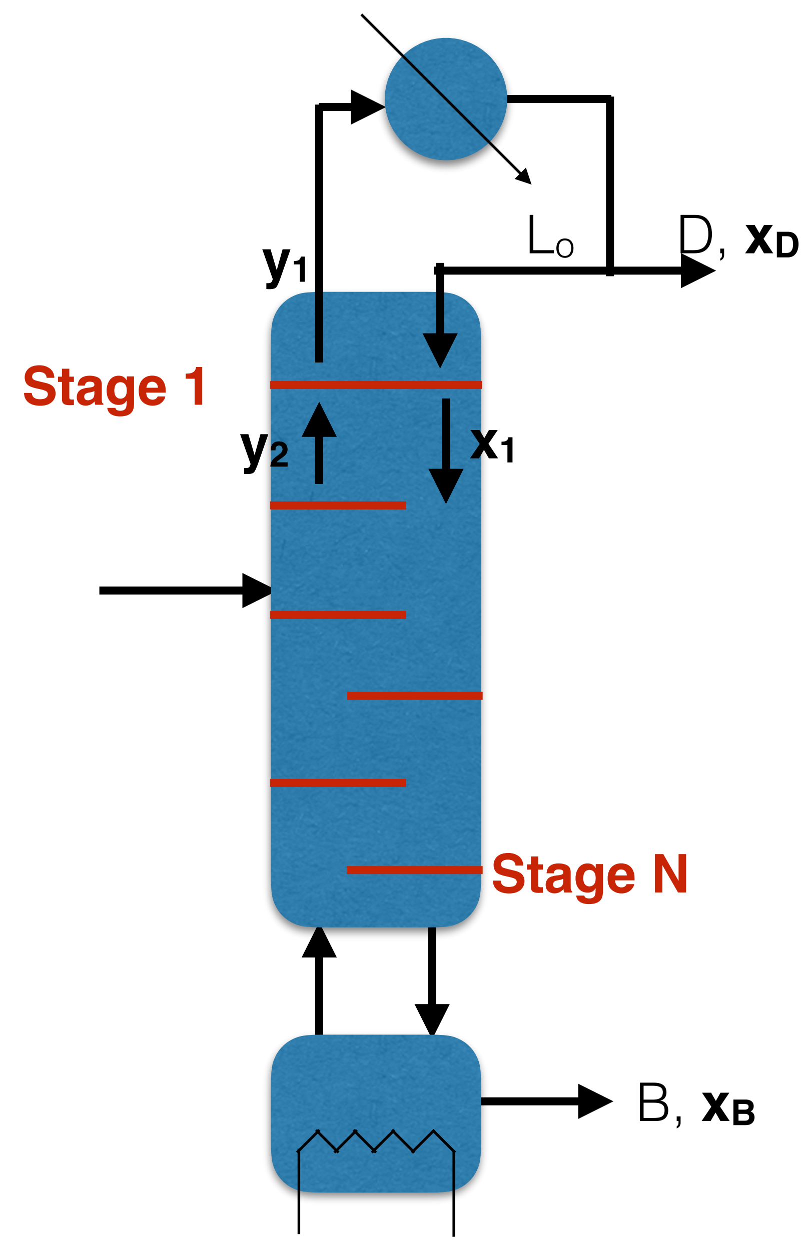
Which points on the plot represent (x_1, y_1)

A. Points 1
B. Points 2
C. Points 3
D. Points 4





Which points on the plot represent (x_N, y_{N+1})

A. Points 1

B. Points 2

C. Points 3

D. Points 4