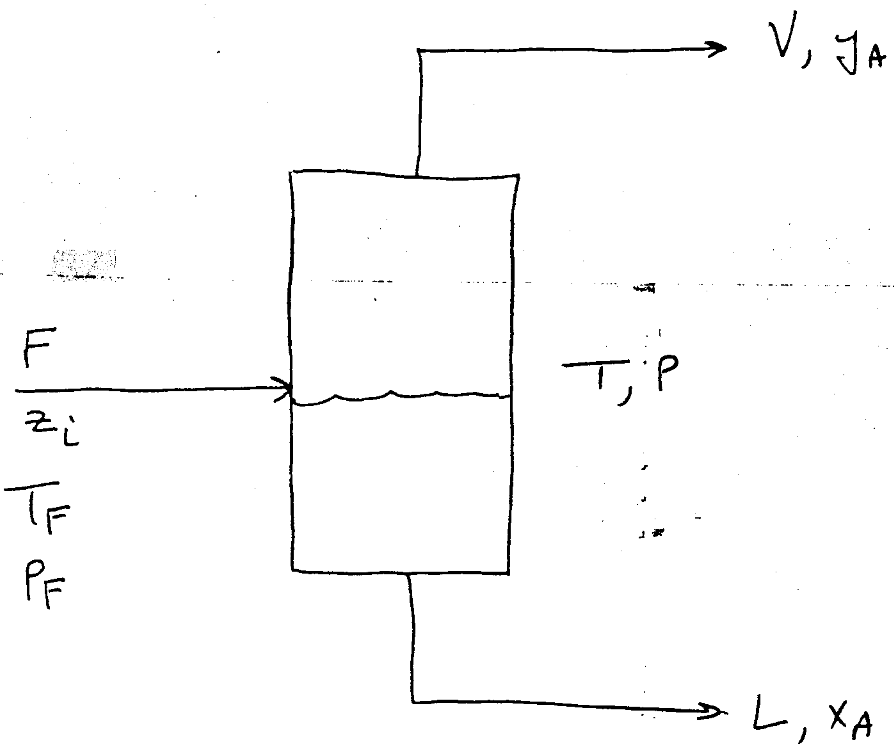
CHAPTER 5: CASCADES

(Multiple Stages in Series)



SINGLE EQUILIBRIUM STAGE

PROBLEM:

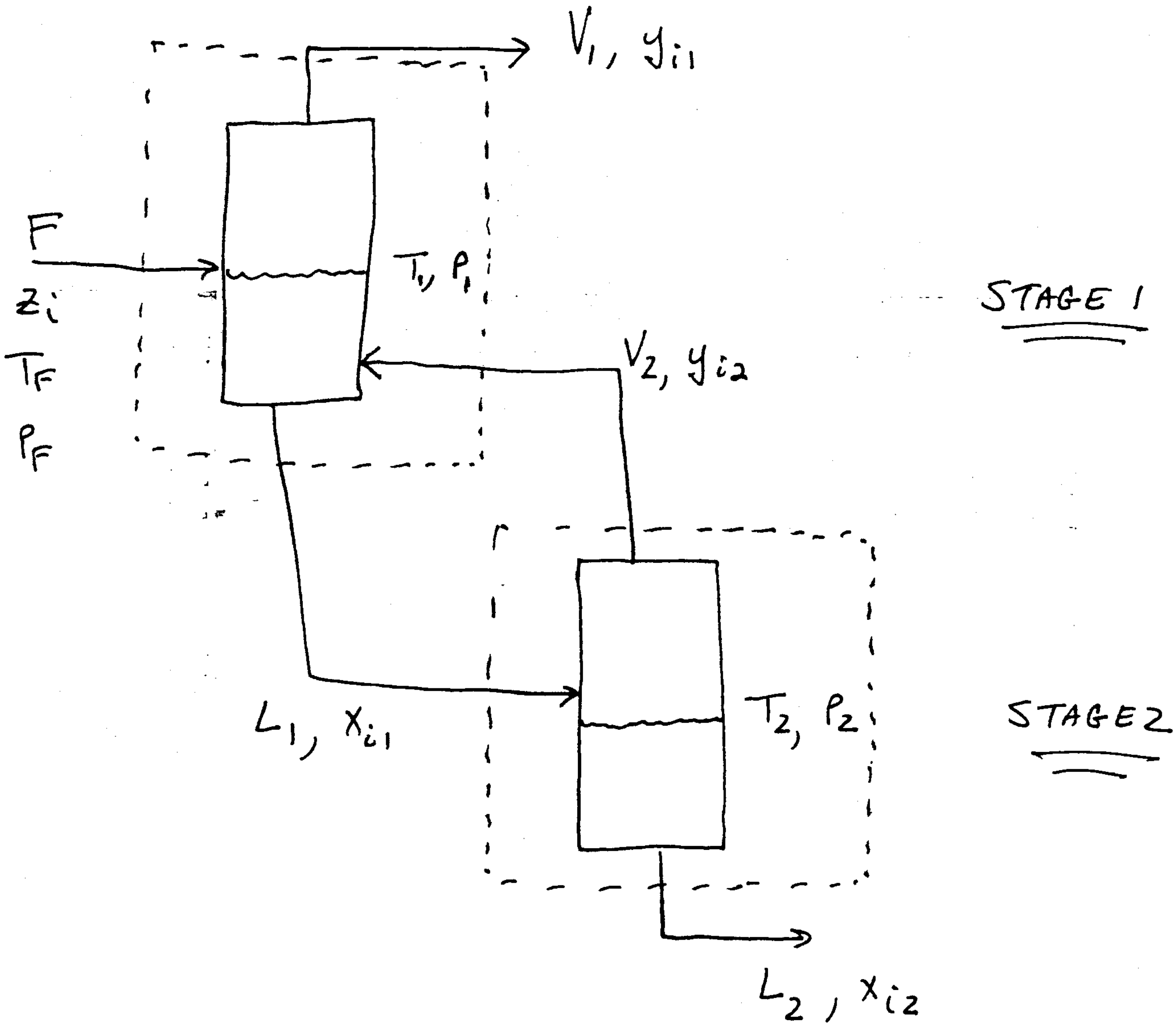
→ Need high α for good Separation.

⇒ Remember:

$\alpha \sim 10{,}000$ for good separation in a single stage.

WHAT WOULD THIS LOOK LIKE AS CASCADE?

⇒ JUST HOOKING TOGETHER MULTIPLE STAGES...



⇒ NOTICE:

STREAMS EXITING A STAGE ARE NAMED BY THAT STAGE.

WHAT CAN WE SAY ABOUT THIS CASCADE?

1) # of stages

2) # of liquid streams

3) # of vapor streams

4) # of feed streams

5) Countercurrent flow

Notice the red dashed boxes on the previous page.

⇒ SINGLE STAGES

→ OVERALL MOLE BALANCES

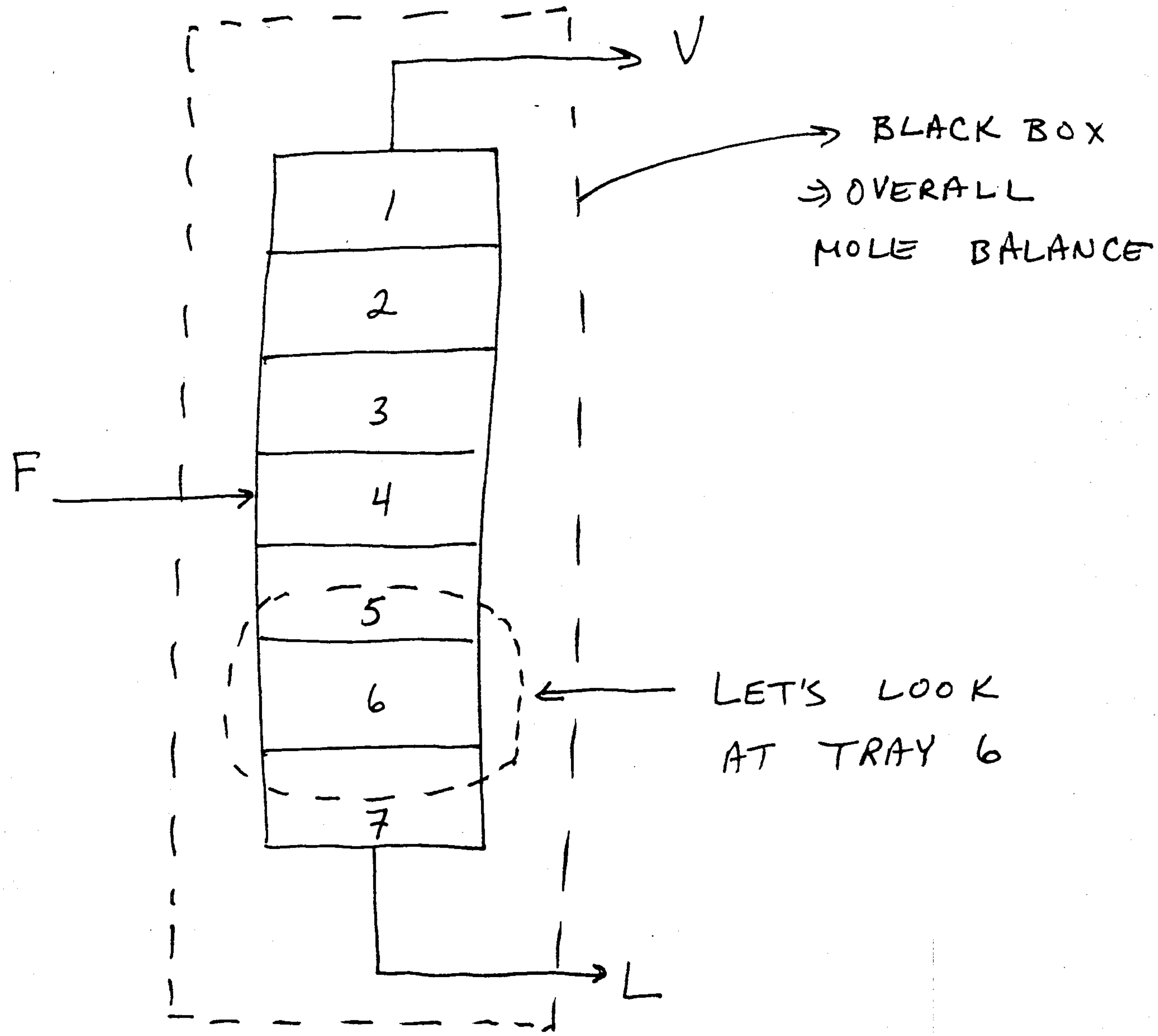
→ COMPONENT MOLE BALANCES

(now on each stage)

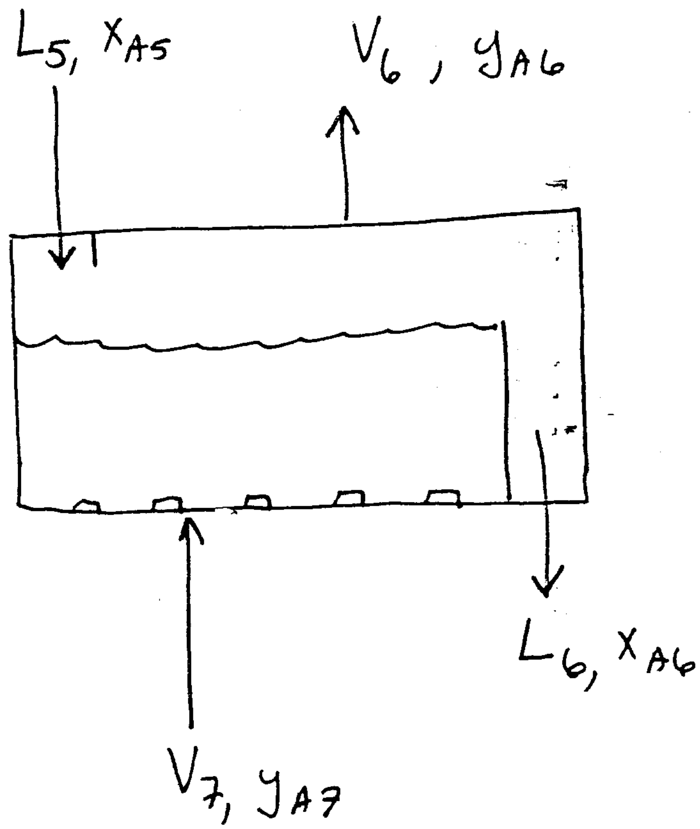
FIGURE 5.2:

WHAT DO DISTILLATION COLUMNS LOOK LIKE?

(OUR SIMPLIFIED VERSION)



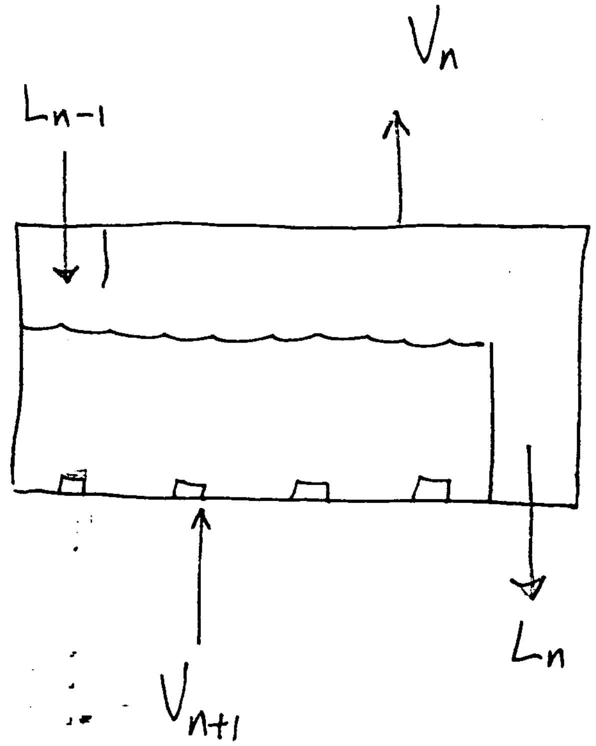
CLOSER LOOK AT TRAY 6

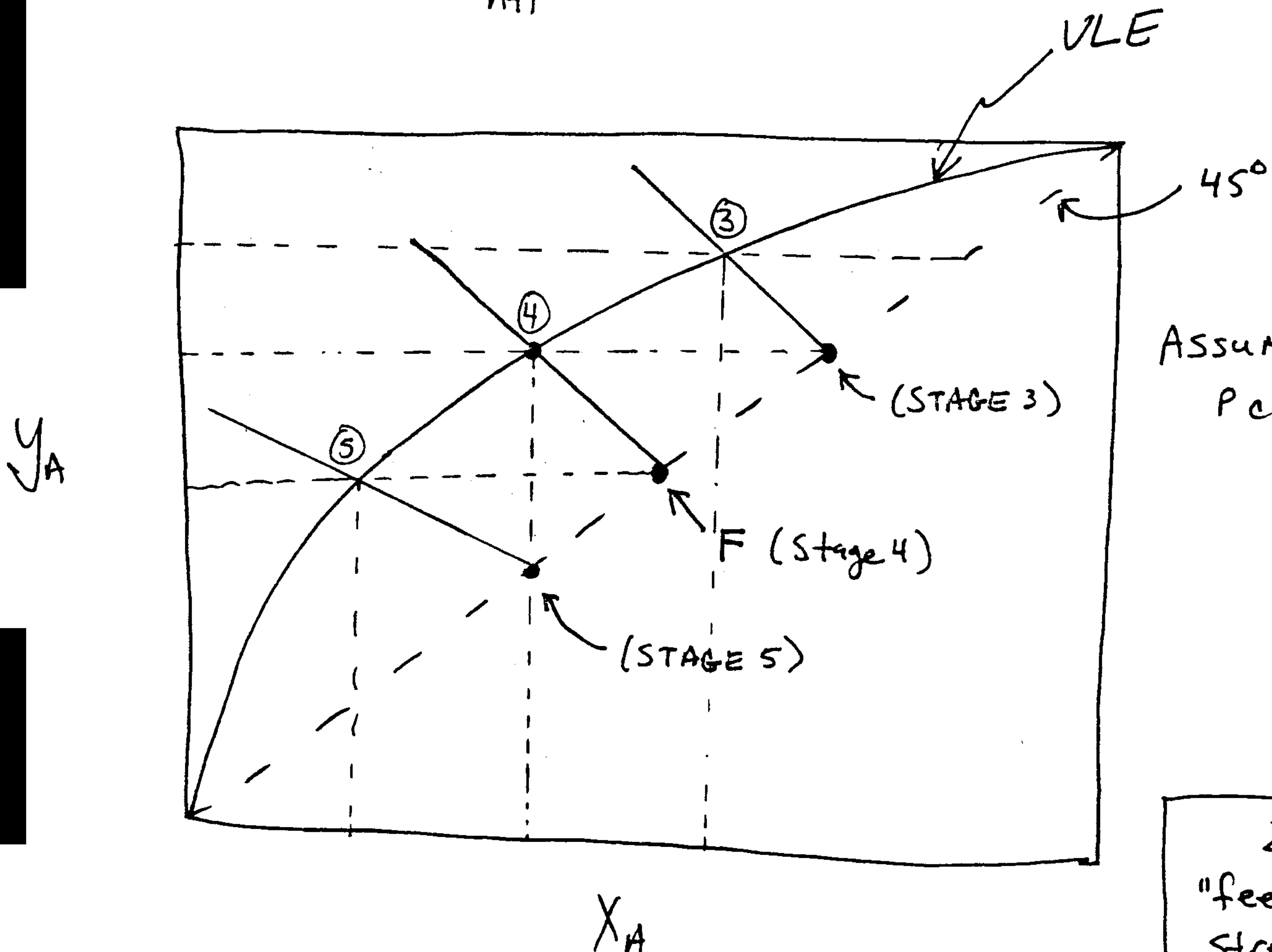


JUST LIKE OUR SINGLE EQUILIBRIUM STAGE.

WHICH STREAMS ARE IN EQUILIBRIUM?

TRAY n





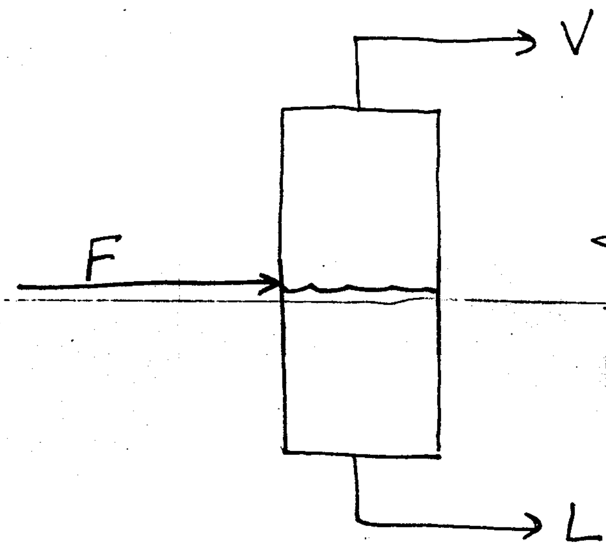
ASSUME
P constant

2
"feed"
streams...

NEXT
TIME

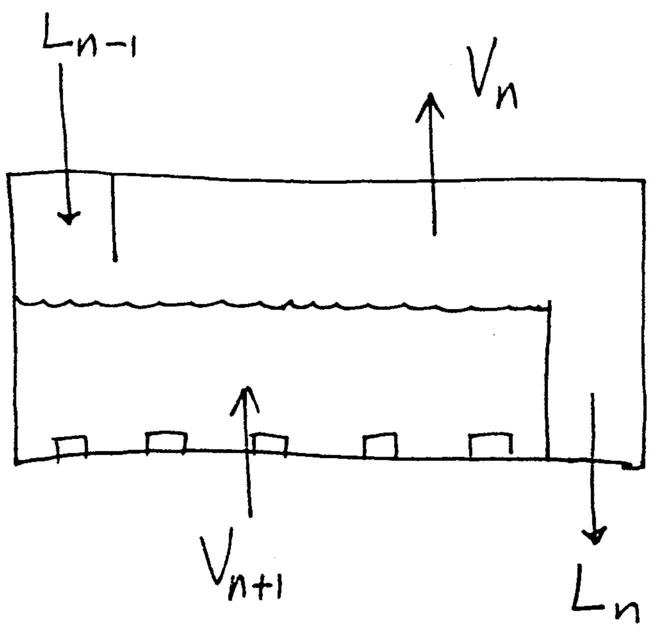
③,④,⑤ are compositions leaving those stages.

MULTIPLE "FEED" STREAMS



SINGLE STAGE FLASH

OUR SINGLE TRAY . . .



TRAY n

⇒ 2 "FEED" STREAMS L_{n-1} , V_{n+1}

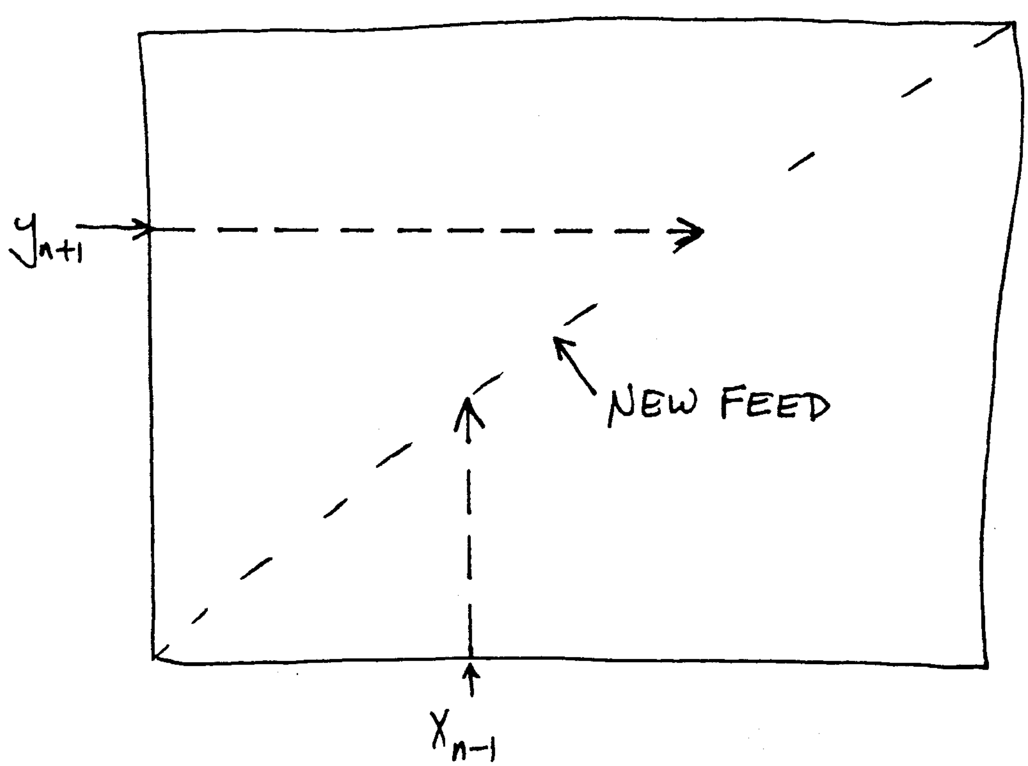
WE CONDENSED V_{n+1} and TREAT THE CONDENSED STREAM AS A SINGLE FEED, F_n, FOR THE SUCCESSIVE FLASH.

L_{n-1} LEFT THE SYSTEM.

RECALL FROM IN CLASS EXERCISE...

THIS LEADS TO LARGE LOSS OF LIGHT KEY.

IN GENERAL, $x_{n-1} < y_{n+1}$



⇒ IF WE ONLY USE CONDENSED V_{n+1} THEN F_n is PURER AND WE START HIGHER ON 45° LINE.

HOWEVER

THIS COMES AT A COST DUE TO LOWER RECOVERY. (⇒ LOST $$)

⇒ IN PRACTICE, L_{n-1} is COMPLETELY RECYCLED TO THE PREVIOUS STAGE/TRAY.

WHICH MEANS

OVERALL F_n is LOWER

BUT

RECOVERY OF ~~[illegible]~~ LIGHT KEY MUCH BETTER.

⇒ DISTILLATION COLUMNS

DESIGN IMPLICATIONS:
(OF STREAM RECYCLE)

→ LARGER HEAT DUTY

Why? ______________________

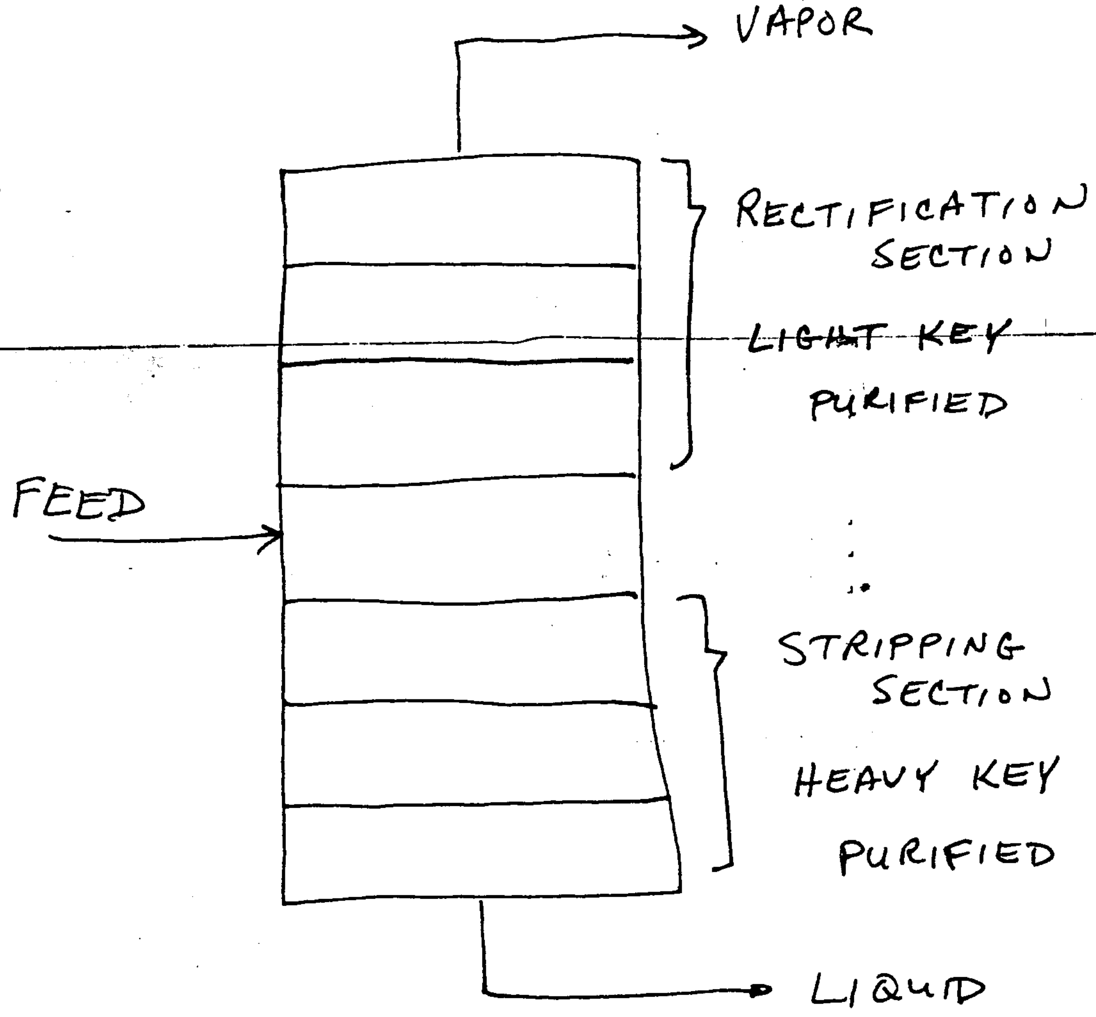
→ LARGER EQUIPMENT

Why? ______________________

→ BETTER RECOVERY

Why? ______________________

RECTIFICATION VS. STRIPPING



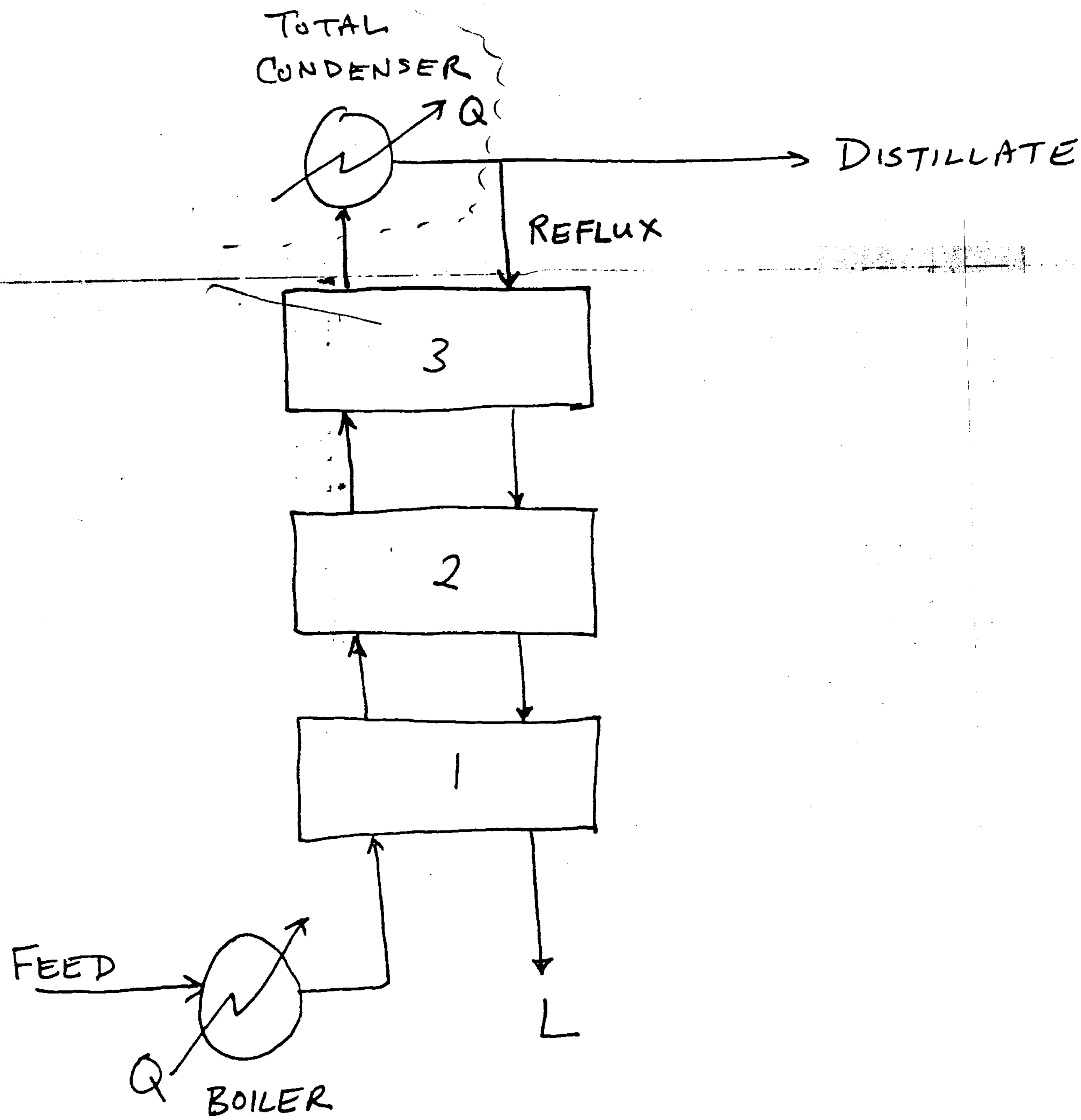
⇒ BREAK INTO 2 COLUMNS

E.G.: EtOH / H_2O — LIGHT KEY : EtOH

Hexane / Octane — LIGHT KEY : HEXANE

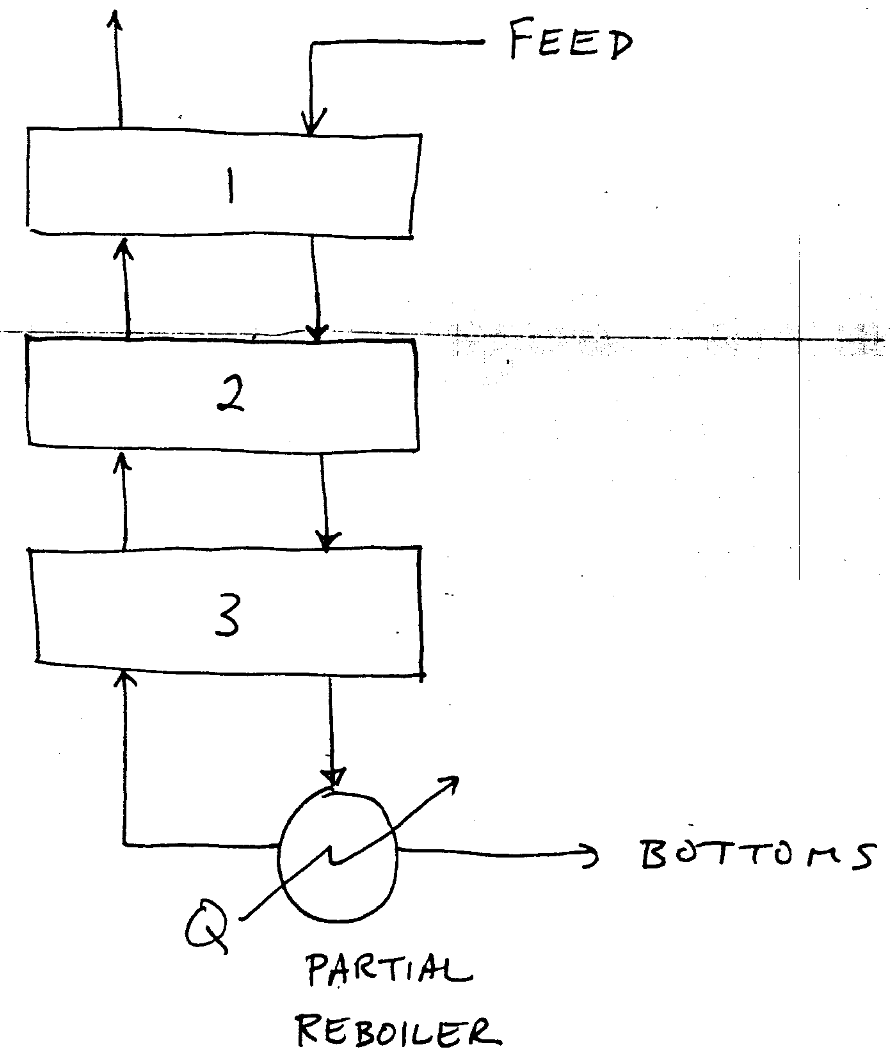
} LOWER B.P. COMPONENT

RECTIFICATION UNIT



- WHAT HAPPENS TO T @ EACH STAGE?
- WHAT ABOUT THE HEAVY KEY CONCENTRATION?

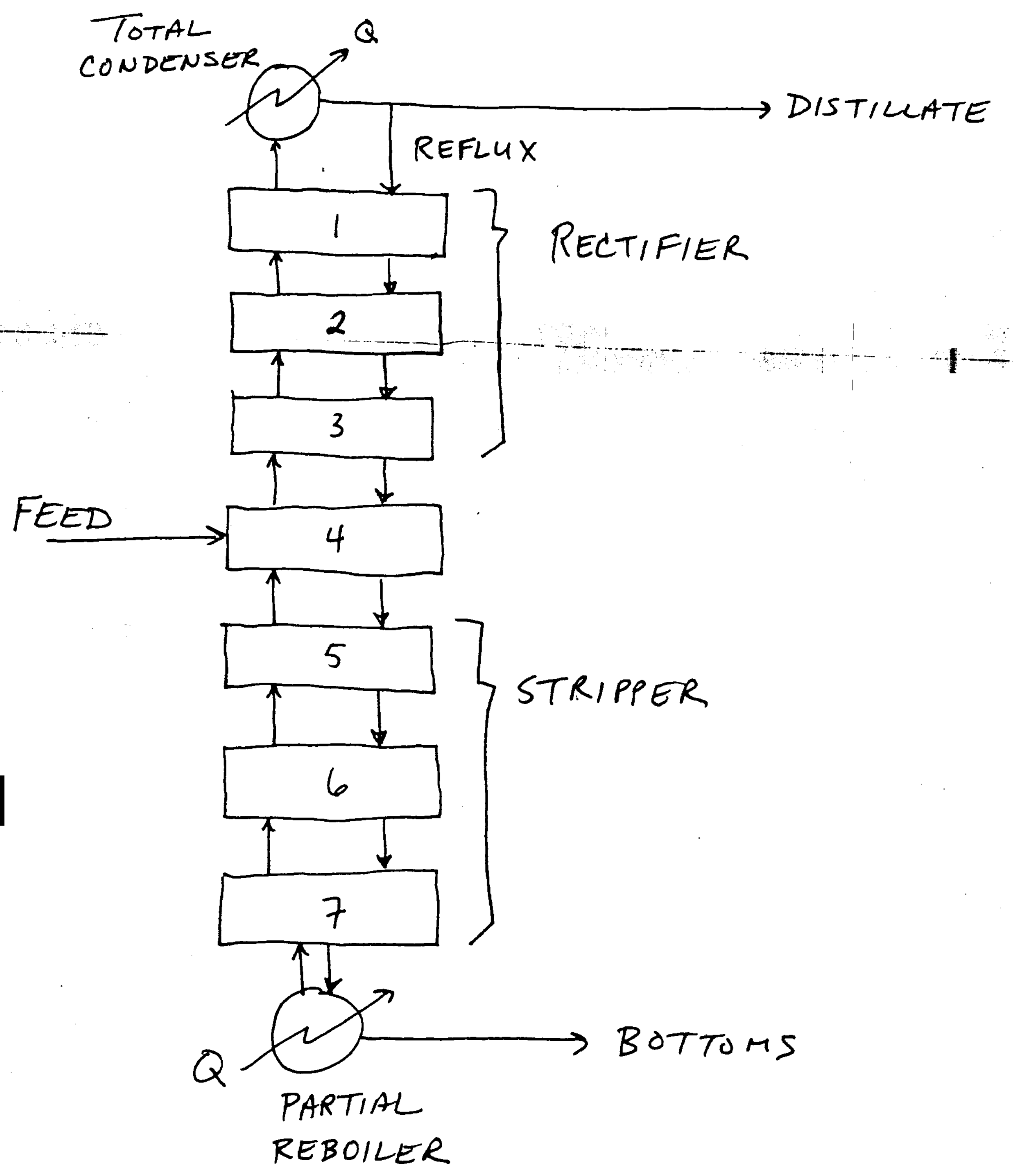
STRIPPING UNIT



- WHAT HAPPENS TO T @ EACH STAGE?
- WHAT ABOUT THE LIGHT KEY COMPONENT?
- WHAT ABOUT GARBAGE?

PUT THESE TOGETHER ...

DISTILLATION COLUMN



USUALLY COUNT REBOILER AS 8th STAGE.

SEADER & HENLEY

5.5 – DEGREES OF FREEDOM IN CASCADES.

Recall: $N_D = N_V - N_E$

$N_D \equiv$ degrees of freedom

$N_V \equiv$ number of variables

$N_E =$ number of equations

WHAT TYPES OF VARIABLES?

→ INTENSIVE
- composition (mole fractions)
- temperature
- pressure

→ EXTENSIVE
- flow rates
- heat transferred

→ EQUIPMENT PARAMETERS
- # of equilibrium stages

WHAT TYPES OF EQUATIONS?

→ Material balances

→ Energy balances

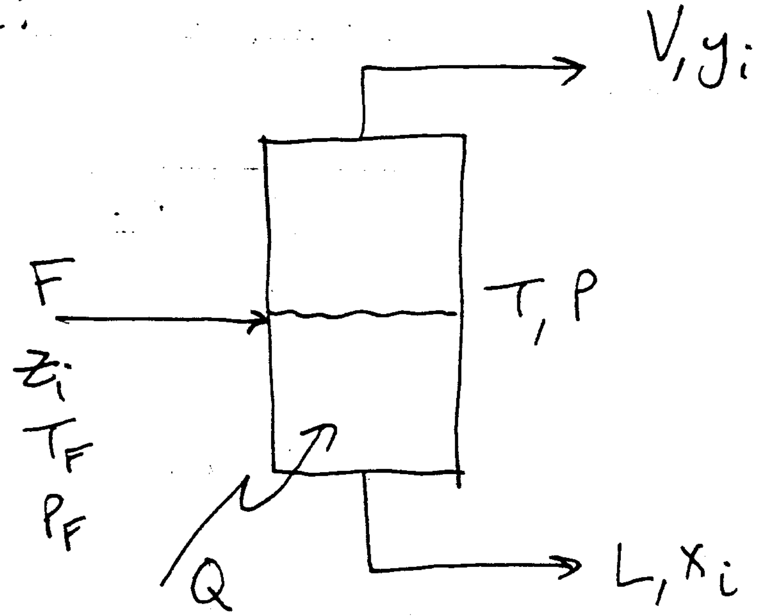
→ Phase equilibria

So...

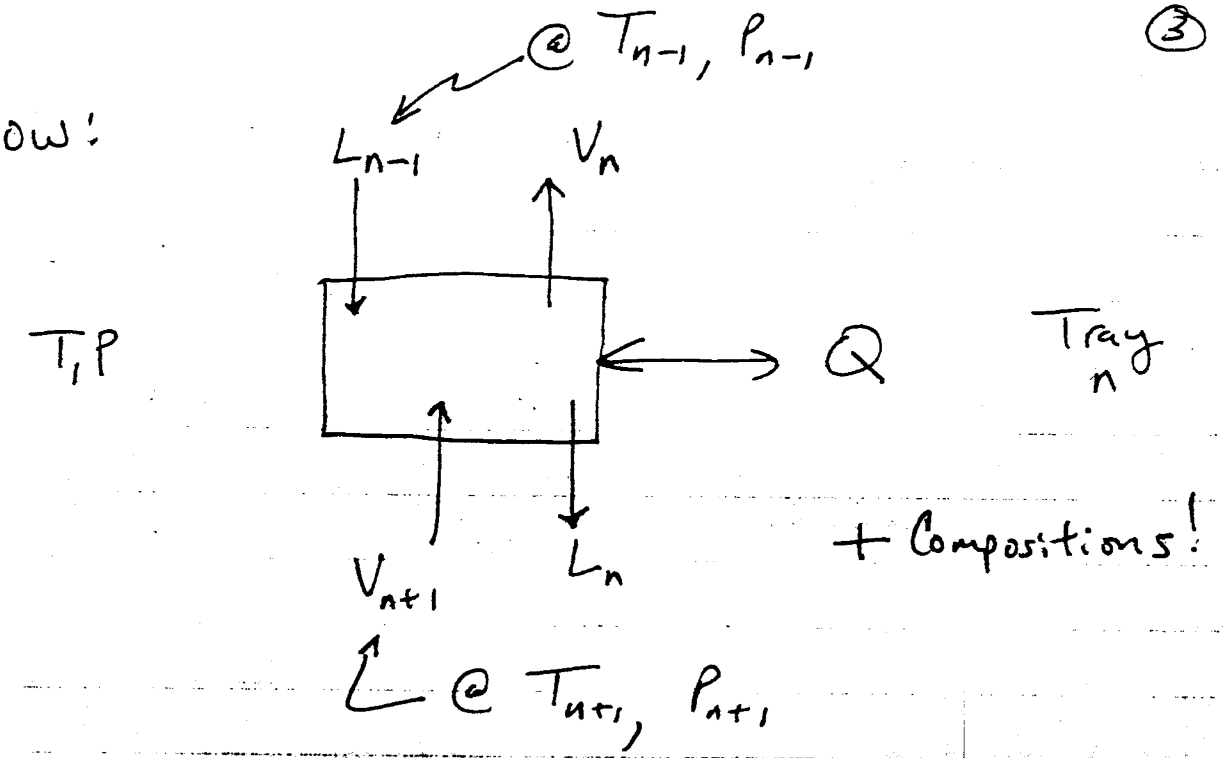
$$N_V - N_E = N_D$$

↑ Need to specify these to set everything else.

Before:



Now:



GET ALL THE SAME EQUATIONS & VARIABLES N TIMES.

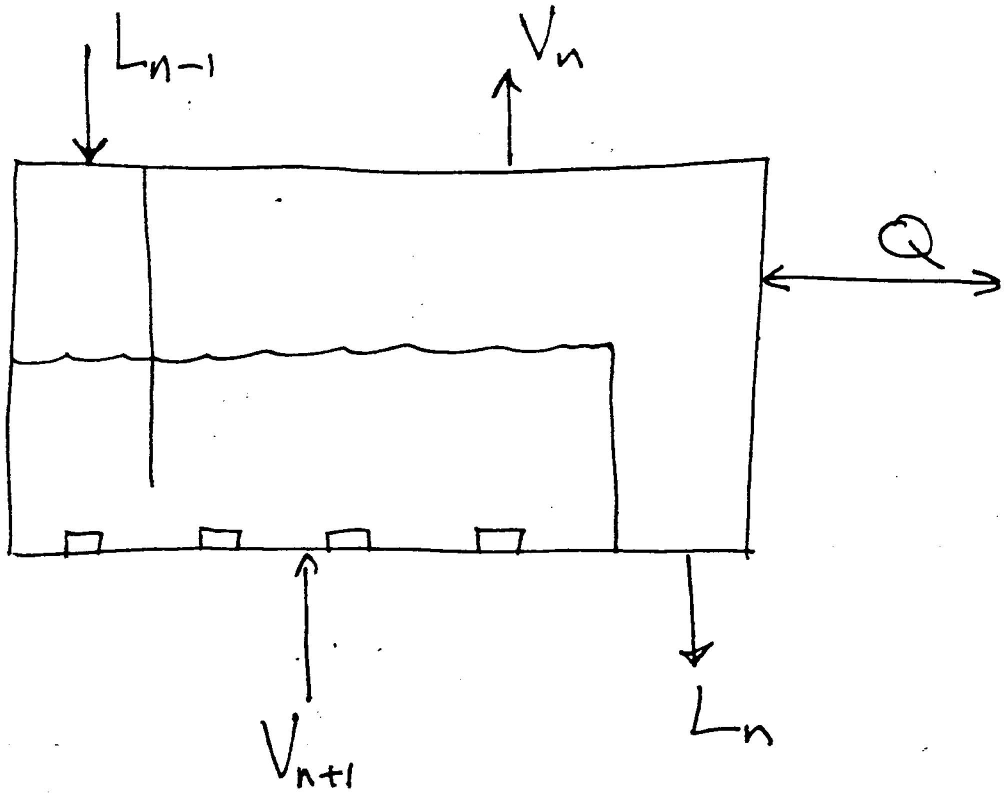
⇒ HUGE PROBLEM ⇒ SIMULATORS

⇒ NEED TO KNOW HOW TO DO BY HAND FIRST SO YOU CAN TROUBLE-SHOOT THE SIMULATOR + EVALATE THE SIMULATOR OUTPUT.

YOUR VALUE AS A CHEMICAL ENGINEER

[redacted]

ADIABATIC OR NONADIABATIC STAGE (@ EQ)



STREAM VARIABLES

$\Rightarrow$ # of Streams?

$\Rightarrow$ $(x_{n-1},\ 1-x_{n-1},\ T_{n-1},\ P_{n-1},\ L_{n-1})$

$\Rightarrow$ $(x_n,\ 1-x_n,\ T_n,\ P_n,\ L_n)$

$\Rightarrow$ $(y_{n+1},\ 1-y_{n+1},\ T_{n+1},\ P_{n+1},\ V_{n+1})$

$\Rightarrow$ $(y_n,\ 1-y_n,\ \boxed{T_n,\ P_n},\ V_n)$

$\Rightarrow$?

$$N_V = 20 + \underset{\uparrow \atop Q}{1} = 21$$

VARIABLES

↑

ON JUST THIS ONE STAGE!

EQUATIONS:

→ Equilibrium restrictions (remember, $L_n + V_n$ in EQ.)

→ Component mole balances

→ Total mole balance

→ Energy balance

→ Mole fraction constraints.

EXAMPLE: BINARY

(1) EQUILIBRIUM RESTRICTIONS

a) THERMAL

$$T_{L_n} = T_{V_n} \qquad (1)$$

b) MECHANICAL

$$P_{L_n} = P_{V_n} \qquad (1)$$

c) PHASE

$$y_n = K_A \, x_n$$

$$(1 - y_n) = K_B (1 - x_n) \qquad (2)$$

(2) COMPINENT MOLE BALANCES

IN = OUT

$$(L_{n-1})(x_{n-1}) + (V_{n+1})(y_{n+1}) = L_n x_n + V_n y_n \quad (1)$$

(3) OVERALL MOLE BALANCE

IN = OUT

$$(L_{n-1}) + (V_{n+1}) = L_n + V_n \quad (1)$$

(4) ENERGY BALANCE

$$Q + (h_{L_{n-1}})(L_{n-1}) + (h_{V_{n+1}})(V_{n+1}) = (h_{L_n})(L_n) + (h_{V_n})(V_n) \quad (1)$$

(5) MOLE FRACTION CONSTRAINTS:

Streams leaving Stage "n"

$$x_n + (1 - x_n) = 1$$

$$y_n + (1 - y_n) = 1$$

(4)

Streams entering Stage "n"

$$x_{n-1} + (1 - x_{n-1}) = 1$$

$$y_{n+1} + (1 - y_{n+1}) = 1$$

$N_E \rightarrow$ (11)

$$N_D = 21 - 11 = 10$$

10 Degrees of freedom for a single EQUILIBRIUM Stage.

(Note duplication in next stage)

SO, WHAT DO WE USUALLY KNOW?

→ Liquid mole fractions entering stage

X_{n-1} $1-X_{n-1}$ (only 1 independent)

→ Total liquid flow rate

L_{n-1}

→ Vapor mole fractions entering stage

y_{n+1} $1-y_{n+1}$ (only 1 independent)

→ Total vapor flow rate

V_{n+1}

→ T+P of entering liquid

→ T+P of entering vapor

→ Stage pressure

→ Heat transfer rate