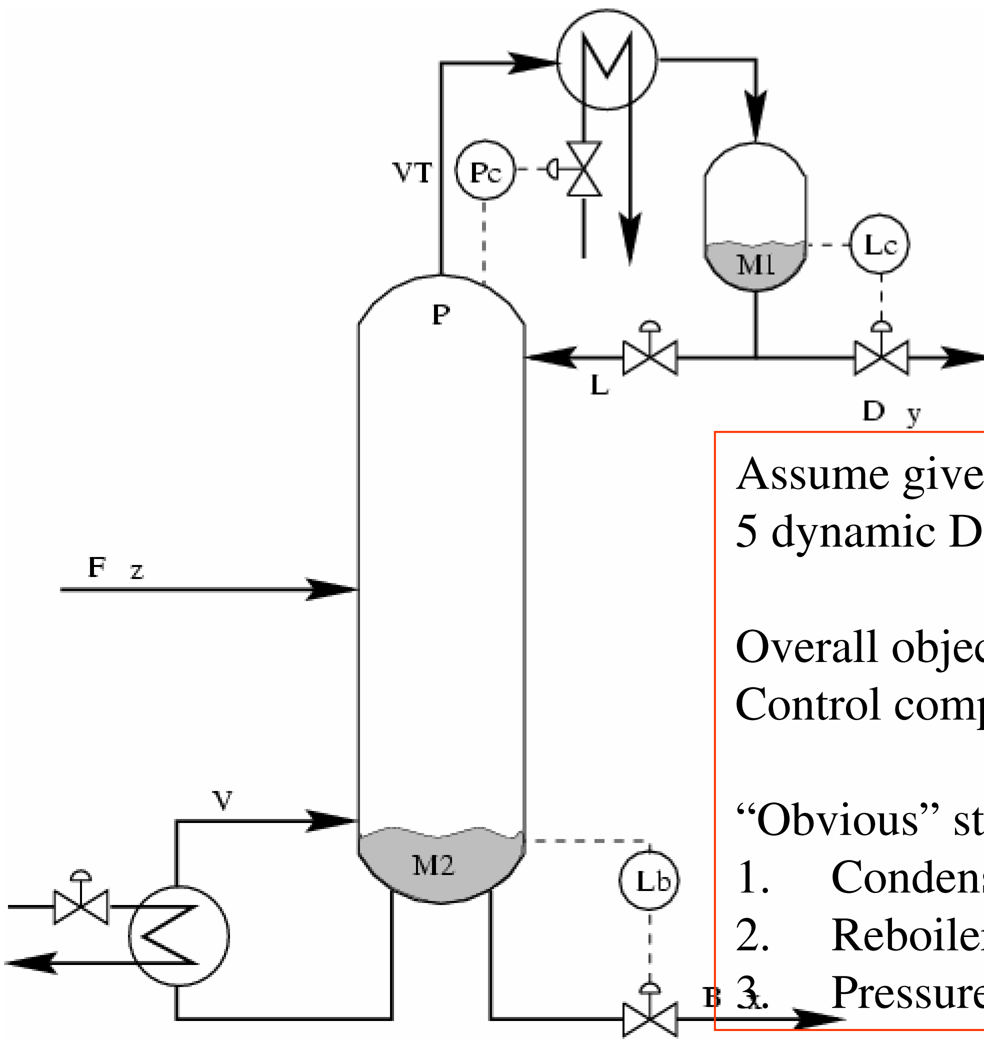
S. Skogestad, 2006

Example regulatory control: Distillation



Assume given feed
5 dynamic DOFs (L,V,D,B,V_T)

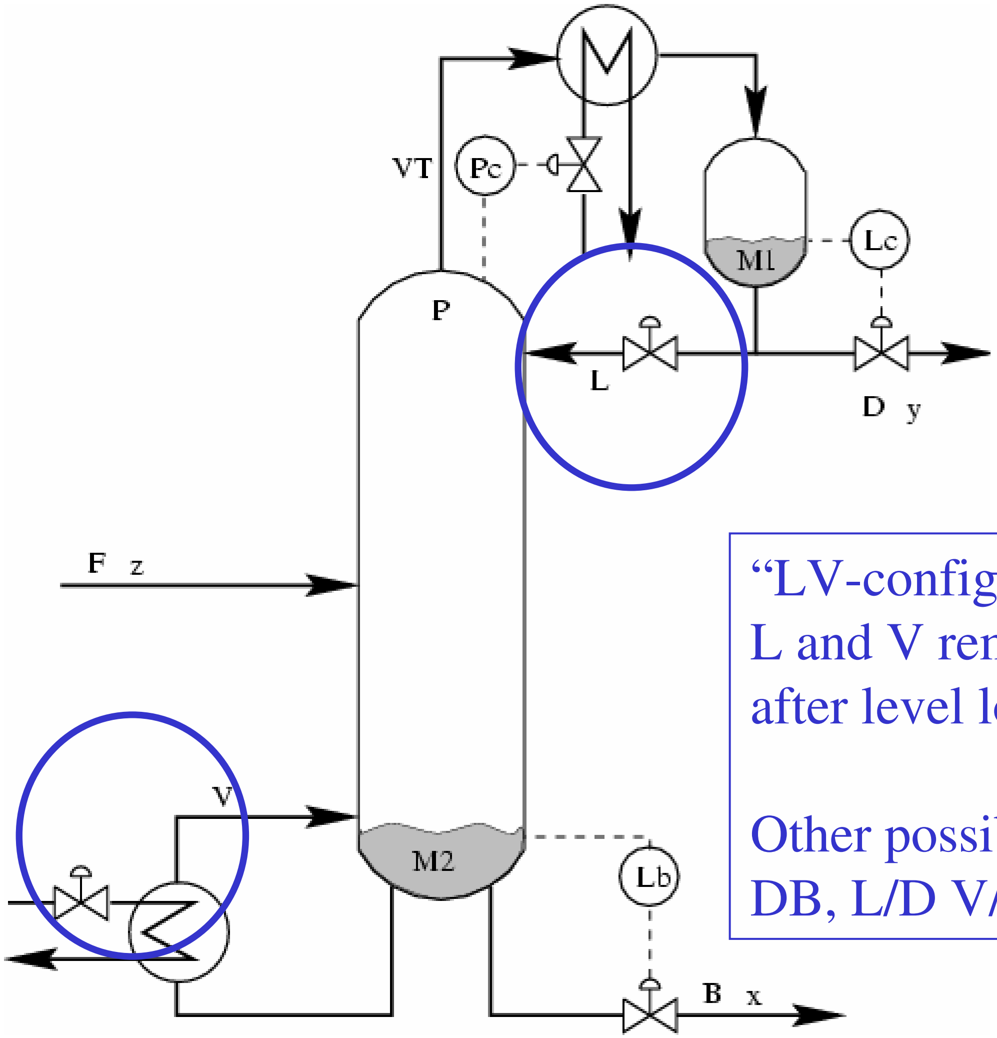
Overall objective:
Control compositions (x_D and x_B)

“Obvious” stabilizing loops:

1. Condenser level (M_1)
2. Reboiler level (M_2)
3. Pressure

E.A. Wolff and S. Skogestad, ``Temperature cascade control of distillation columns'', *Ind.Eng.Chem.Res.*, **35**, 475-484, 1996.

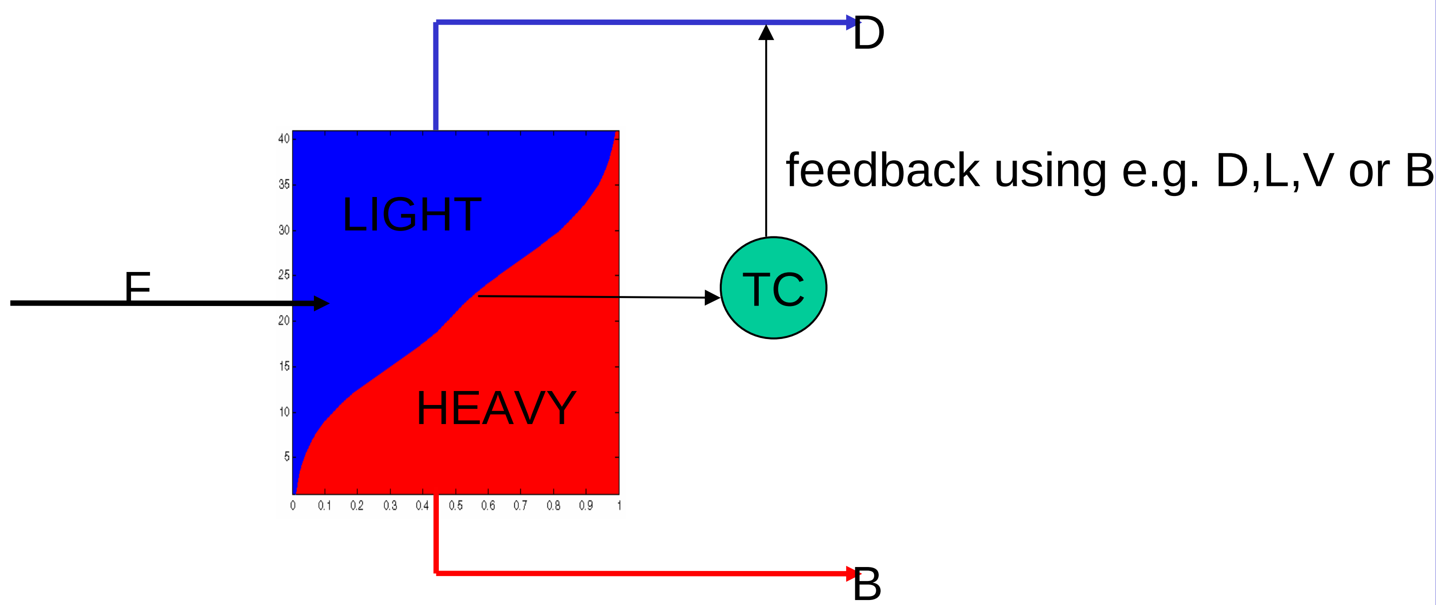
LV-configuration used for levels (most common)



"LV-configuration":
L and V remain as degrees of freedom after level loops are closed

Other possibilities:
DB, L/D V/B, etc….

BUT: To avoid strong sensitivity to disturbances: Temperature profile must also be “stabilized”



Even with the level and pressure loops closed the column is <u>practically unstable</u> - either close to integrating or even truly unstable (e.g. with mass reflux: Jacobsen and Skogestad, 1991)

- To stabilize the column we <u>must</u> use feedback (feedforward will give drift)
- Simplest: “Profile feedback” using sensitive temperature

Stabilizing the column profile

- Should close one “fast” loop (usually temperature) in order to “stabilize” the column profile
  - Makes column behave more linearly
  - Strongly reduces disturbance sensitivity
  - Keeps disturbances within column
  - Reduces the need for level control
  - Makes it possible to have good dual composition control
- P-control usually OK (no integral action)
  - Similar to control of liquid level

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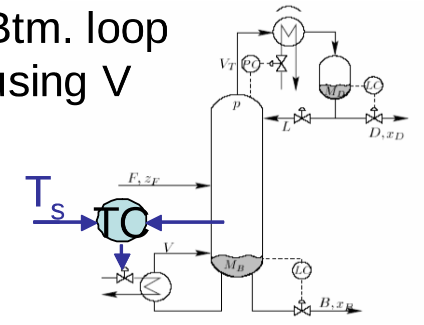
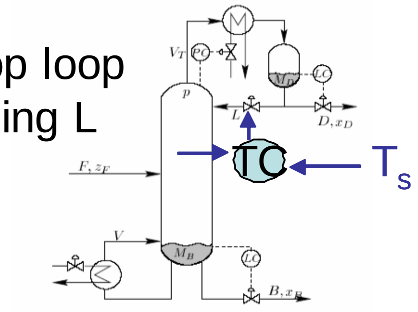
Stabilizing the column profile

- Which fast loop should be closed ("pairing")?
  - Which end? Close loop in end with "most important" product
  - Which output (temperature)? Choose "sensitive" stage
  - Which input (flow)? Want fast control ⇒ "pair close"
    - "Use same end" (reduces interactions for composition control):
      - Use V (or indirect by B) for temperature control in bottom section
      - Use L (or indirect by D) for temperature control in top section
    - Dynamics
      - L: Some delay for liquid to go down the column
      - V: Vapor flow moves quickly up the column, but may take some time before it starts changing (heat transfer dynamics)
    - In general, for stabilizing loops: Avoid using an input (flow) that can saturate

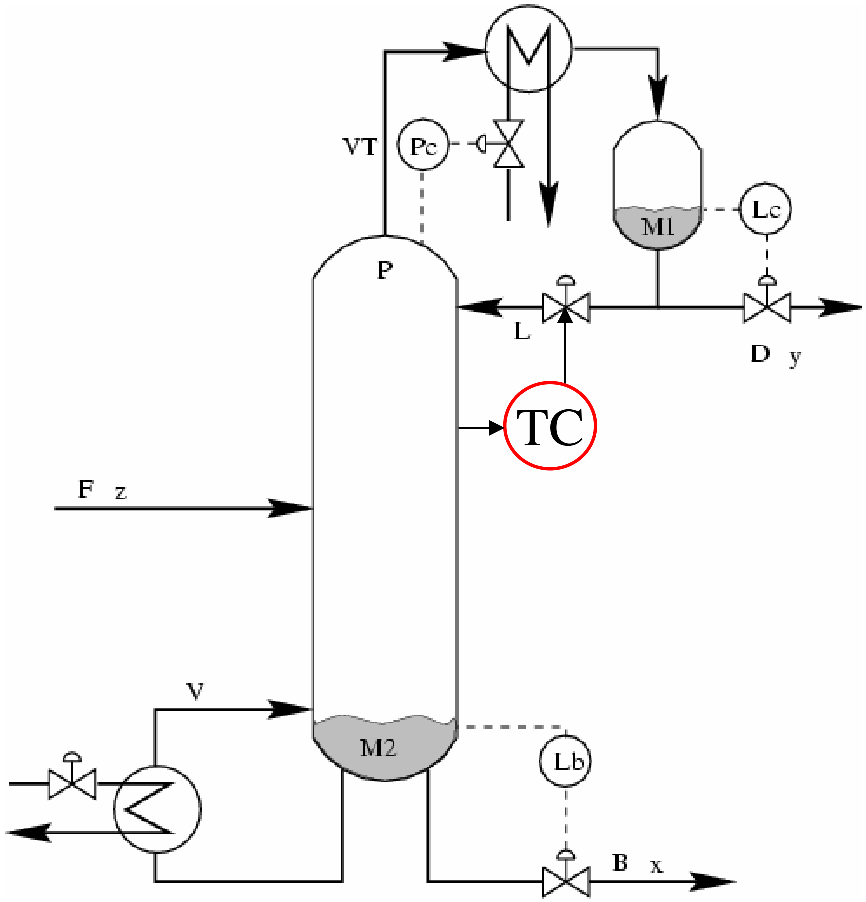
Btm. loop using V



Top loop using L



Temperature control: Which stage?



Example column

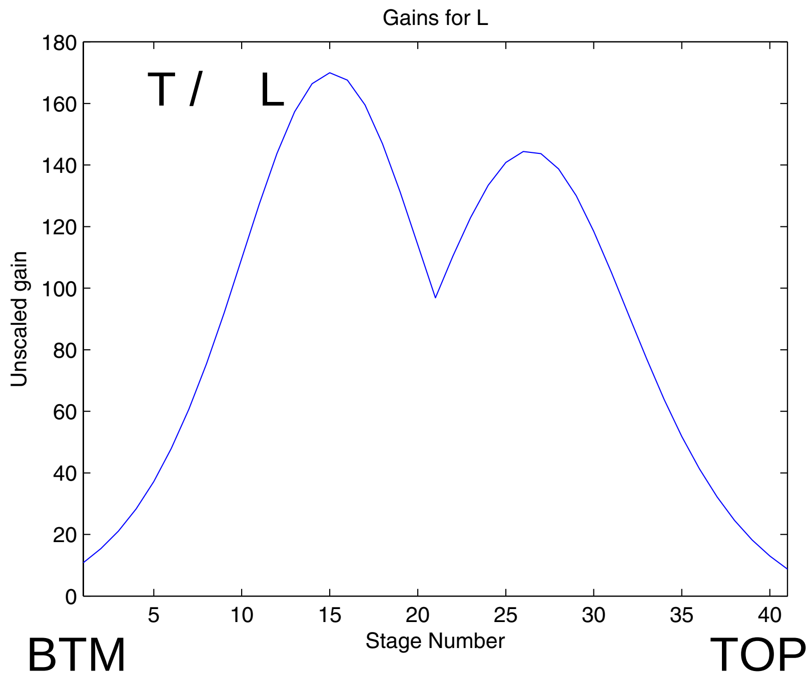
- Example: Ideal 4-component mixture (A,B,C,D) with all relative volatilities = 1.5
  - $\alpha_{AB} = \alpha_{BC} = \alpha_{CD} = 1.5$
- 40 stages and feed in middle of column
- Two cases:
  - Binary: 50% B and 50% C ("column A")
  - Multicomponent: Equimolar feed (25% if each)
- B and C are key components
- Top product: 1% H (C), Bottom product: 1% L (B)

Which temperature?
Rule: Maximize the scaled gain

- Scalar case. Minimum singular value = gain |G|

- Maximize scaled gain: $|G| = |G_0| / \text{span}$
  - $|G_0|$: gain from independent variable (u) to candidate controlled variable (c)
  - span (of c) = variation (of c) = optimal variation in c + control error for c

Binary distillation: Unscaled steady-state gain $G_0 = \Delta T/\Delta L$ for small change in L



Procedure scaling

1. Nominal simulation

2. Unscaled gains (“steady-state sensitivity”)
   - Make small change in input (L) with the other inputs (V) constant.
     Find gain = T_i/ L
   - Do the same for change in V

3. Obtain scalings (“optimal variation for various disturbances”)

   Find $T_{i,opt}$ for the following disturbances

   1. F (from 1 to 1.2) yoptf
   2. z_F from 0.5 to 0.6 yoptz

   “Optimal” may be defined in two different ways

   1. SCALING 1 (normally used). Keep constant x_D and x_B by changing <u>both</u> L and V (disturbance in F has no effect in this case)
   2. SCALING 2 (in some cases). Change only L (or V) and minimize 2-norm of product composition offset

4. Control (implementation) error. Assume=0.5 K on all stages
5. Find

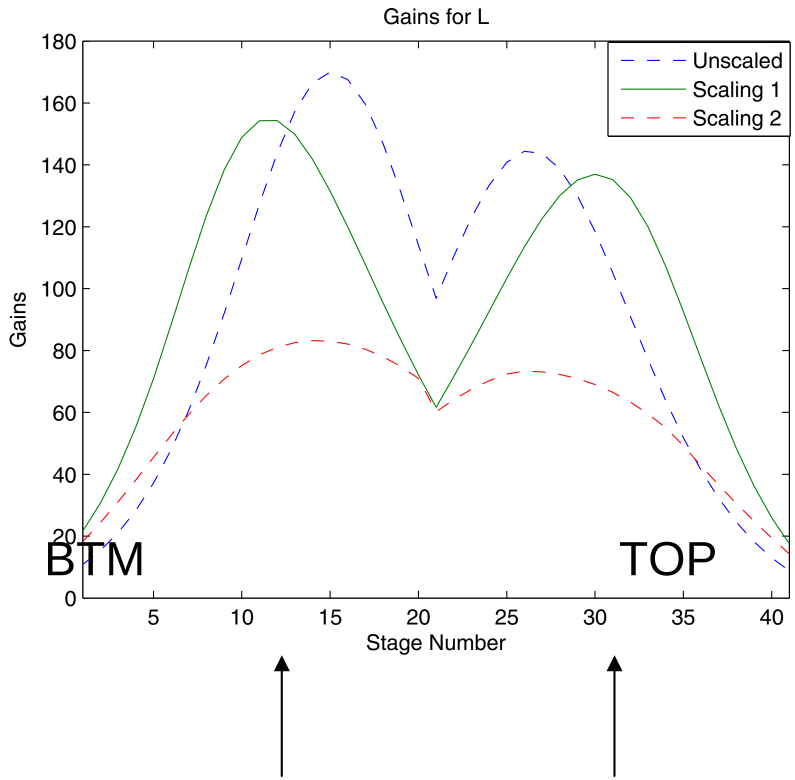
   scaled-gain = gain/span

   where span = abs(yoptf)+abs(yoptz)+0.5

   “Maximize gain rule”: Prefer stage where scaled-gain is large

$$\text{Scaled gain} = \frac{\text{Gain}}{\text{span}} = \frac{\text{(unscaled) Gain}}{\text{noise} + \text{opt.variation}}$$

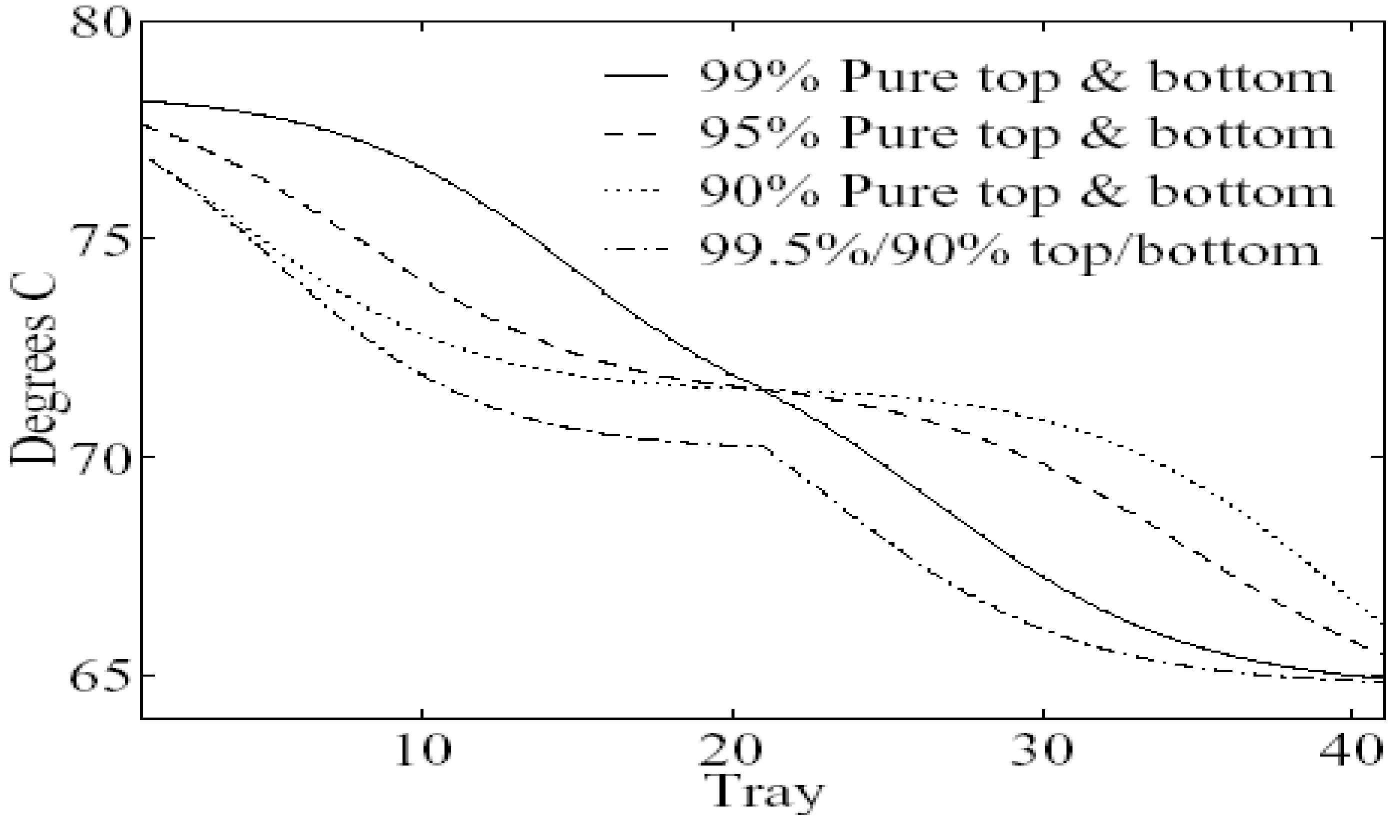
Implementation error used , n = 0.5C



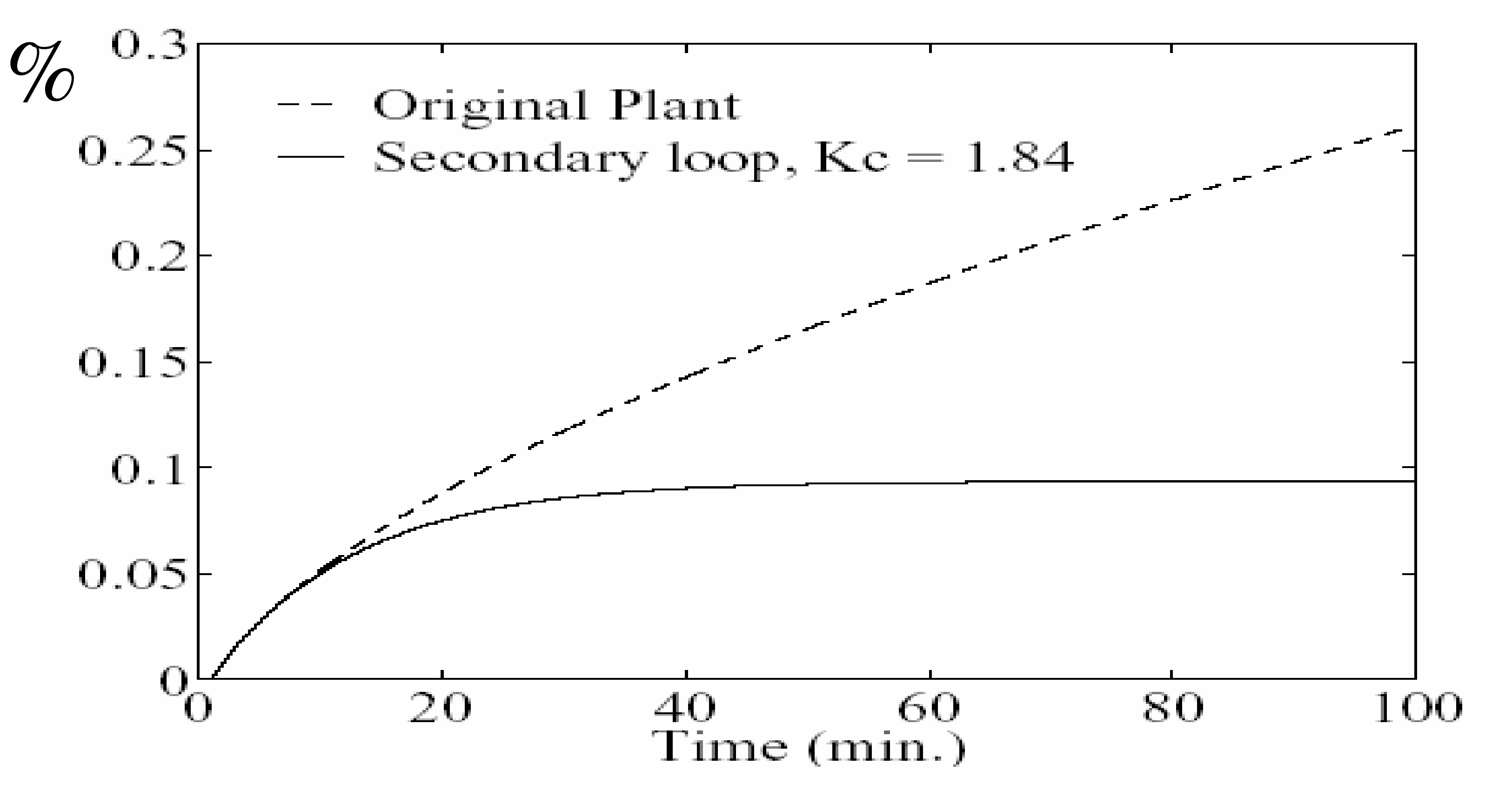
Conclusion:

- Control in middle of section (not at column ends or around feed)
- Scalings not so important here

Maximum gain rule:
Tray 30 is most sensitive (middle top section)

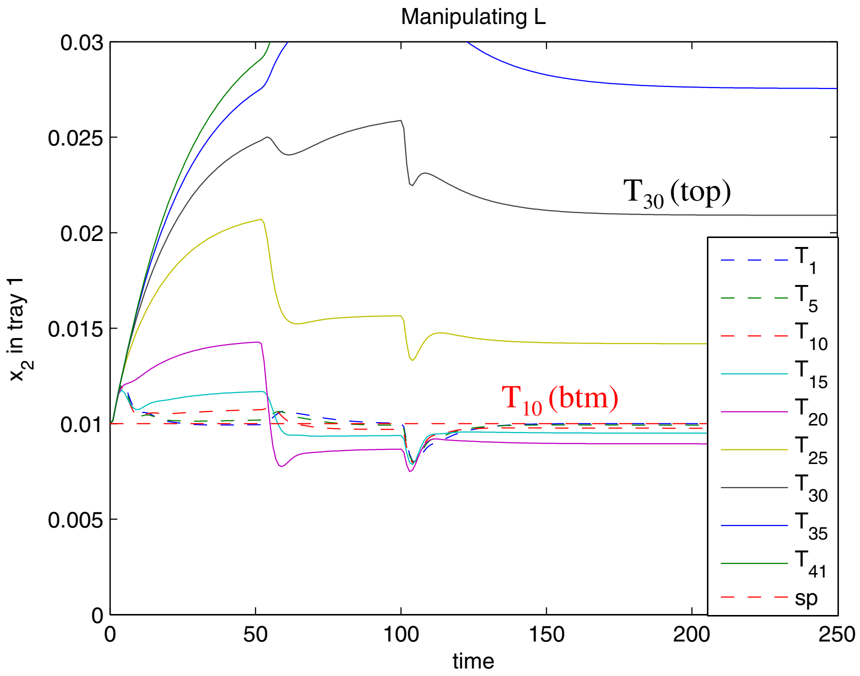


Simulation with temperature loop closed: Response in x_B to 1% feedrate change

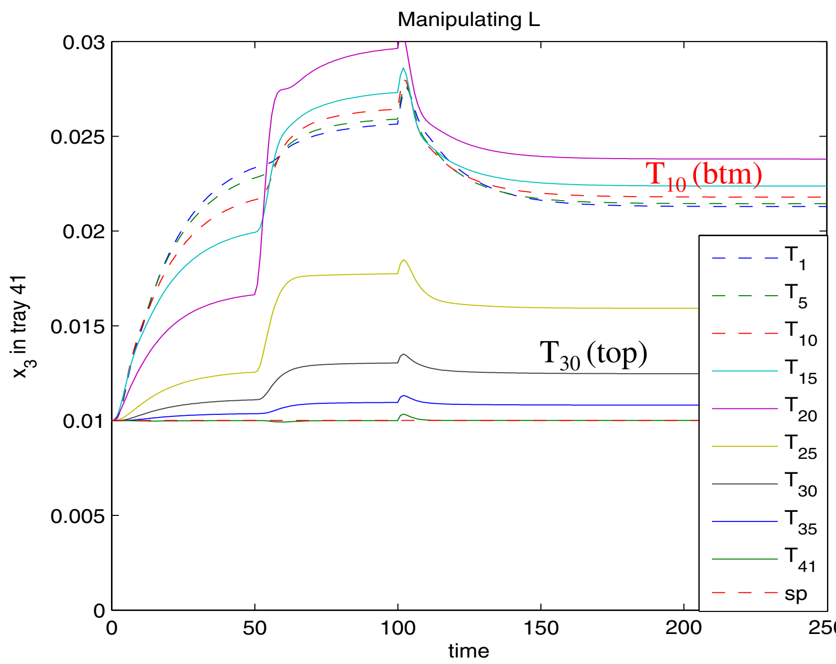


Simulation: Response with temperature loop closed using L (can improve with L/F!)

BTM COMPOSITION ($x_{impurity}$)



TOP COMPOSITION ($x_{impurity}$)



Disturbances:

F changes from 1 to 1.1 at t = 0

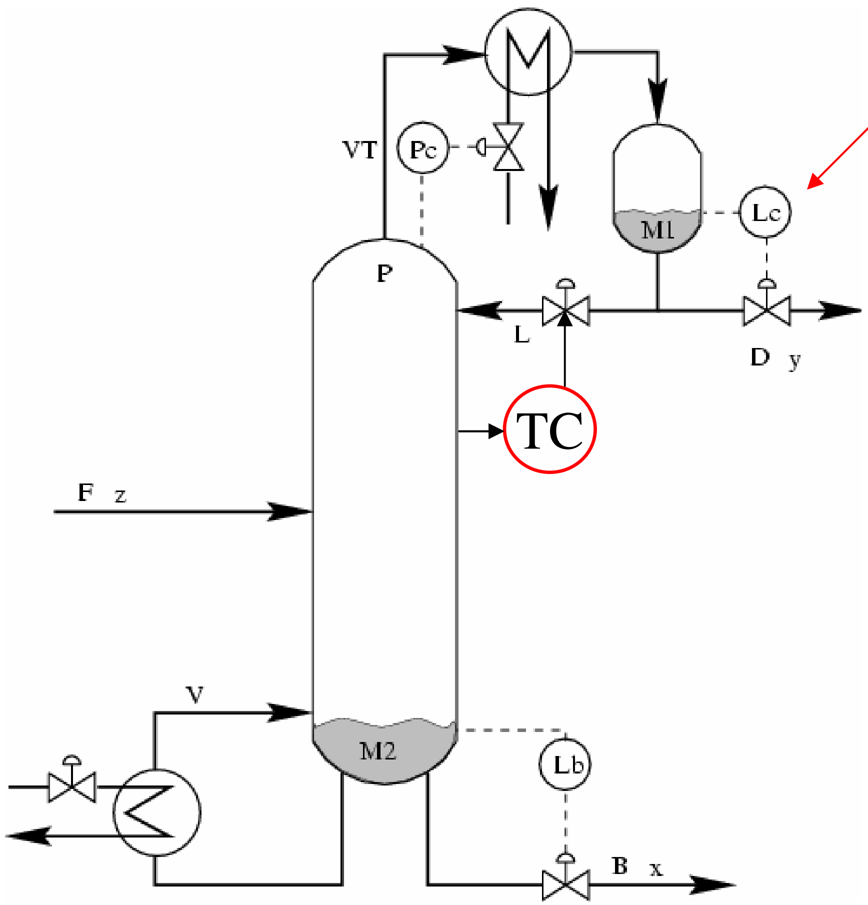
z_F changes from 0.5 to 0.55 at t = 50

q_F changes from 1 to 0.9 at t = 100

Note(as expected!):

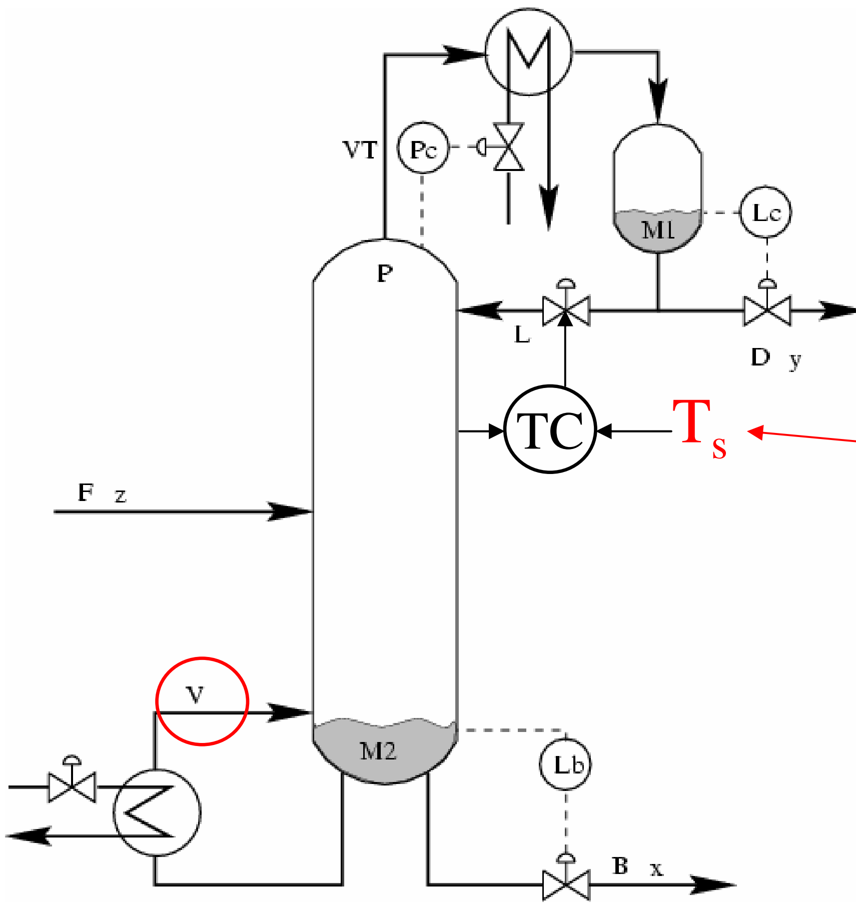
- Temp. meas. in top -> Top comp. OK
- Temp. meas. in btm -> Btm. comp. OK

Bonus 1 of temp. control: Indirect level control



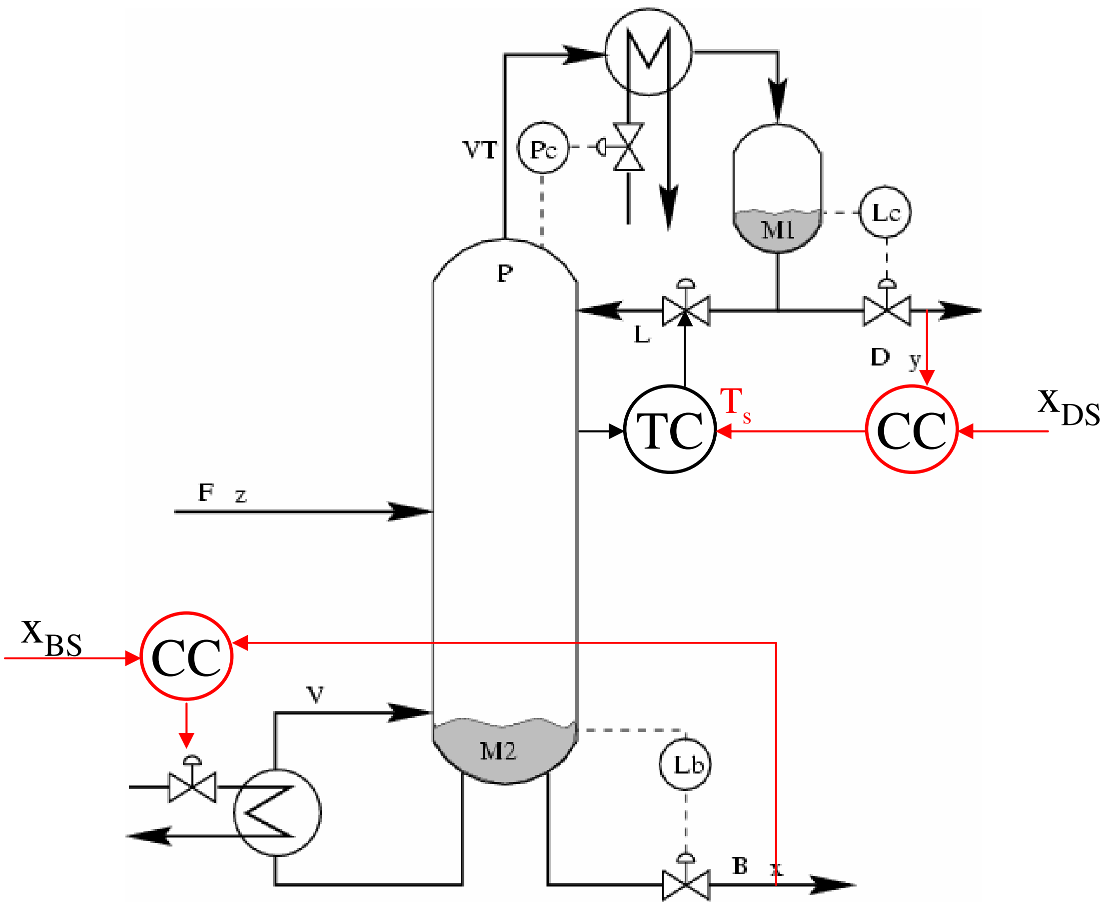
Disturbance in V, q_F:
Detected by TC
and counteracted by L
-> Smaller changes
in D required to keep
M_d constant!

Bonus 2 of temp. control: Less interactive

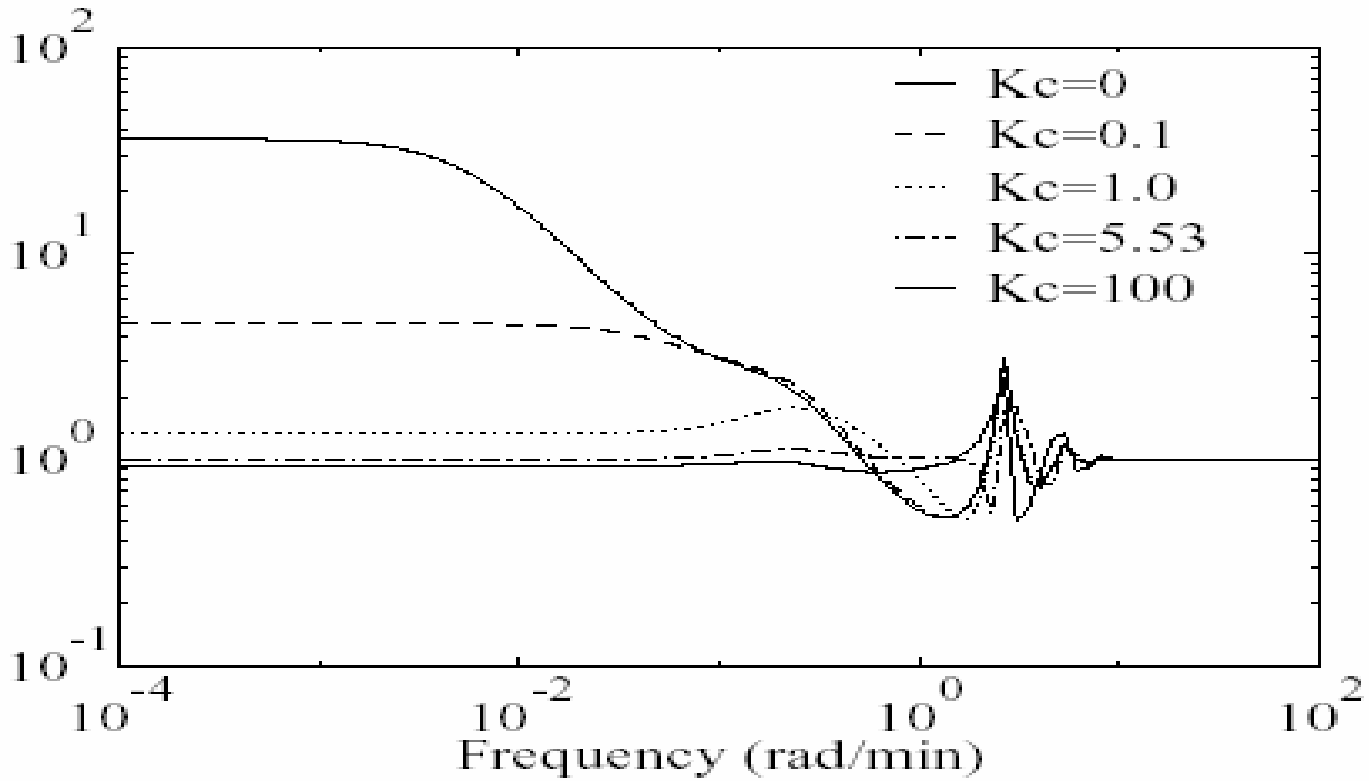


Setpoint T:
New "handle"
instead of L

Bonus 2 of temp. control: Less interactive



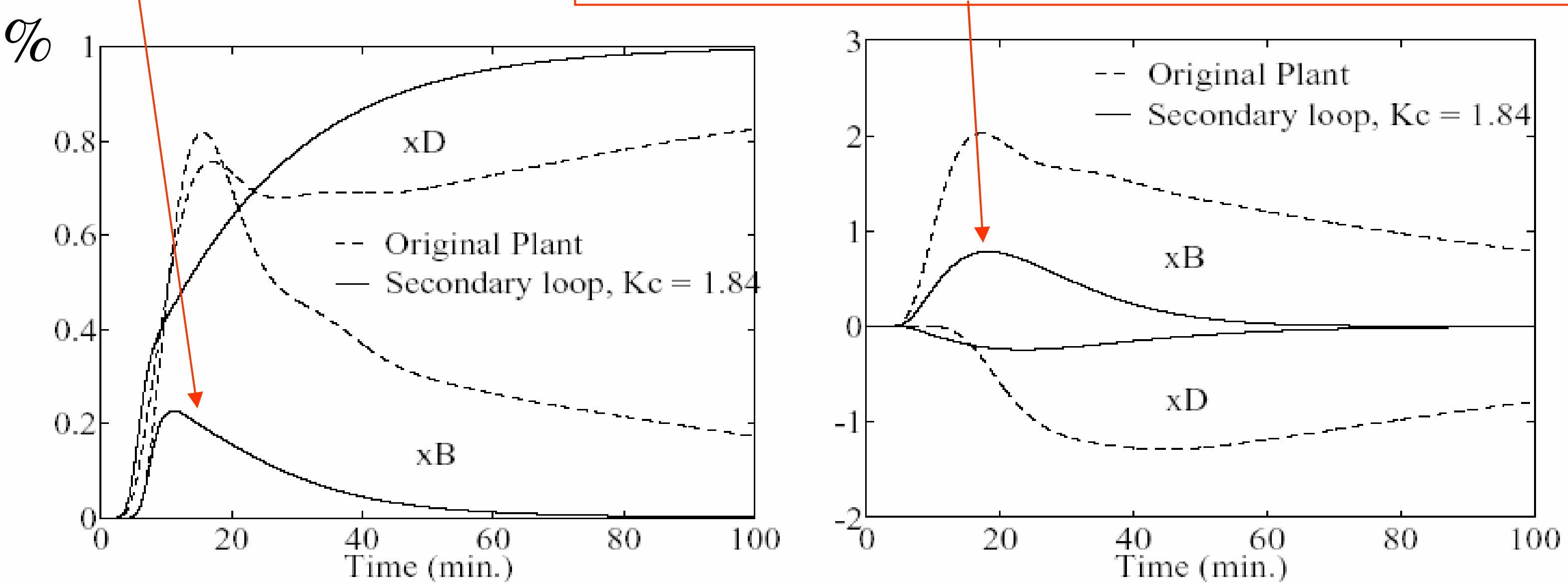
Less interactive:
RGA with temperature loop closed



Less interactive: Closed-loop response with decentralized PID-composition control

Interactions much smaller with "stabilizing" temperature loop closed

… and also disturbance sensitivity is expected smaller



(a) Response to a setpoint change in distillate; $\Delta x_D = 0.01$ (scaled to 1).

(b) Response to a 50% step change in feed rate.

Figure 4.9: Time simulations with composition loops closed.

Integral action in temperature loop has little effect

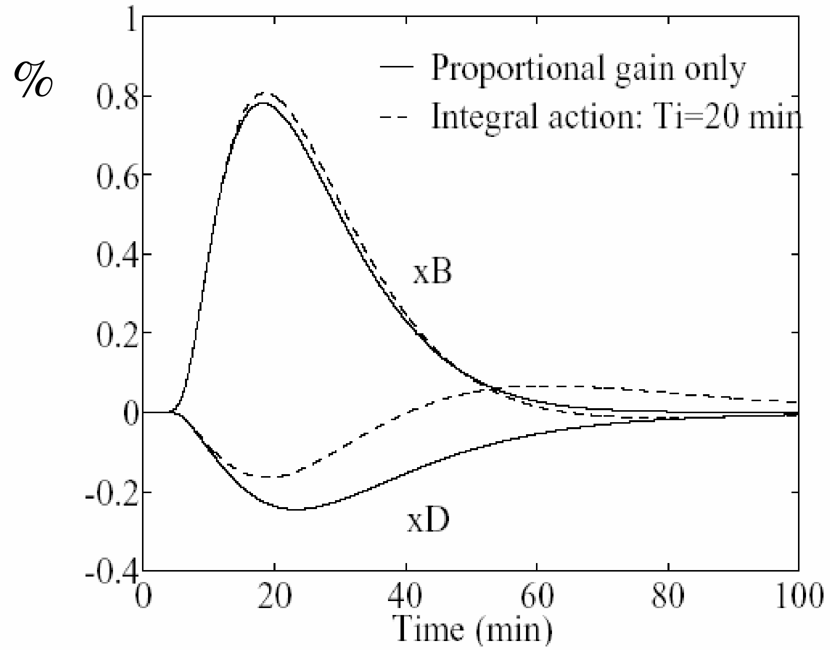
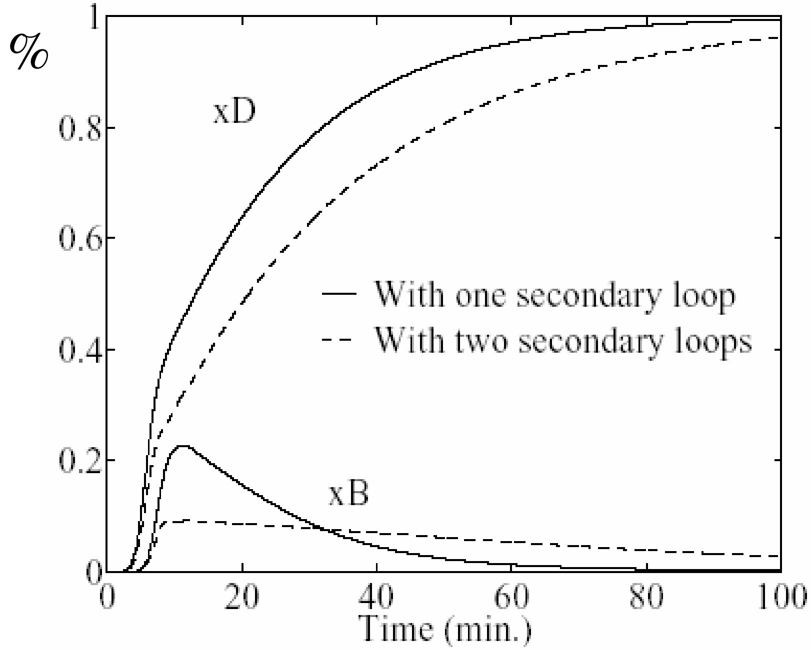
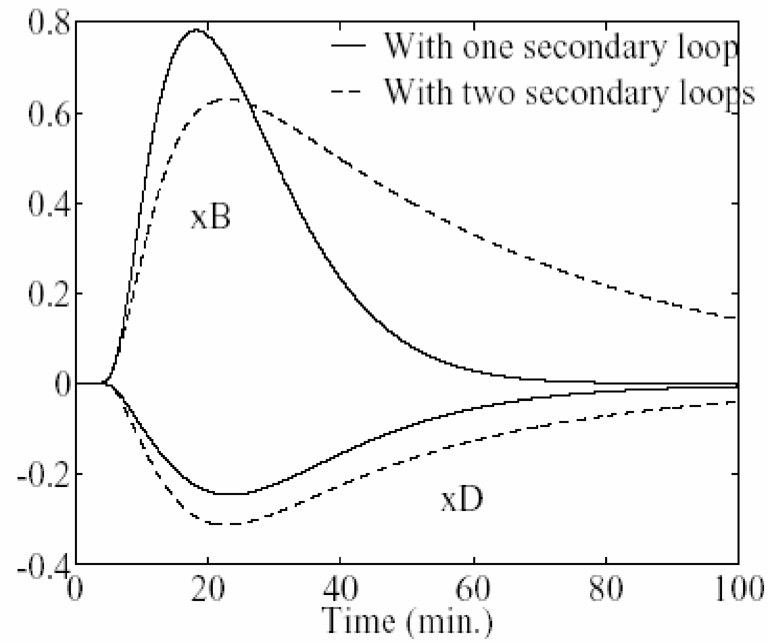


Figure 4.11: Response to a 50% step change in feed rate F with and without integral action in the secondary loop.

No need to close two inner temperature loops



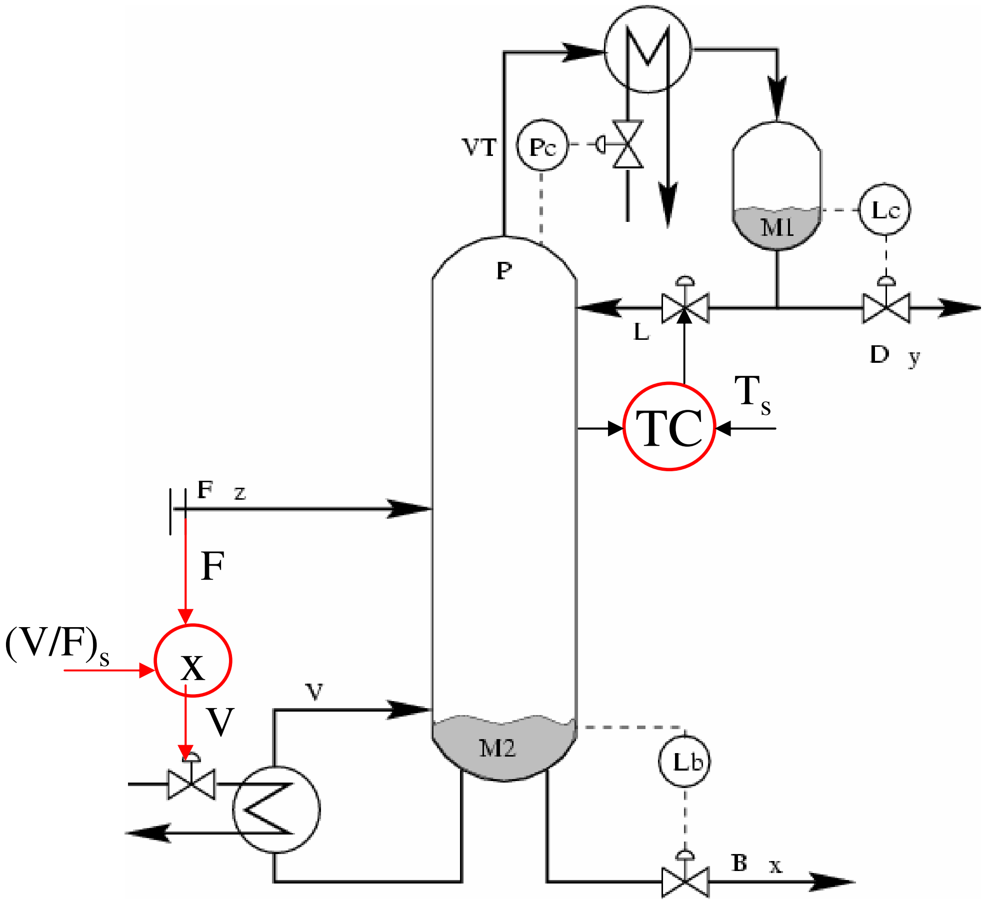
(a) Response to a setpoint change in distillate; $\Delta x_D = 0.01$.



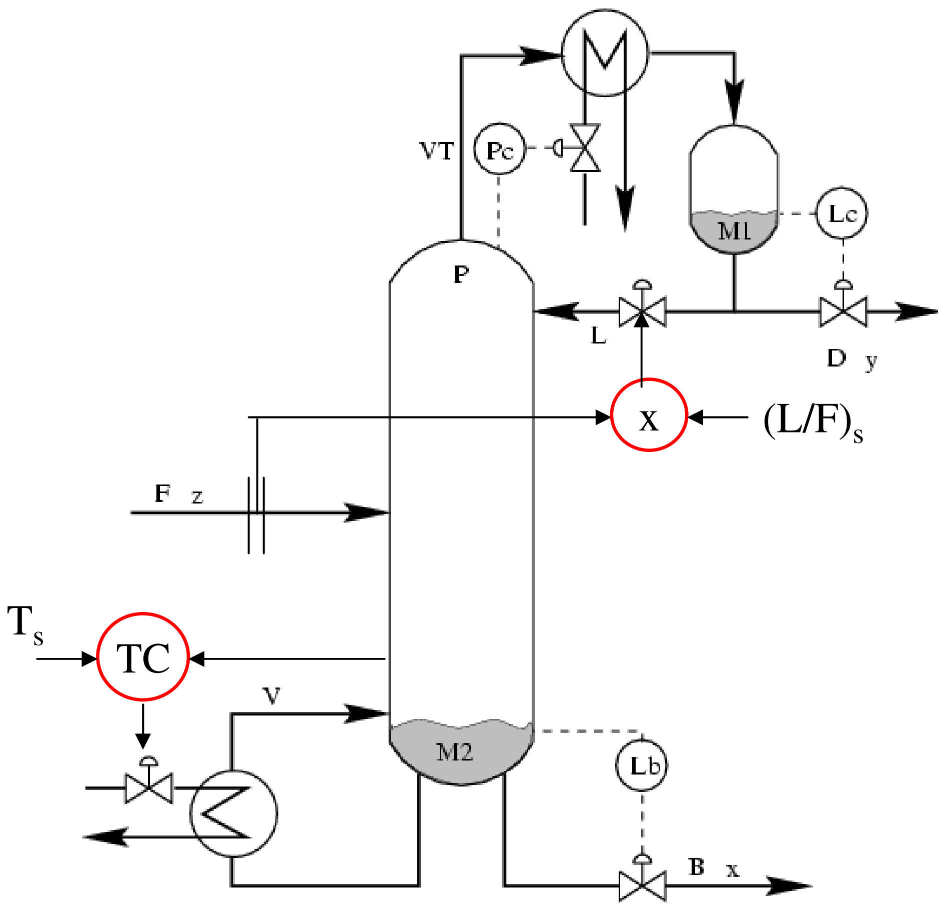
(b) Response to a 50% step change in feed rate.

Would be even better with V/F

Would be even better with V/F:



A “winner”: L/F-T-conguration



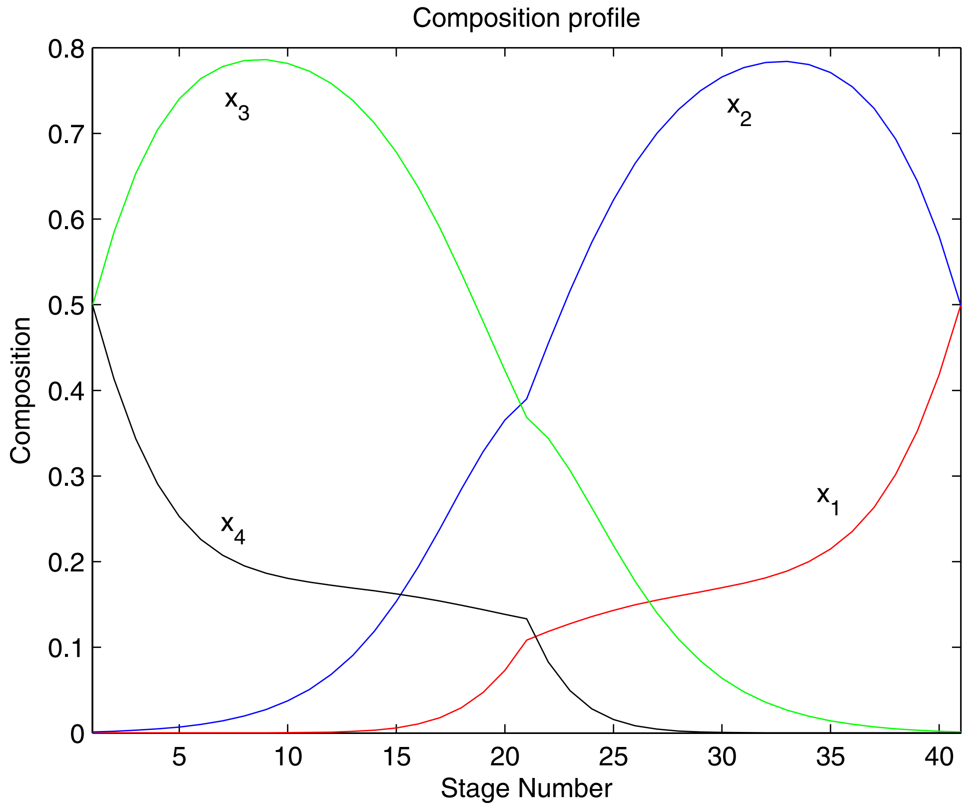
Only caution: V should not saturate

$$J = (x_D - x_{Ds})^2 + (x_B - x_{Bs})^2$$

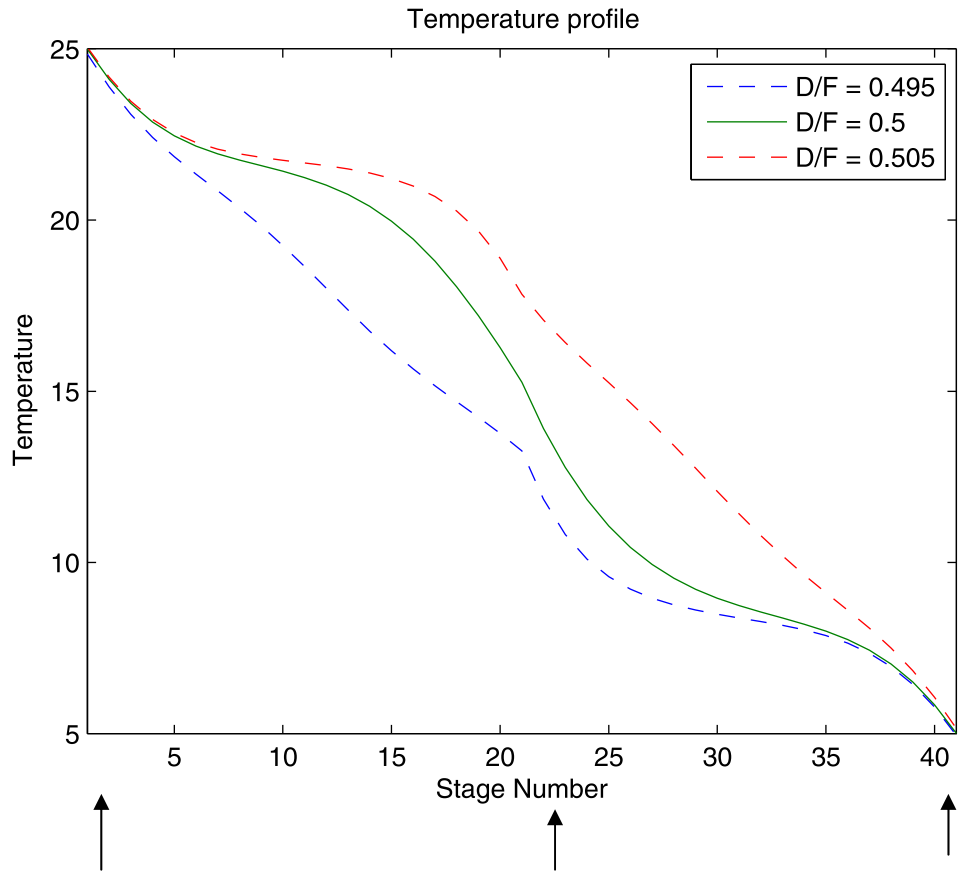
Table 1: Losses of several possible configurations for binary mixture.

Configuration	Exact loss ($x10^{-6}$)	Configuration	Exact loss ($x10^{-6}$)
T_{12} - T_{30}	28	L – B	44300
T_{15} – L/F	83	D – V	45000
T_{16} - V/F	131	L/D – V	53400
T_{19} – L	149	T_{40} – B/F	62800
T_{15} – L/D	174	T_{40} – D/F	62800
T_{22} – V	216	T_{40} –B	89200
T_{24} – V/B	292	T_{40} –D	89200
L/D – V/B	25100	L – V	402200
L/F – V/B	34600	L/F – V/F	810600

Multicomponent: Composition profiles



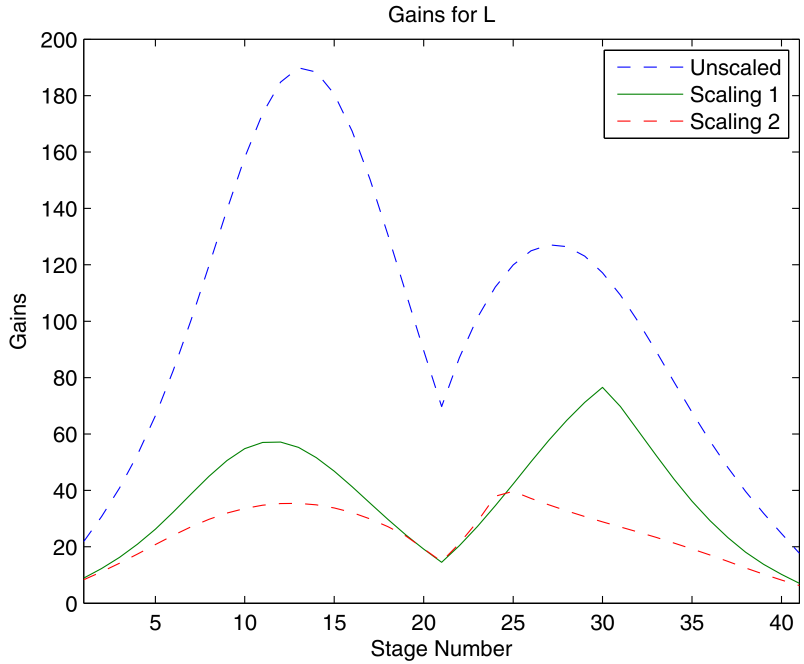
Multicomponent: Temperature profile



Profile steepest in middle and at column ends (!??)

Multicomponent distillation

$$\text{Scaled gain} = \frac{\text{Gain}}{\text{span}} = \frac{\text{(unscaled)Gain}}{\text{noise+opt.variation}}$$



Conclusion: Control temperature in middle of sections

- Almost same as for binary
- Very different from slope of temperature profile (initial response):

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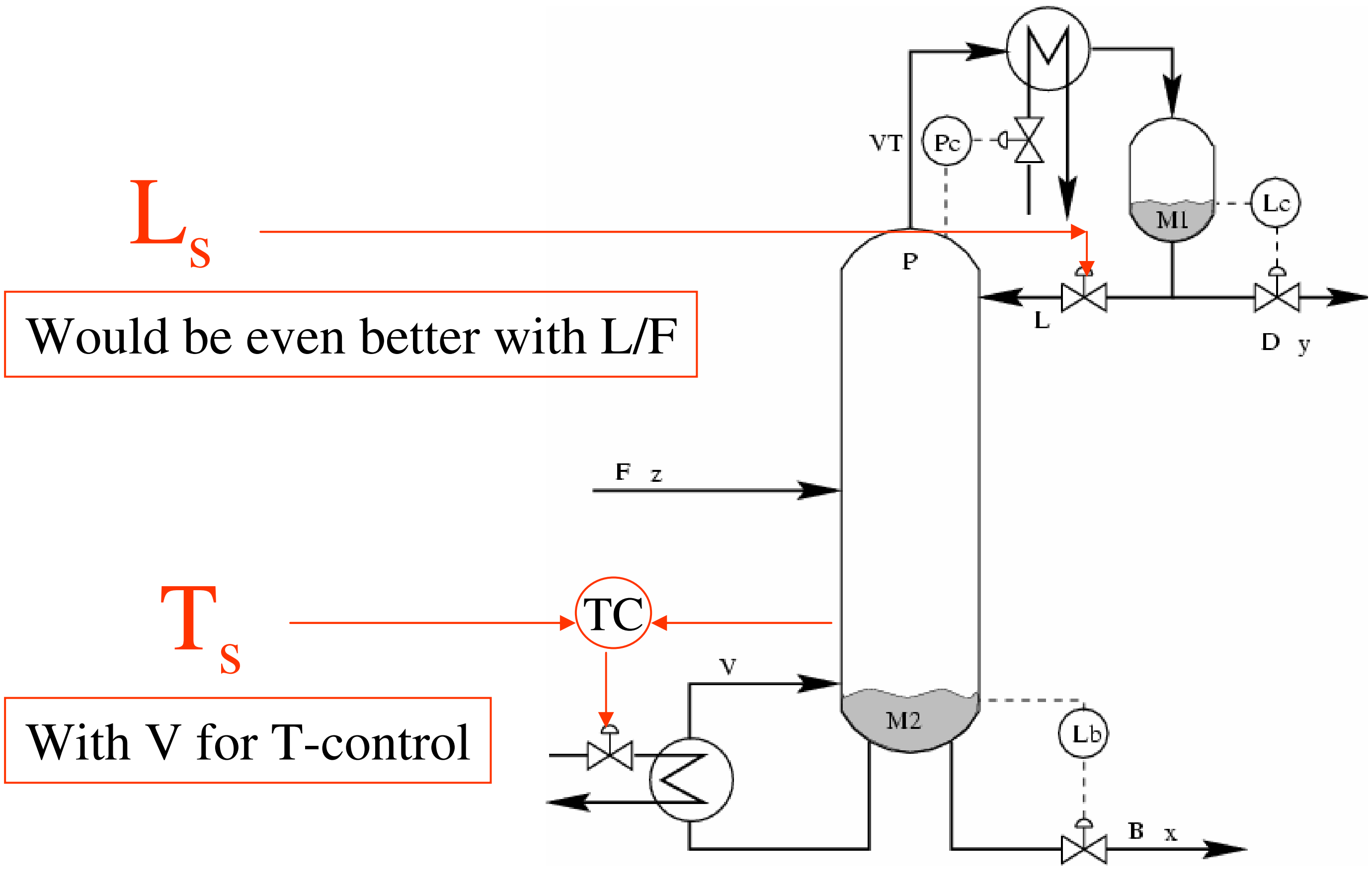
Conclusion: Stabilizing control distillation

- Control problem as seen from layer above becomes much simpler if we control a sensitive temperature inside the column ($y_2 = T$)
- Stabilizing control distillation
  1. Condenser level
  2. Reboiler level
  3. Pressure (sometimes left "floating" for optimality)
  4. Column temperature
- Most common pairing:
  - "LV"-configuration for levels
  - Cooling for pressure
  - (a) L for T-control (if V may saturate; or top composition important)
  - (b) V for T-control (if delay from L to T; or btm composition important)

Conclusion stabilizing control: Remaining supervisory control problem



+ may adjust setpoints for p, M_1 and M_2 (MPC)