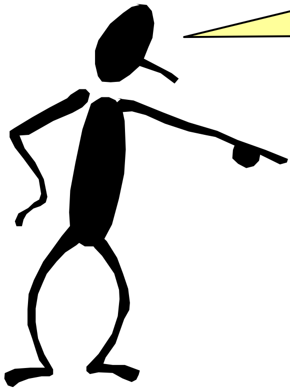
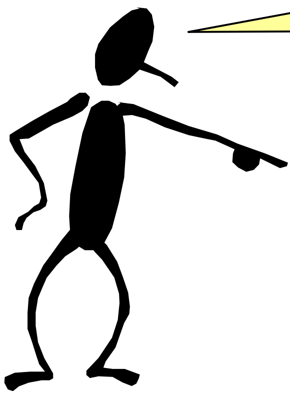
CHAPTER 18: LEVEL CONTROL



When I complete this chapter, I want to be able to do the following.

- **Determine the proper location and volume of liquid inventories in a process**
- **Determine the dynamics of typical level processes**
- **Tune level controllers for <u>two</u> typical control objectives**

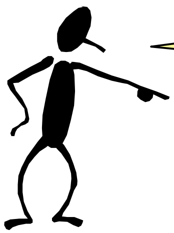
CHAPTER 18: LEVEL CONTROL



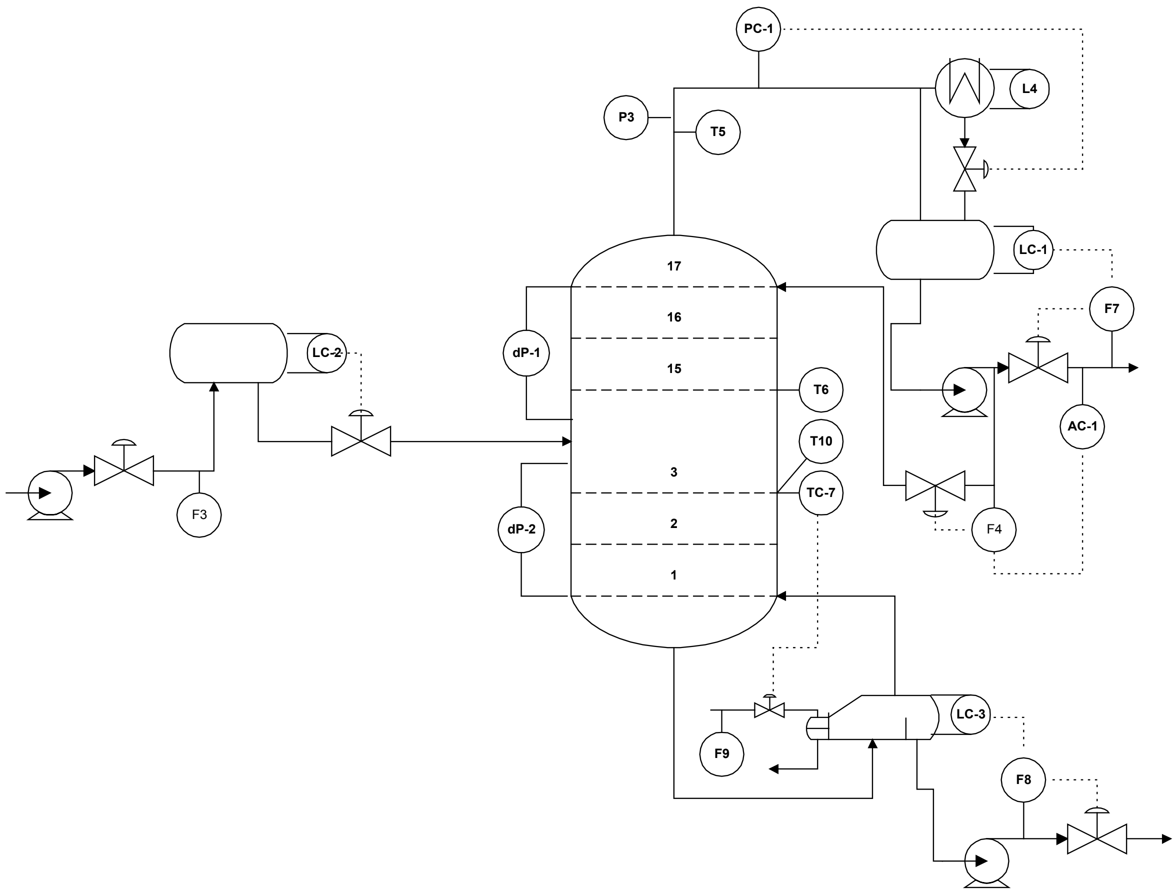
Outline of the lesson.

- **Levels, where are they?**
- **Levels - good and bad aspects**
- **Level dynamics**
- **Level tuning**
- **Determining inventory size**

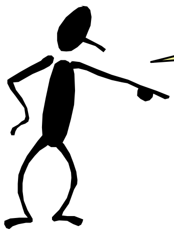
CHAPTER 18: LEVEL CONTROL



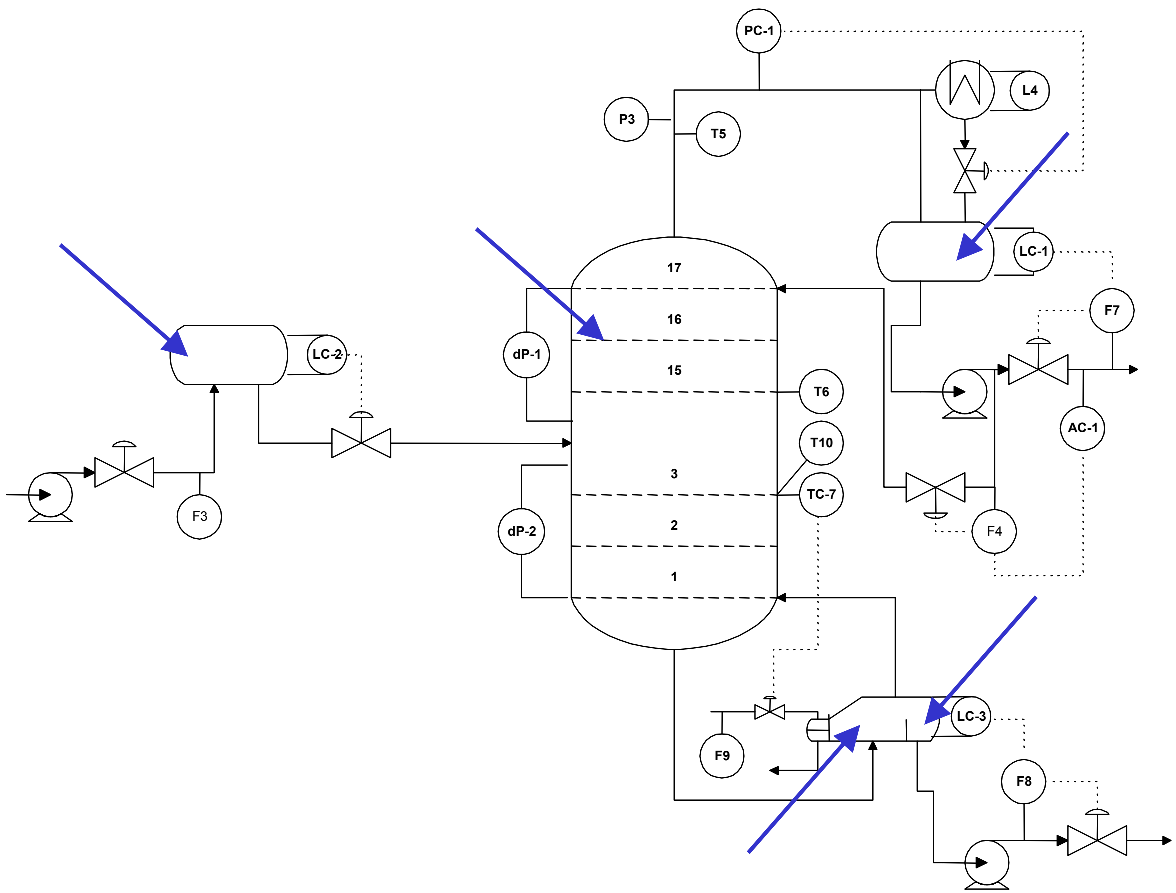
- **Where are liquid inventories?**
- **Why do we design equipment with inventories?**



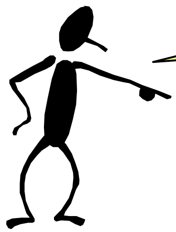
CHAPTER 18: LEVEL CONTROL



- Where are liquid inventories?



CHAPTER 18: LEVEL CONTROL

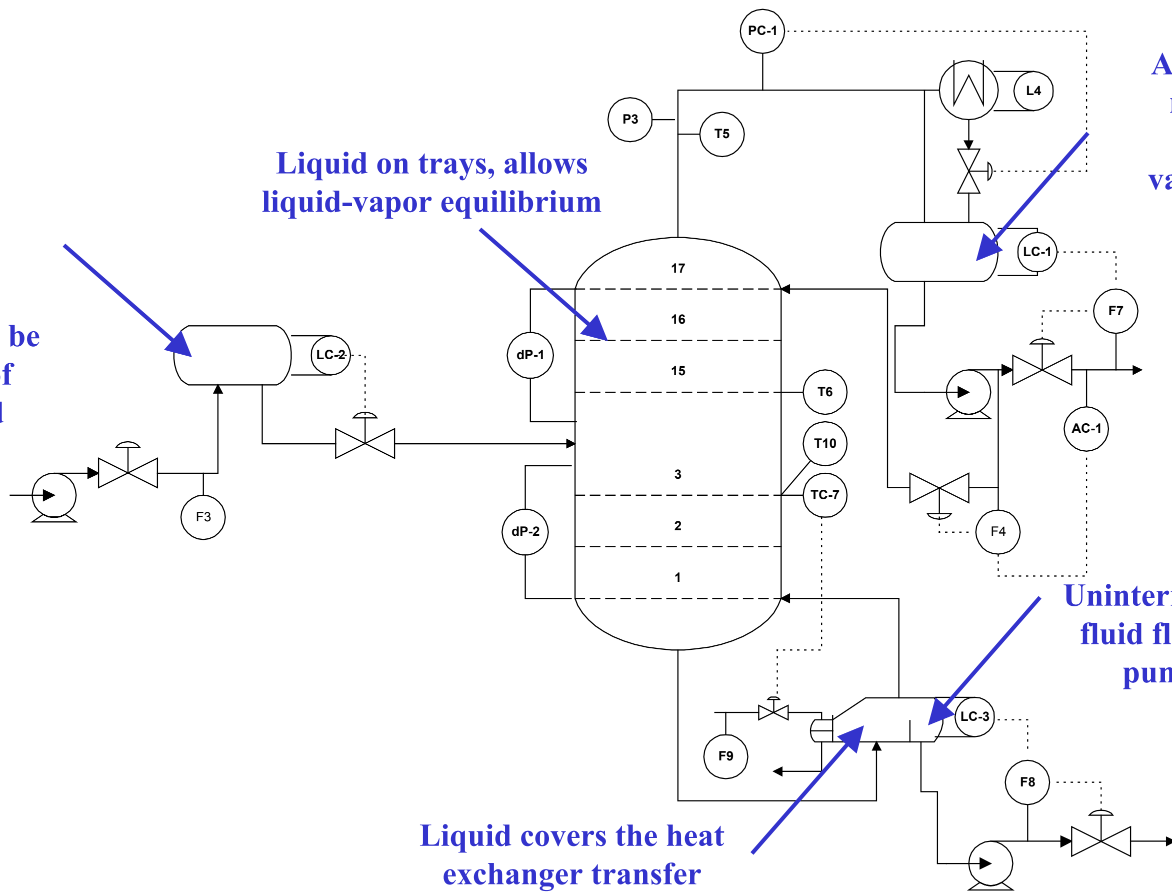


- Where are liquid inventories? Why?

- Liquid mixing reduces effects of composition disturbances
- Flow to tower can be constant in spite of fluctuation in feed flow

Liquid on trays, allows liquid-vapor equilibrium

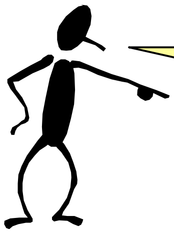
Allows uninterrupted reflux and product flows in spite of variable condensation



Uninterrupted fluid flow to pump

Liquid covers the heat exchanger transfer area

CHAPTER 18: LEVEL CONTROL



- **How do inventories affect performance of the process containing the liquid?**

<u>Strongly</u>

- Volume of chemical reactors, volume has strong effect on conversion
- Fast material degradation (reduce residence time)

<u>Weakly</u>

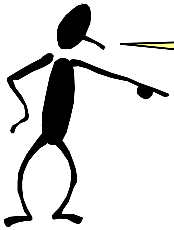
- Equilibrium stages, both phases must be present, but amount beyond minimum does not affect process
- Heat exchangers, must have contact with area

<u>Insignificant</u>

- Drums and tanks, no change to material properties

But these inventories have <u>strong effects</u> on the other processes influenced by the flows from these inventories

CHAPTER 18: LEVEL CONTROL



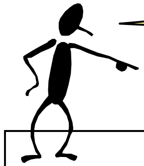
- What are ++ and -- for having liquid inventories?

<u>POSITIVE ASPECTS</u>

<u>NEGATIVE ASPECTS</u>

Conclusion: ??

CHAPTER 18: LEVEL CONTROL



• What are ++ and -- for having liquid inventories?

POSITIVE ASPECTS

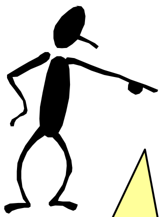
- Provide liquid to pumps
- Mixing to reduce effects of stream property disturbances
- Inventory enables flow out constant as flow in varies
- Required - process principles, e.g.,
  - chemical reactors
  - heat exchangers

NEGATIVE ASPECTS

- Hazards - large inventory
- Product quality - degradation
- Space in plant
- Cost
  - Equipment costs
  - Material costs (inventory)

Conclusion: We use only the <u>minimum</u> liquid inventory needed to achieve the desired process performance.

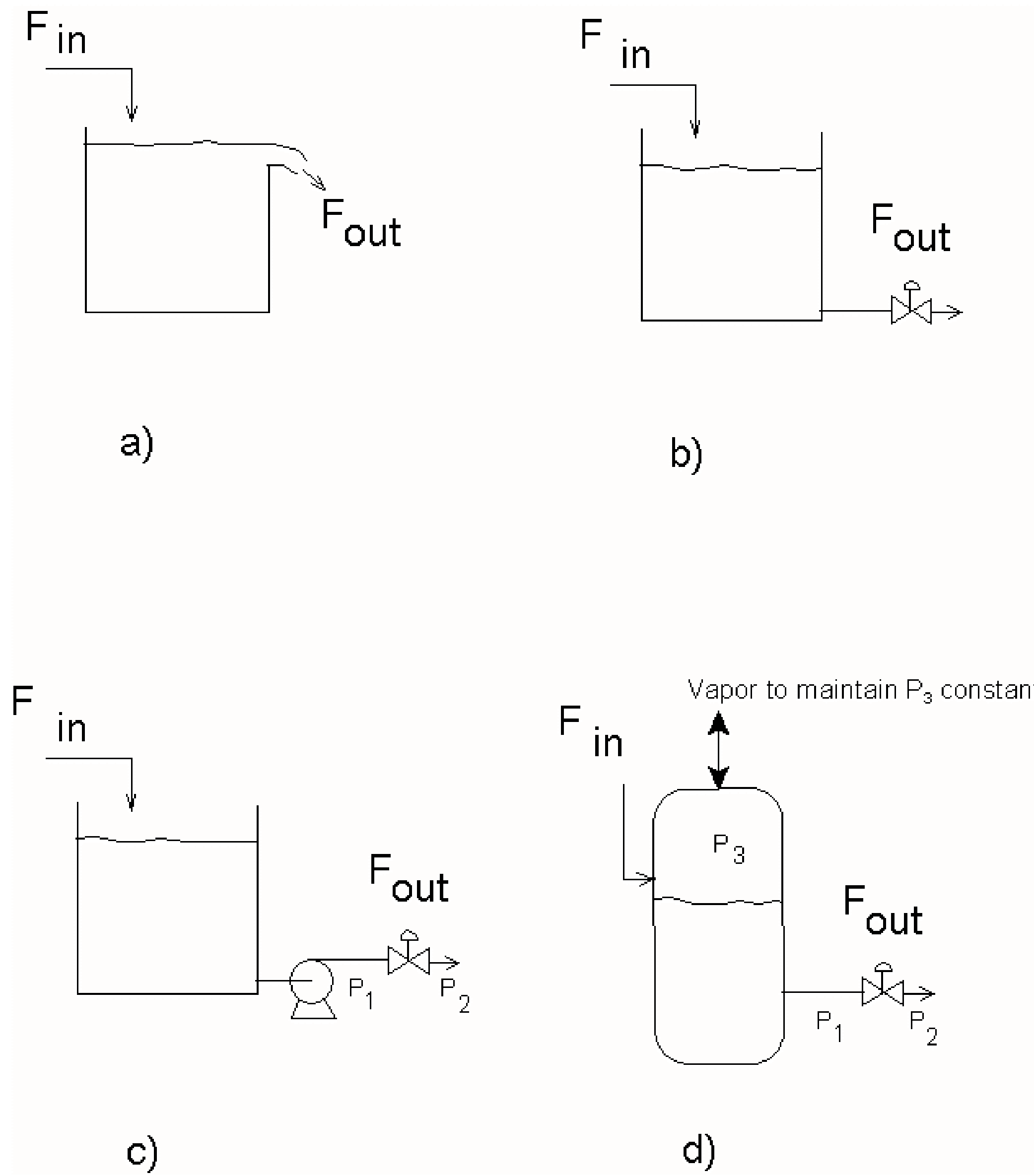
CHAPTER 18: LEVEL CONTROL



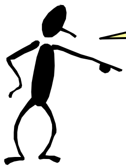
To design control, we need to understand the

- **process dynamics**
- **control objectives**
- **algorithm & tuning**
- **level sizing**

Let's determine the dynamics for each of the designs

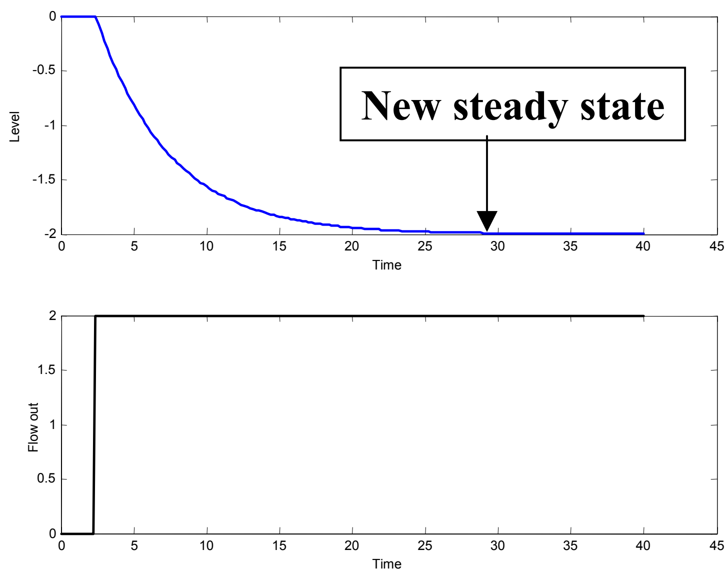


CHAPTER 18: LEVEL CONTROL



Quick reminder of key property of dynamic process behavior

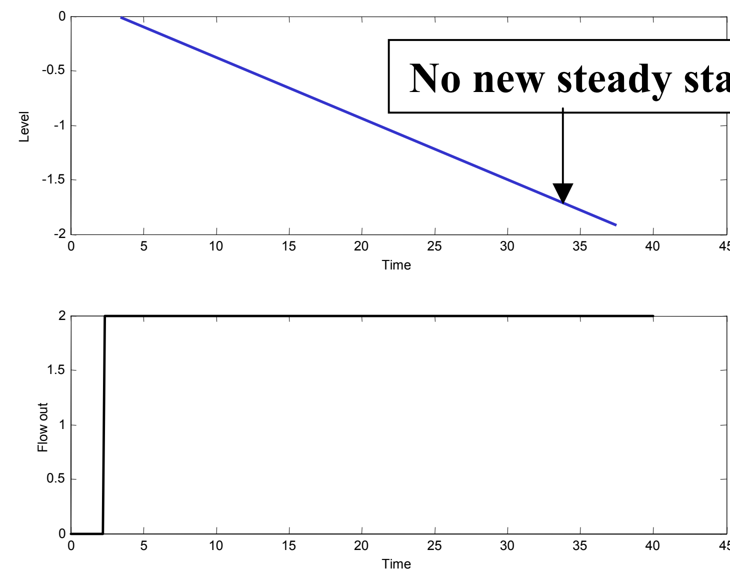
Self-regulatory



$$A\frac{dL}{dt} = F_{in} - F_{out}$$

F_{out} increases as level increases

Non-self-regulatory

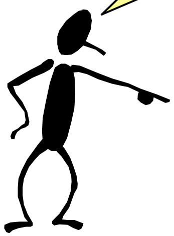


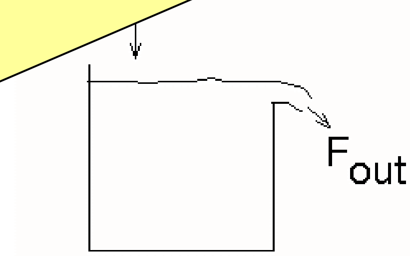
$$A\frac{dL}{dt} = F_{in} - F_{out}$$

F_{out} does not depend on the level

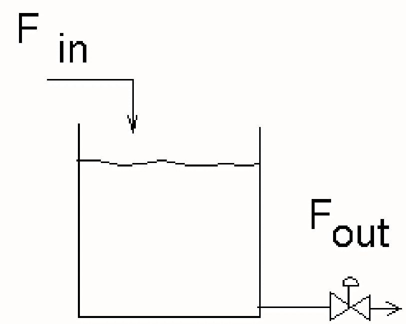
Determine if each level is self-regulatory or not

$$\frac{dL}{dt} \approx 0$$



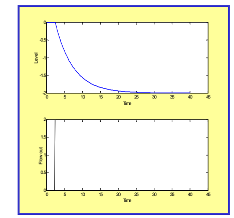


a) **Constant**

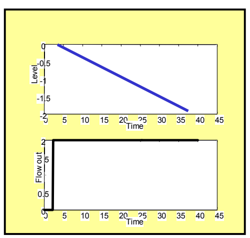


$$A\frac{dL}{dt} = F_{in} - F_{out}$$

$$= F_{in} - K(L)$$



b) **Self-regulatory**

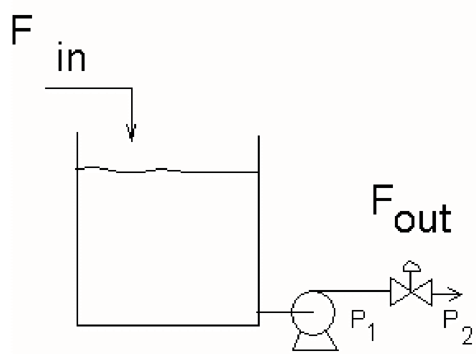


$$A\frac{dL}{dt} = F_{in} - F_{out}$$

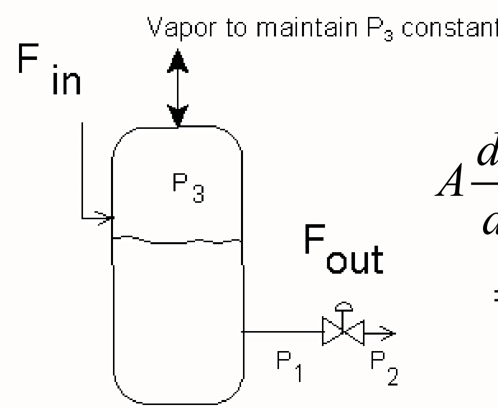
$$= F_{in} - K\sqrt{P_1 - P_2}$$

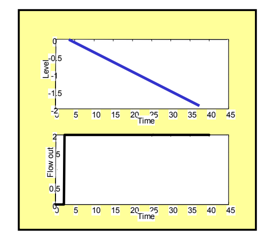
P_1 = pump head + ρgL

≈ 0



c) **Non-Self-regulatory**





$$A\frac{dL}{dt} = F_{in} - F_{out}$$

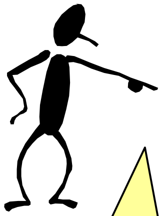
$$= F_{in} - K\sqrt{P_1 - P_2}$$

$P_1 = P_3$ + ρgL

≈ 0

d) **Non-Self-regulatory**

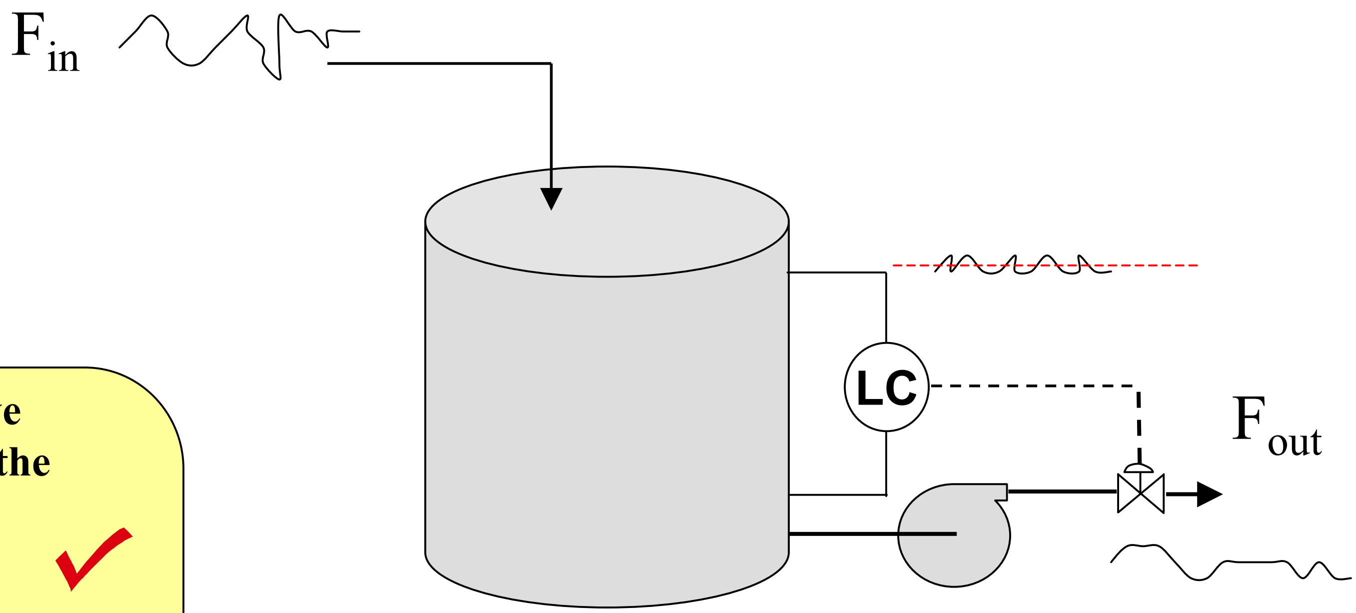
CHAPTER 18: LEVEL CONTROL



To design control, we need to understand the

- process dynamics ✓
- control objectives
- algorithm & tuning
- level sizing

Let's determine the **control objectives** for level control

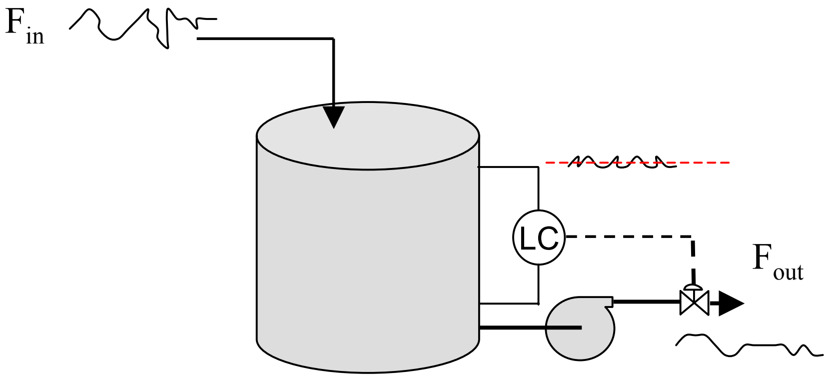


What is important?

- The level
- The manipulated flow

CHAPTER 18: LEVEL CONTROL

Control objectives



1. Since the level in unstable, we must control it!

2. We have two different categories of objectives

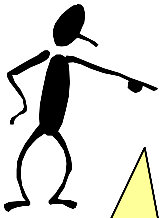
A. Tight level control for levels that strongly influence process performance (or are very small).

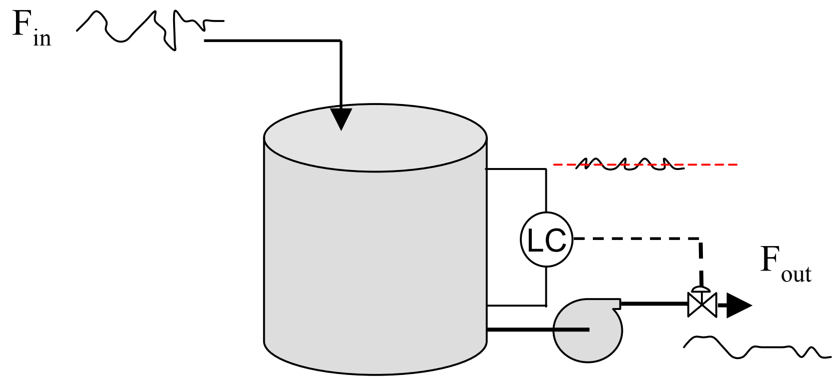
- Level near set point, aggressive flow adjustments

B. Averaging level control for drums and tanks, where smooth manipulation of flows will be beneficial to other units in the plant.

- Level far from set point (but doesn't overflow), slower flow adjustments

CHAPTER 18: LEVEL CONTROL





To design control, we need to understand the

- process dynamics
- control objectives
- algorithm & tuning
- level sizing

Let's determine the **algorithm & tuning** for level control

1. Is the control in the figure

a. feedback

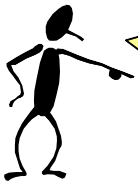
b. feedforward

c. neither

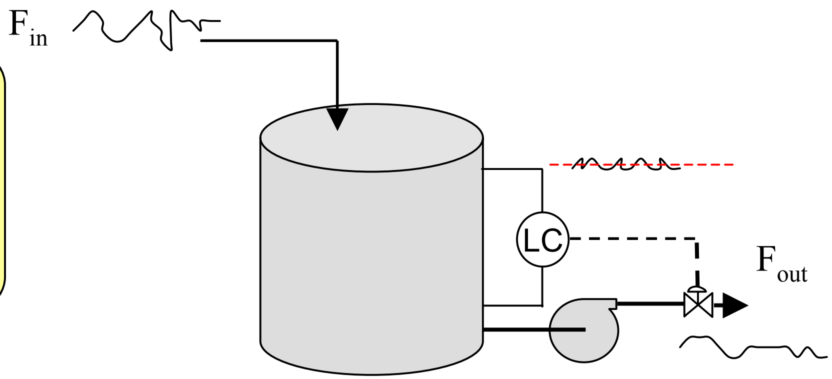
d. both

2. What makes control difficult?

CHAPTER 18: LEVEL CONTROL



Since this is feedback, let's use the old standard, PI control ("D" isn't needed).



1. Is the control in the figure

a. feedback
b. feedforward
c. neither
d. both

Feedback: The flow out has a causal effect on the level.

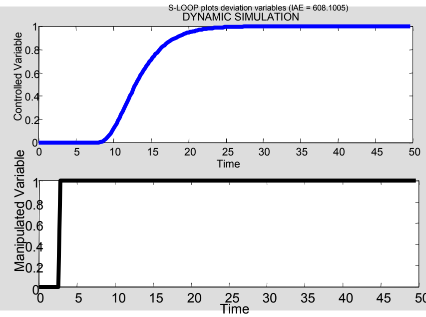
2. What makes control difficult?

Dead time makes feedback difficult, but we see that this process has negligible dead time!

CHAPTER 18: LEVEL CONTROL

Controller Tuning

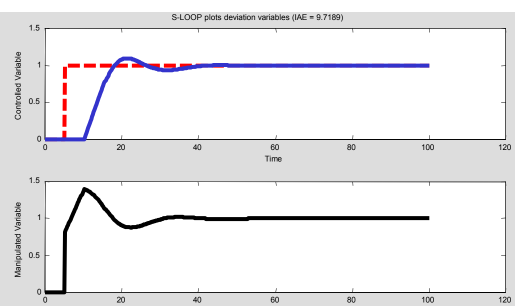
Can we use the standard PI tuning approach shown in the schematic?



Determine a model using the process reaction curve experiment.

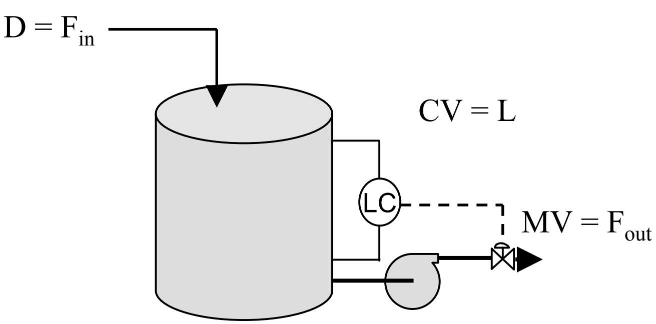
Kc **TI**

Determine the initial tuning constants from a correlation.



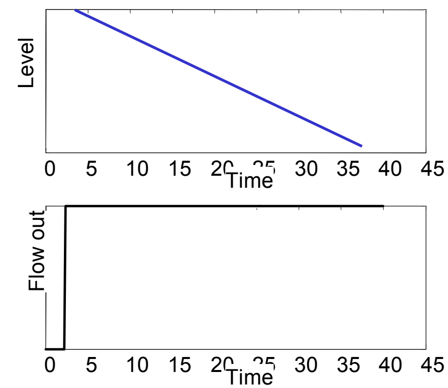
Apply and fine tune as needed.

$$F_{out}(t) = K_C\left[(L_{SP} - L(t)) + \frac{1}{T_I}\int_0^t (L_{SP} - L(t'))dt'\right] + I$$

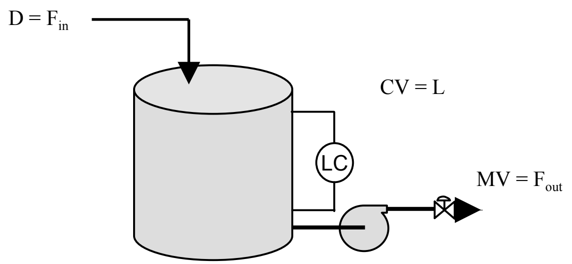


CHAPTER 18: LEVEL CONTROL

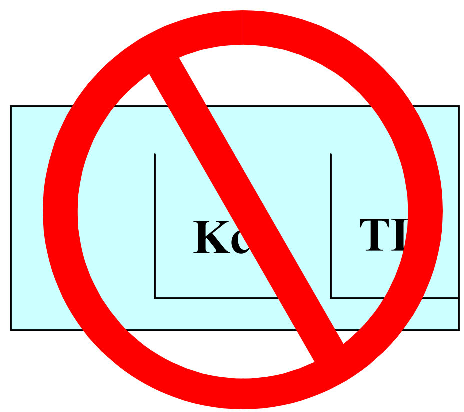
The level process is unstable. Without control, it never reaches a new steady state



Cannot determine a model using the process reaction curve experiment.

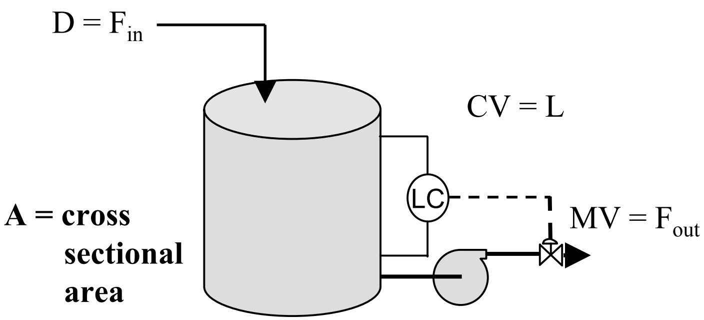


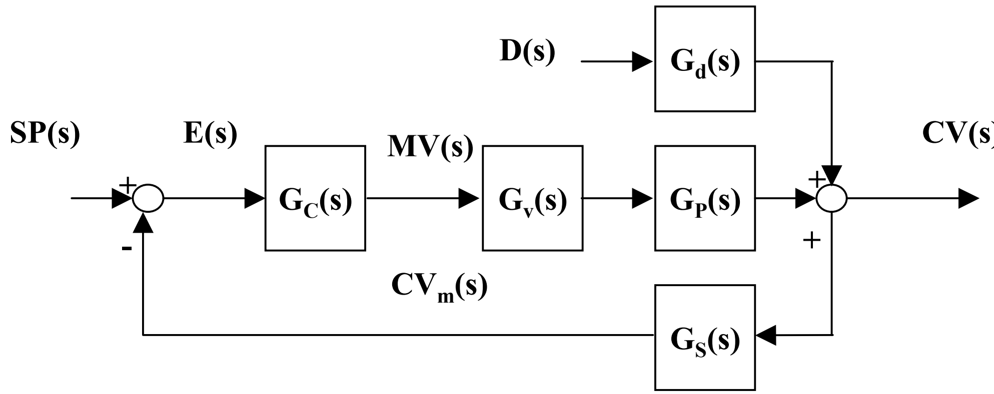
Standard tuning charts are not applicable to a non-self-regulating level.



Cannot determine the initial tuning constants from Ciancone (or Ziegler-Nichols step) correlation.

CHAPTER 18: LEVEL CONTROL





Let's build a model of the process with the controller, i.e, the closed-loop system. We will ignore the fast sensor and valve dynamics.

Using block diagram algebra, we obtain

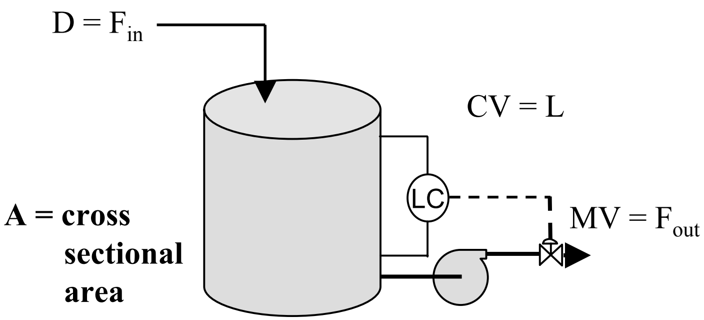
$$\frac{L(s)}{F_{in}(s)} = \frac{G_D(s)}{1 + G_C(s) G_P(s)}$$

With $G_c(s)$ being either P-only of PI

For a non-self regulating level

$$G_P(s) = G_D(s) = \frac{1}{As}$$

CHAPTER 18: LEVEL CONTROL



We substitute the appropriate models for each process and controller to obtain the following transfer function models, which we can solve analytically for a step disturbance!

$$\frac{L(s)}{F_{in}(s)} = \frac{\frac{1}{-K_C}}{\left(\frac{A}{-K_C}\right)s+1}$$

Proportional-only control

$$F_{out}(t) = K_C\left[L_{SP} - L(t)\right] + I$$

$$G_C(s) = -K_C$$

$$\frac{L(s)}{F_{in}(s)} = \frac{\left[\frac{T_I}{-K_C}\right]}{\tau^2 s^2 + 2\tau\xi s + 1}$$

$$\tau = \sqrt{\frac{AT_I}{-K_C}} \quad and \quad \xi = \frac{1}{2}\sqrt{\frac{T_I(-K_C)}{A}}$$

Proportional-integral control

$$F_{out}(t) = K_C\left[(L_{SP} - L(t)) + \frac{1}{T_I}\int_0^t (L_{SP} - L(t'))dt'\right] + I$$

$$G_C(s) = -K_C\left(1 + \frac{1}{T_I s}\right)$$

CHAPTER 18: LEVEL CONTROL

P-only

$$F_{out}(t) = K_C\left[L_{SP} - L(t)\right] + I$$

- Disturbance step response

$$L'(t) = \Delta F_{in}\left(1 \big/ -K_C \right)\left[1 - e^{-t/\left(A / -K_c \right)} \right]$$

- Stable, first order
- Never underdamped
- Non-zero s-s offset

PI

$$F_{out}(t) = K_C\left[(L_{SP} - L(t)) + \frac{1}{T_I}\int_0^t (L_{SP} - L(t'))dt' \right] + I$$

- Disturbance step response

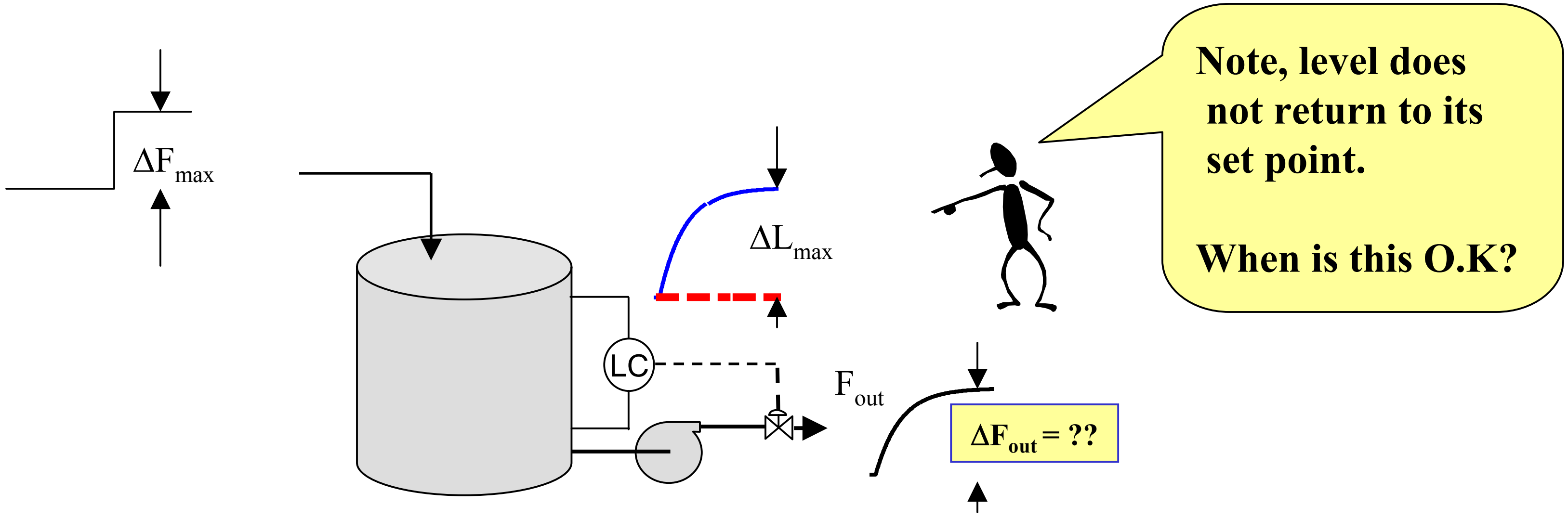
$$L'(t) = \left(\frac{\Delta F_{in}}{A} \right)\left[t\, e^{-t/\left(2A / -K_c \right)} \right]$$

- Stable, second order
- Underdamped when $\xi < 1$
  (We want overdamped!)
- Zero s-s offset

CHAPTER 18: LEVEL CONTROL

P-only Tuning

Determine the expected maximum step disturbance size (ΔF_{max}) and calculate the K_c to give the maximum allowed change in the level (ΔL_{max}) .



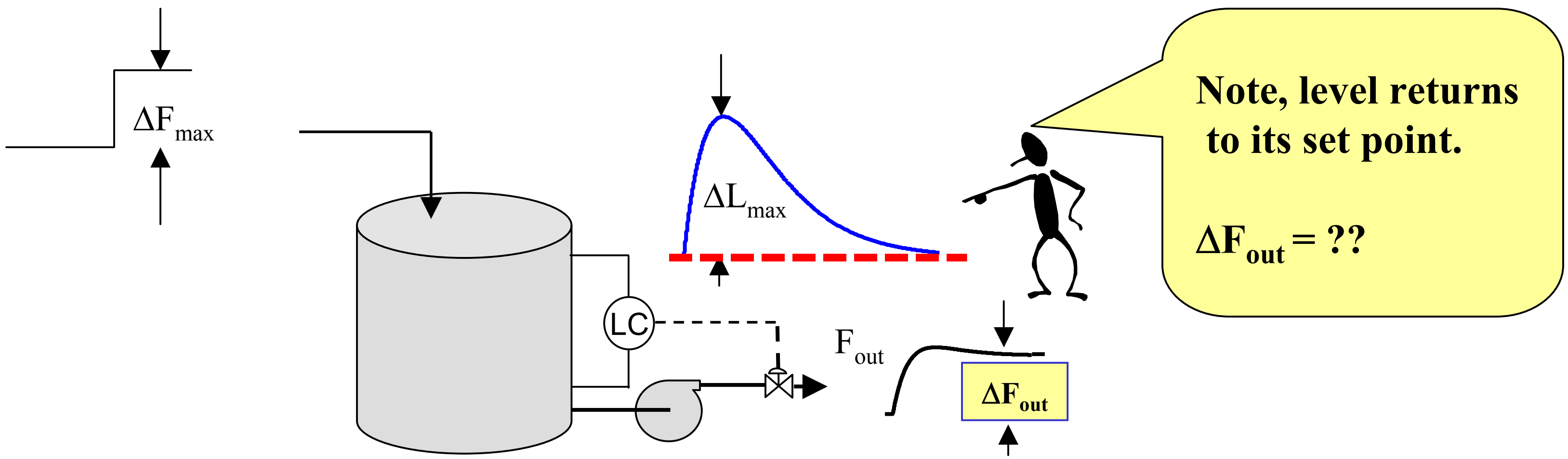
$$F_{out}(t) = K_C\left[L_{SP} - L(t)\right] + I$$

$$\boxed{K_c = -\,(\Delta F_{max}) / (\Delta L_{max})}$$

CHAPTER 18: LEVEL CONTROL

PI Tuning

- Determine the expected maximum step disturbance size (ΔF_{max}) and calculate the K_c and T_I to give the maximum allowed change in the level (ΔL_{max}).
- Set tuning so that damping coefficient, $\xi = 1$.

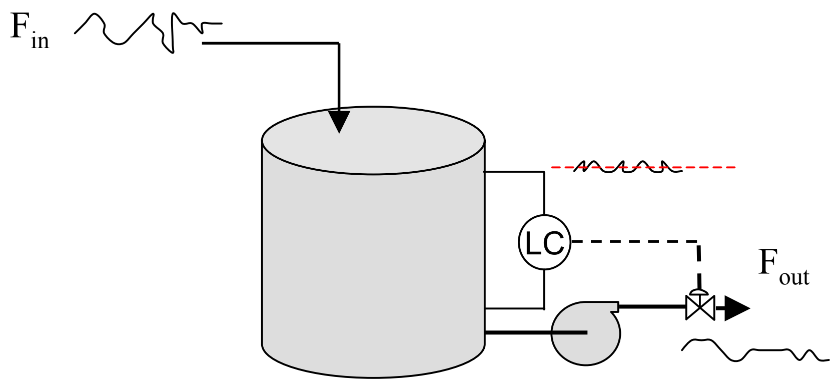


$$F_{out}(t) = K_C\left[(L_{SP} - L(t)) + \frac{1}{T_I}\int_0^t (L_{SP} - L(t'))dt'\right] + I$$

$$K_c = -0.736\,(\Delta F_{max})/(\Delta L_{max}) \qquad T_I = 4\,(\xi^2)\,A/(-K_c)$$

CHAPTER 18: LEVEL CONTROL

Let's use these results for averaging and tight level control.



P-only control: $K_c = -(\Delta F_{max})/(\Delta L_{max})$

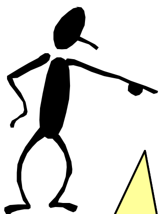
PI Control: $K_c = -0.736\,(\Delta F_{max})/(\Delta L_{max})$ $T_I = 4\,(\xi^2)\,A/(-K_c)$

Averaging level control, $\Delta L_{max} \approx 40\%$ of maximum range

Tight level control, $\Delta L_{max} \approx 5\%$ of maximum range

CHAPTER 18: LEVEL CONTROL

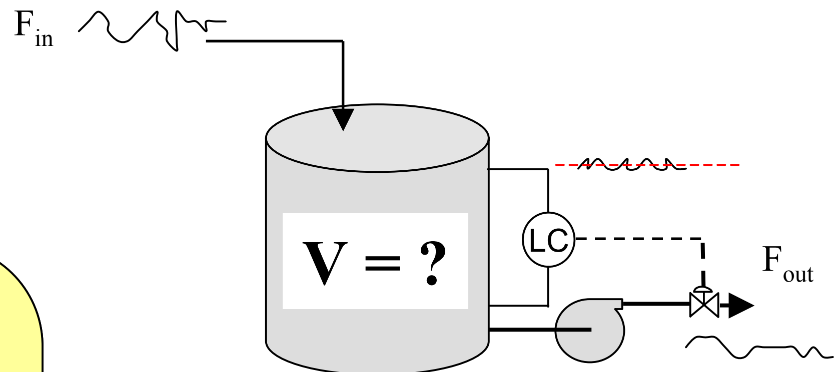
How do we determine the proper vessel volume?



To design control, we need to understand the

- process dynamics
- control objectives
- algorithm & tuning
- level sizing

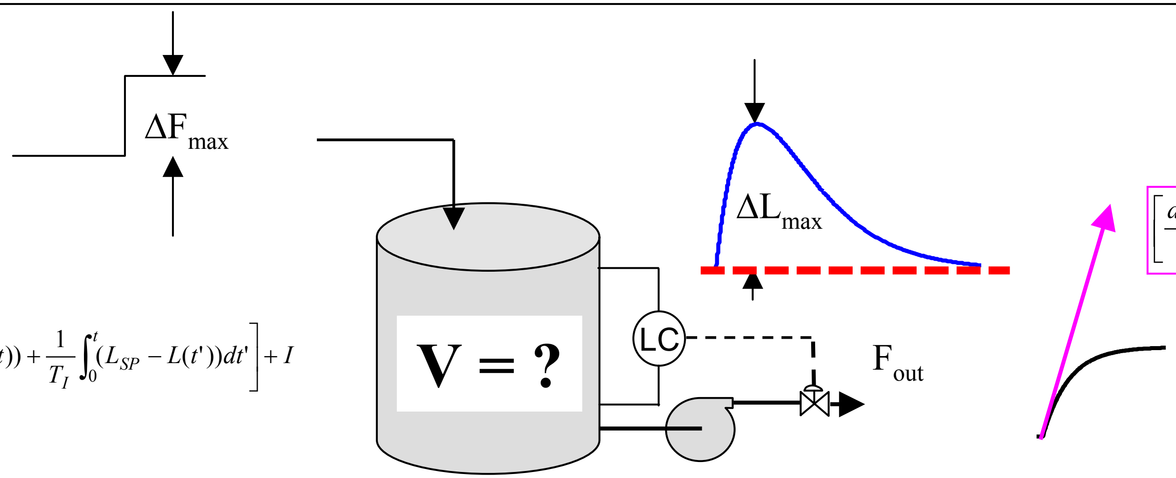
Let's look again at the process



That is a good question. Averaging level control will not provide improvement unless the vessel is large enough!

CHAPTER 18: LEVEL CONTROL

One key design goal: maintain the rate of change of the manipulated flow below a maximum when using averaging tuning. This "protects" the <u>downstream units</u> from fast disturbances.



$$F_{out}(t) = K_C\left[(L_{SP} - L(t)) + \frac{1}{T_I}\int_0^t (L_{SP} - L(t'))dt'\right] + I$$

$$\left[\frac{dF_{out}}{dt}\right]_{max}$$

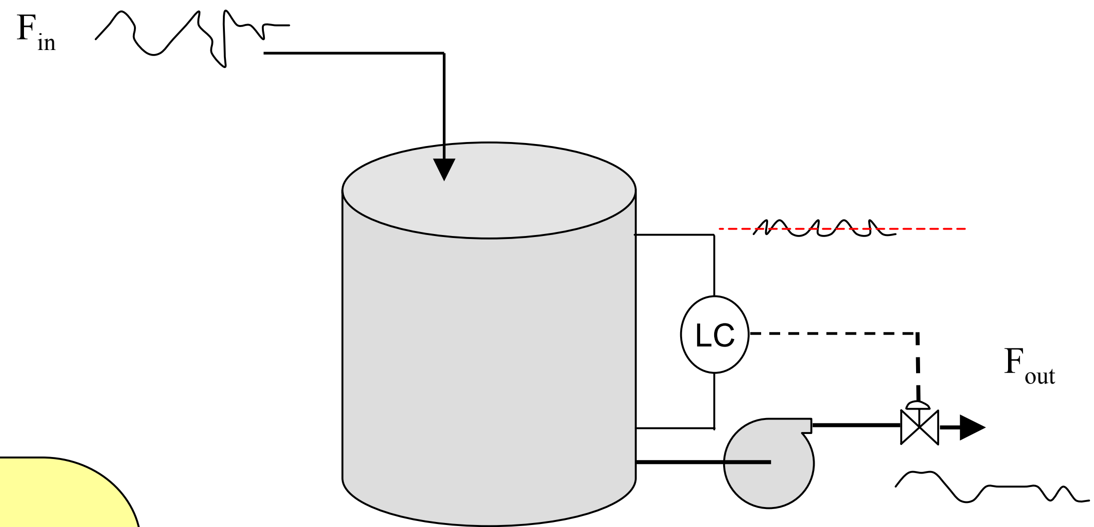
$$V = \frac{1.84(\Delta F_{max})^2}{\left[\dfrac{dF_{out}}{dt}\right]_{max}}$$

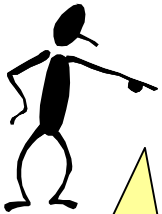
The equation is based on a PI controller with the "averaging" tuning recommended in this chapter.

See Chapter 18 for derivation

CHAPTER 18: LEVEL CONTROL

Now, we understand control of a single level!





To design control, we need to understand the

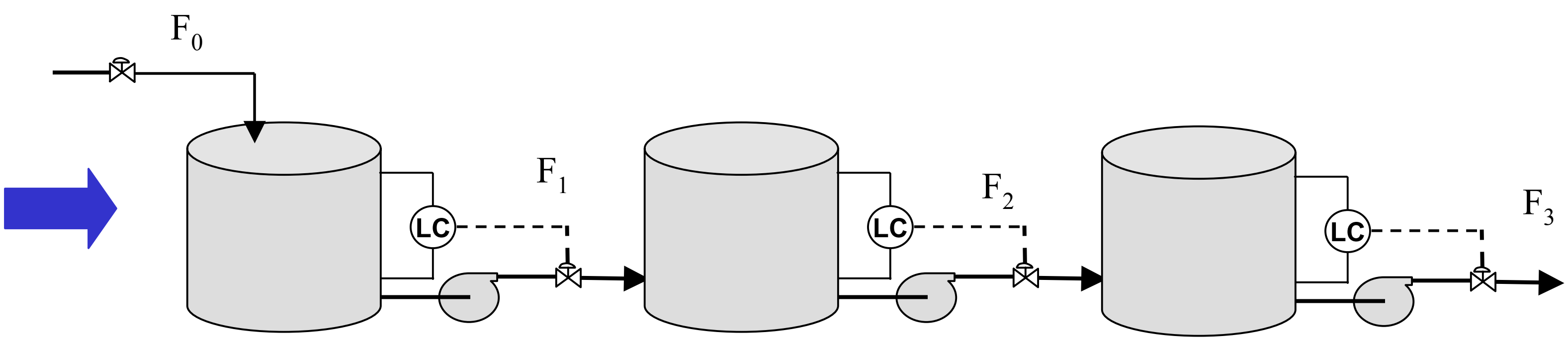
- process dynamics
- control objectives
- algorithm & tuning
- level sizing

How small can we make the levels?
Do we have a guideline?

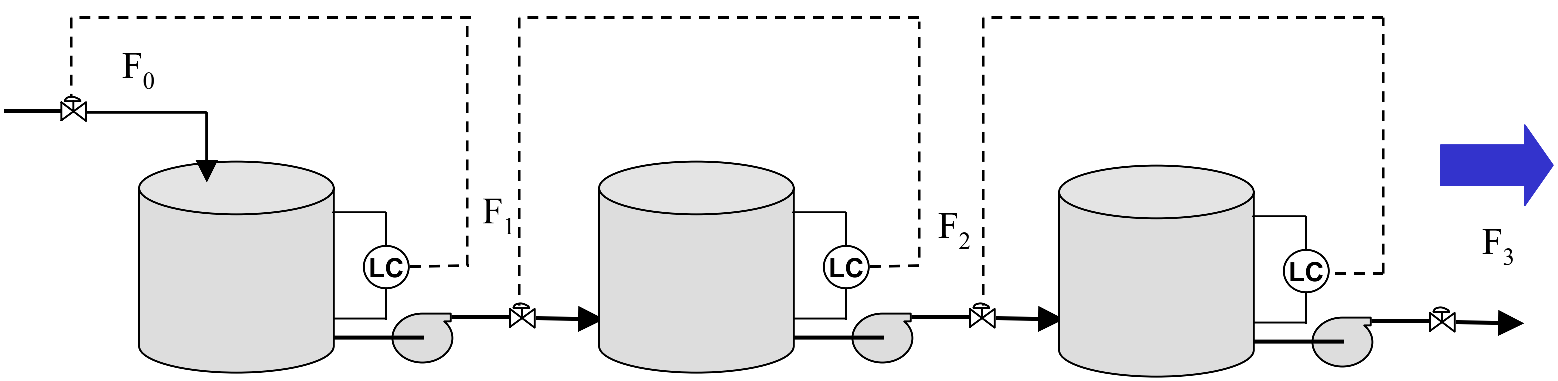
CHAPTER 18: LEVEL CONTROL

Process plants have many units in series. Inventory control behaves similar to a series of tanks. How should they be controlled?

"Feed push" with levels adjusting flows out



"Product pull" with levels adjusting flows in

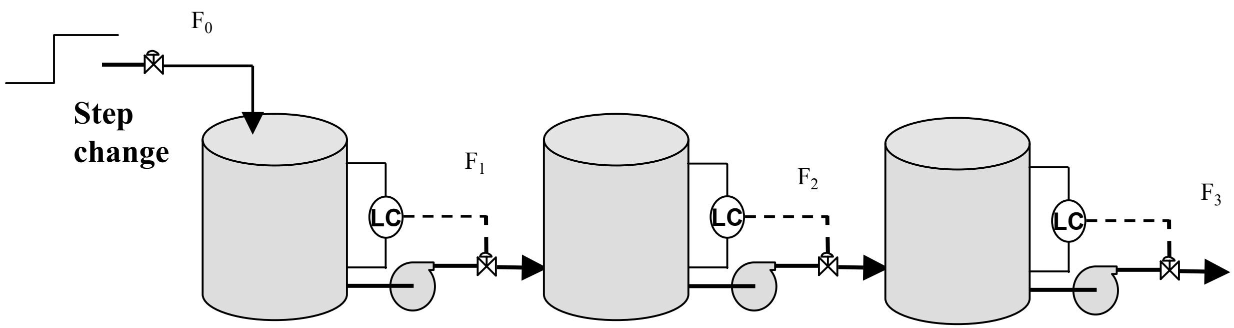


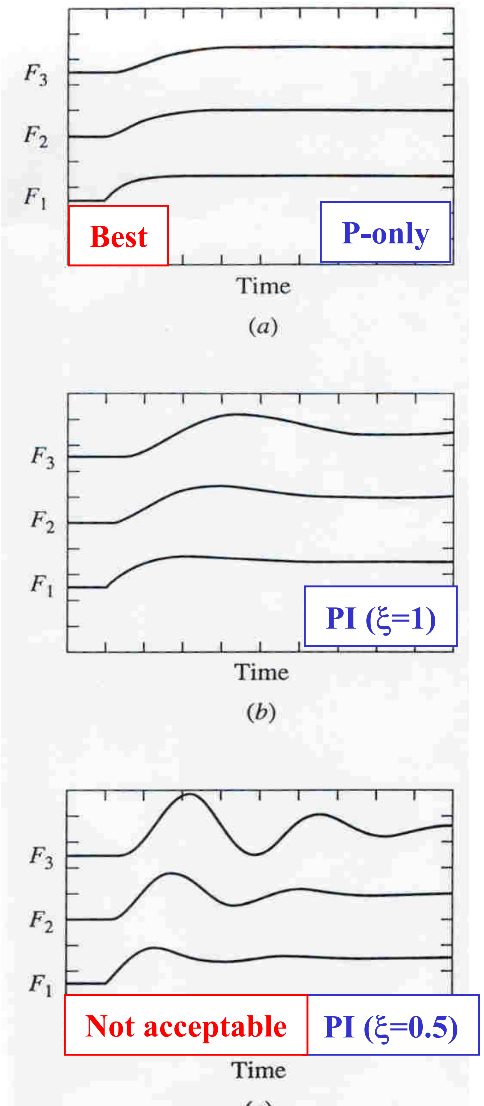
CHAPTER 18: LEVEL CONTROL

For a series of levels, what is the importance of damping?

We see that flow variation <u>increases with number of levels in series</u>

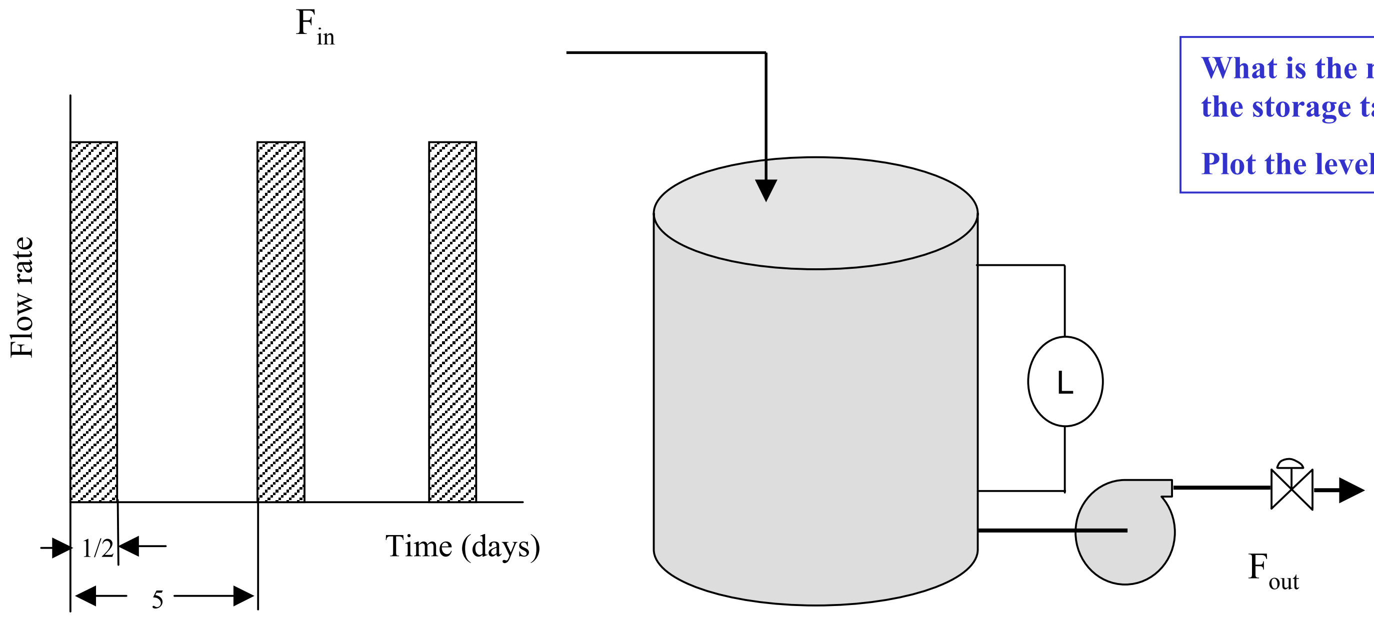
- **P-only control is not oscillatory**
- **PI (ξ=1) experiences overshoot**
- **PI (ξ=0.5) experiences large oscillations**





CHAPTER 18: LEVEL CONTROL WORKSHOP 1

We can have a liquid inventory that is not controlled, if the vessel is large enough. Let's look at an example.



What is the minimum volume for the storage tank?

Plot the level vs. time.

The flow in involves batches of 24,000 m^3 delivered over 12 hours, with a batch delivered every five days.

The flow out is the feed to the plant. It must be continuous and have a constant value.

CHAPTER 18: LEVEL CONTROL WORKSHOP 2

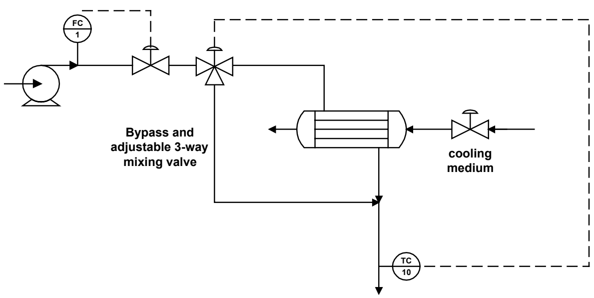
The principles we have learned for liquid level control apply to solid and gas inventories as well.

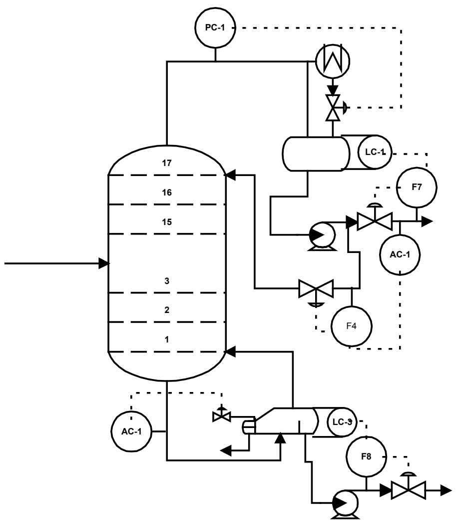
1. Think of an example in a process plant in which we need to have an inventory of
   a. (granular) solids
   b. gas
2. Describe the storage equipment for each.
3. Select a sensor to measure the inventory for each
4. Determine whether the inventory is self-regulating or non-self-regulating.
5. Sketch the process with control.

CHAPTER 18: LEVEL CONTROL WORKSHOP 3

Discuss how you determine the proper liquid inventories for the following unit operations.

1. **Liquid on the shell side of a shell and tube heat exchanger.**



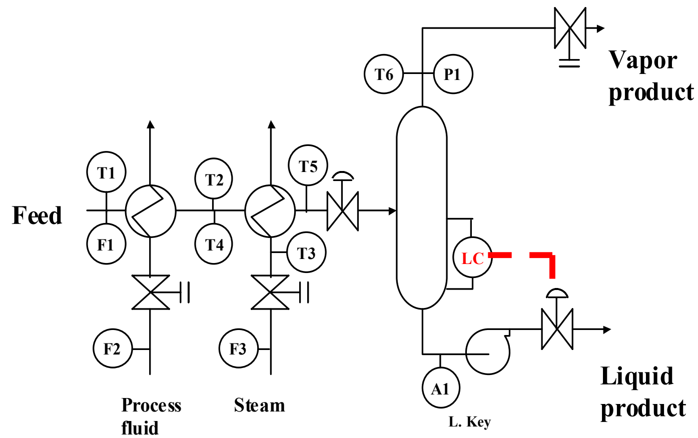


2. **Liquid on a distillation tray**

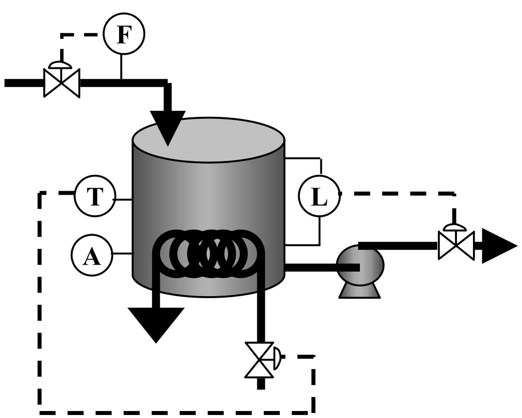
CHAPTER 18: LEVEL CONTROL WORKSHOP 3

Discuss how you determine the proper liquid inventories for the following unit operations.

3. **Liquid in a flash drum**



4. **Liquid in a CSTR**



CHAPTER 18: LEVEL CONTROL WORKSHOP 4

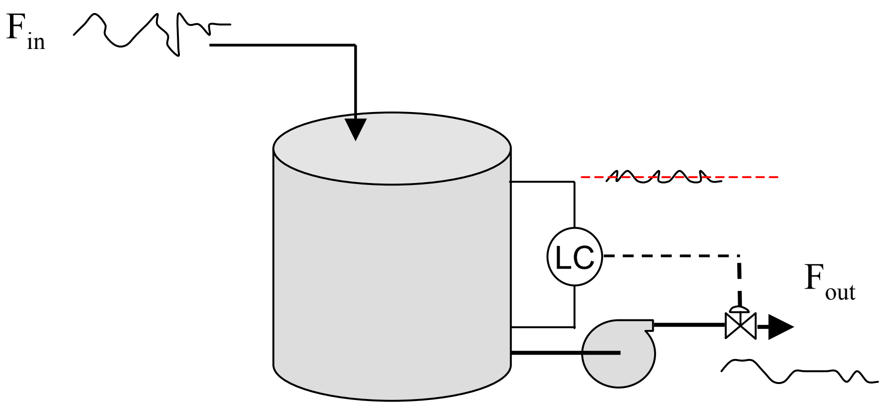
Calculate the level tuning for the situation described below. Determine the tuning for tight and for averaging control.

$V = 50\ m^3$

$A = 25\ m^2$

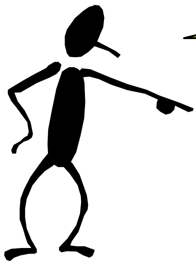
$F = 1.5\ m^3/min$

$\Delta F_{max} = 1.0\ m^3/min$



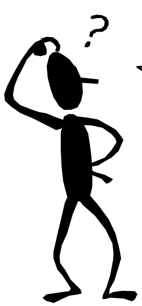
For each tuning, what would be the maximum rate of change of the manipulated flow for a step disturbance of $\Delta F_{max} = 1.0\ m^3/min$?

CHAPTER 18: LEVEL CONTROL



When I complete this chapter, I want to be able to do the following.

- **Determine the location and volume of liquid inventories in a process**
- **Determine the dynamics of various level processes**
- **Tune level controllers for both typical control objectives**



Lot's of improvement, but we need some more study!

- **Read the textbook**
- **Review the notes, especially learning goals and workshop**
- **Try out the self-study suggestions**
- **Naturally, we'll have an assignment!**

CHAPTER 18: LEARNING RESOURCES

- **<u>SITE PC-EDUCATION WEB</u>**
  - Instrumentation Notes - Level sensors!
  - Interactive Learning Module (Chapter 18)
  - Tutorials (Chapter 18)

- **The Textbook, naturally, for many more examples.**

- **An entire book on inventory control? Sure, it is an important issue in corporate-wide production management.**

  Nahmias, S., *Production and Operations Analysis*, McGraw-Hill Irwin, New York, 2001.

CHAPTER 18: SUGGESTIONS FOR SELF-STUDY

1. **Storing hazardous materials increases the risk in case of an accident. Search the WEB for information on the incident at Bhopal, India. Discuss the effect of the storage volume of methyl isocyanate on the number of deaths. A good place to start is**

   http://www.unu.edu/unupress/unupbooks/uu21le/uu21le00.htm#Contents

2. **You are designing a reflux drum for a distillation tower that operates at 10 atm. How does the cost of a carbon steel, horizontal drum depend on the volume?**

3. **Discuss how you would monitor the performance of averaging level control. Based on plant data, define rules for fine tuning the controller.**

CHAPTER 18: SUGGESTIONS FOR SELF-STUDY

4. **Inventories are provided for all essential materials. Discuss how you would determine the proper storage inventory for some key materials, such as**

   a. Blood for transfusions
   b. Food, e.g., grains and rice
   c. Water for a city

5. **Describe the physical principles for sensors to measure the inventory of liquids, gases, and solids.**