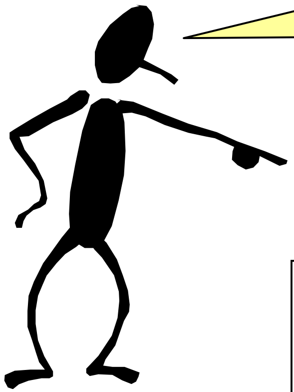
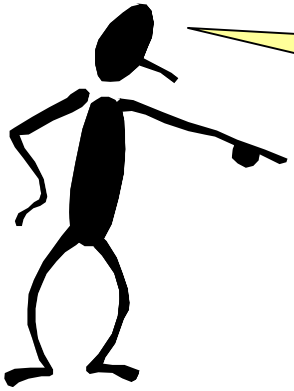
CHAPTER 5 : TYPICAL PROCESS SYSTEMS



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

- **Predict output for typical inputs for common dynamic systems**
- **Derive the dynamics for important structures of simple dynamic systems**
- **Recognize the strong effects on process dynamics caused by process structures**

CHAPTER 5 : TYPICAL PROCESS SYSTEMS



Outline of the lesson.

- **Common simple dynamic systems**
  - First order　　-Second order
  - Dead time　　- (Non) Self-regulatory
- **Important structures of simple systems**
  - Series　　- Parallel
  - Recycle　　- Staged
- **Workshop**

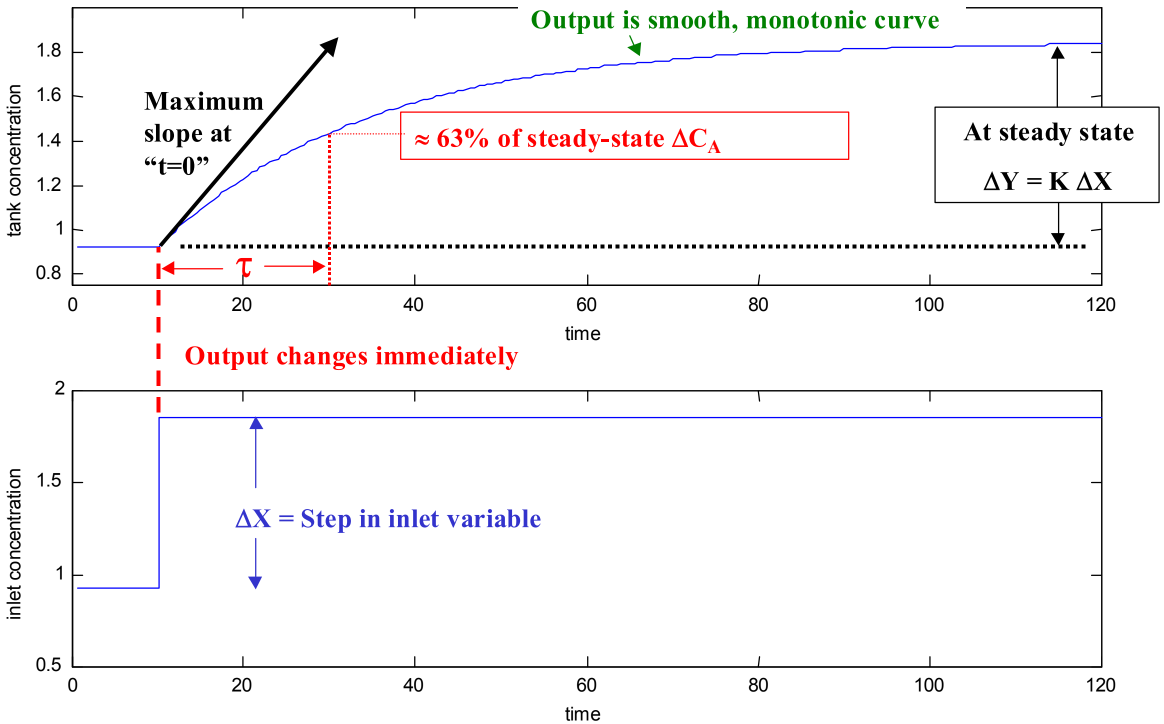
SIMPLE PROCESS SYSTEMS: 1st ORDER

The basic equation is:

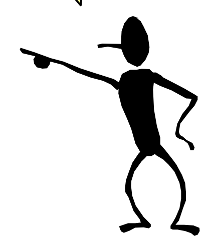
$$\tau \frac{dY(t)}{dt} + Y(t) = K\,X(t)$$

K = s-s gain

τ = time constant



Would this be easy/difficult to control?



SIMPLE PROCESS SYSTEMS: 1st ORDER

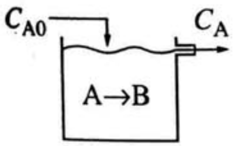
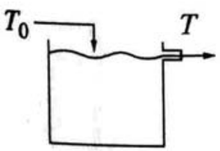
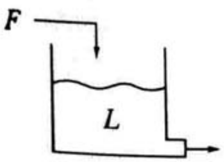
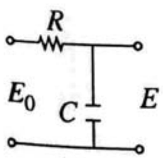
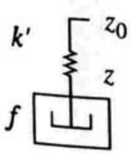
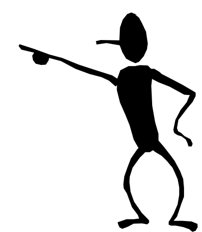
	Balance	Input	Output	K_P	τ
	Component material	C_{A0}	C_A	$\frac{F}{F+Vk}$	$\frac{V}{F+Vk}$
	Energy	T_0	T	1.0	$\frac{V}{F}$
	Overall material	F	L	$\frac{1}{0.5kL_s^{-0.5}}$	$\frac{A}{0.5kL_s^{-0.5}}$
	Current	E_0	E	1.0	RC
	Force	z_0	z	1.0	f/k'

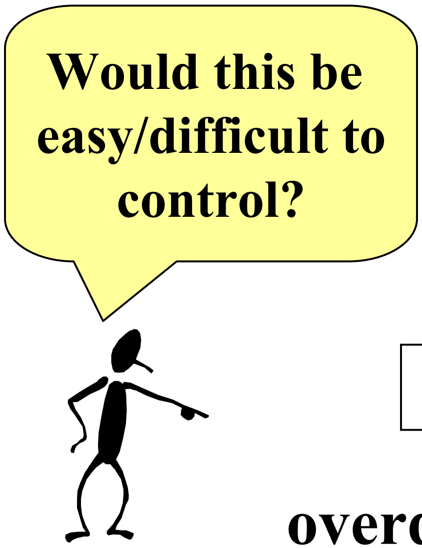
FIGURE 5.2

First-order processes (E = voltage, z = position, k' = spring constant, and f = friction coefficient).

These are simple first order systems from several engineering disciplines.



SIMPLE PROCESS SYSTEMS: 2nd ORDER

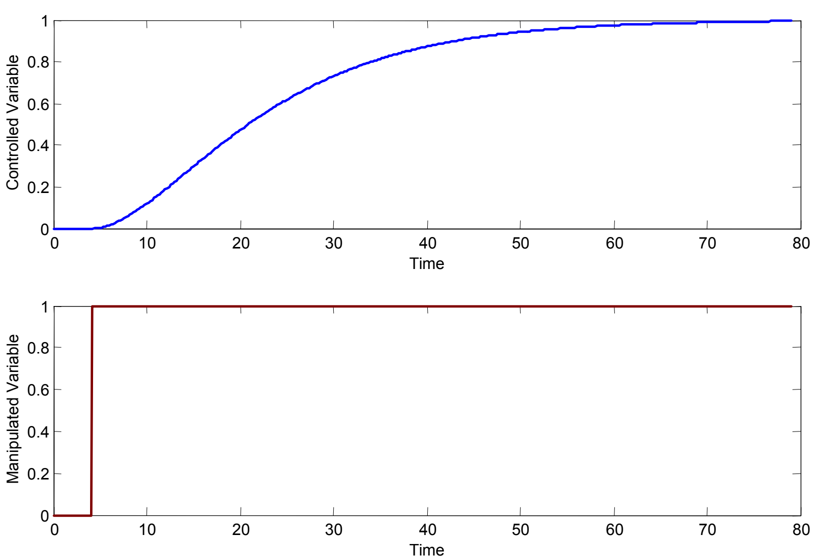


The basic equation is:

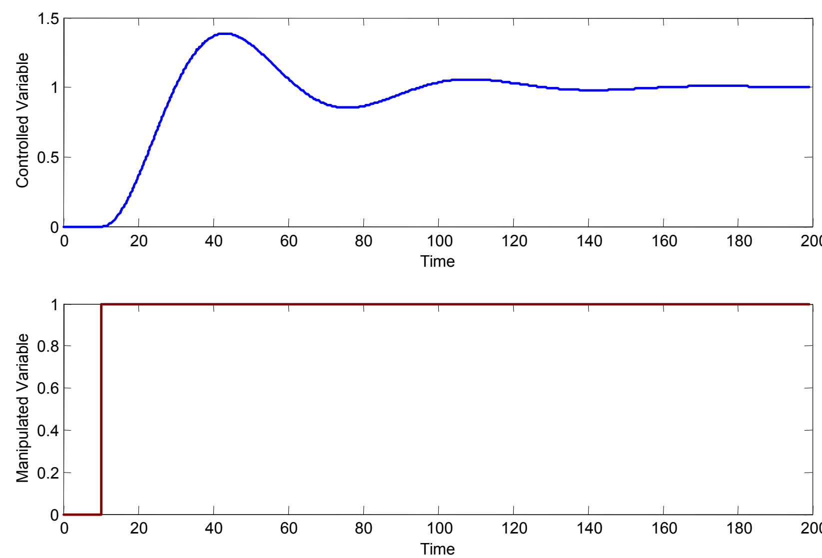
$$\tau^2 \frac{d^2Y(t)}{dt^2} + 2\xi\tau \frac{dY(t)}{dt} + Y(t) = K\ X(t)$$

K = s-s gain , τ = time constant , ξ = damping factor

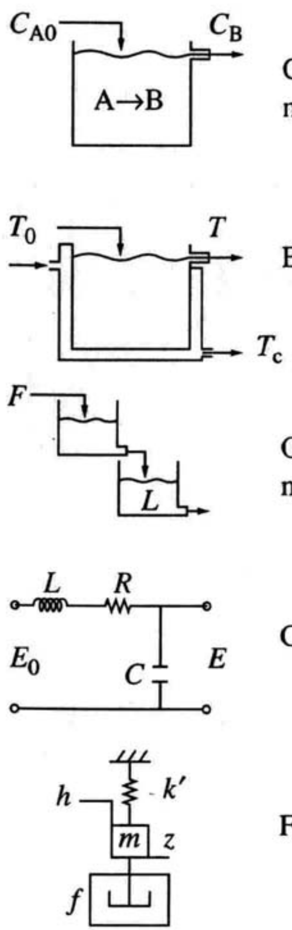
overdamped



underdamped



SIMPLE PROCESS SYSTEMS: 2nd ORDER

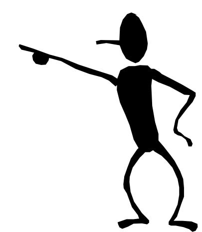


Balance	Input	Output	K_P	τ^2	$2\xi\tau$
Component material	C_{A0}	C_B	$\frac{Vk}{F+Vk}$	$\tau_A\tau_B$	$\tau_A+\tau_B$
Energy	T_0	T	[see question 5.2]		
Overall material	F	L	$\frac{1}{0.5kL_s^{-0.5}}$	$\left[\frac{A}{0.5kL_s^{-0.5}}\right]^2$	2τ
Current	E_0	E	1.0	LC	RC
Force	h	z	$1/k'$	m/k'	f/k'

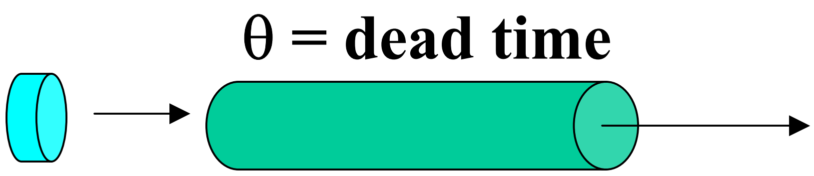
FIGURE 5.3

Second-order processes (E = voltage, z = position, k' = spring constant, f = friction coefficient, h = force, m = mass, $\tau_A = V/(F + Vk)$, and $\tau_B = V/F$).

These are simple second order systems from several engineering disciplines.

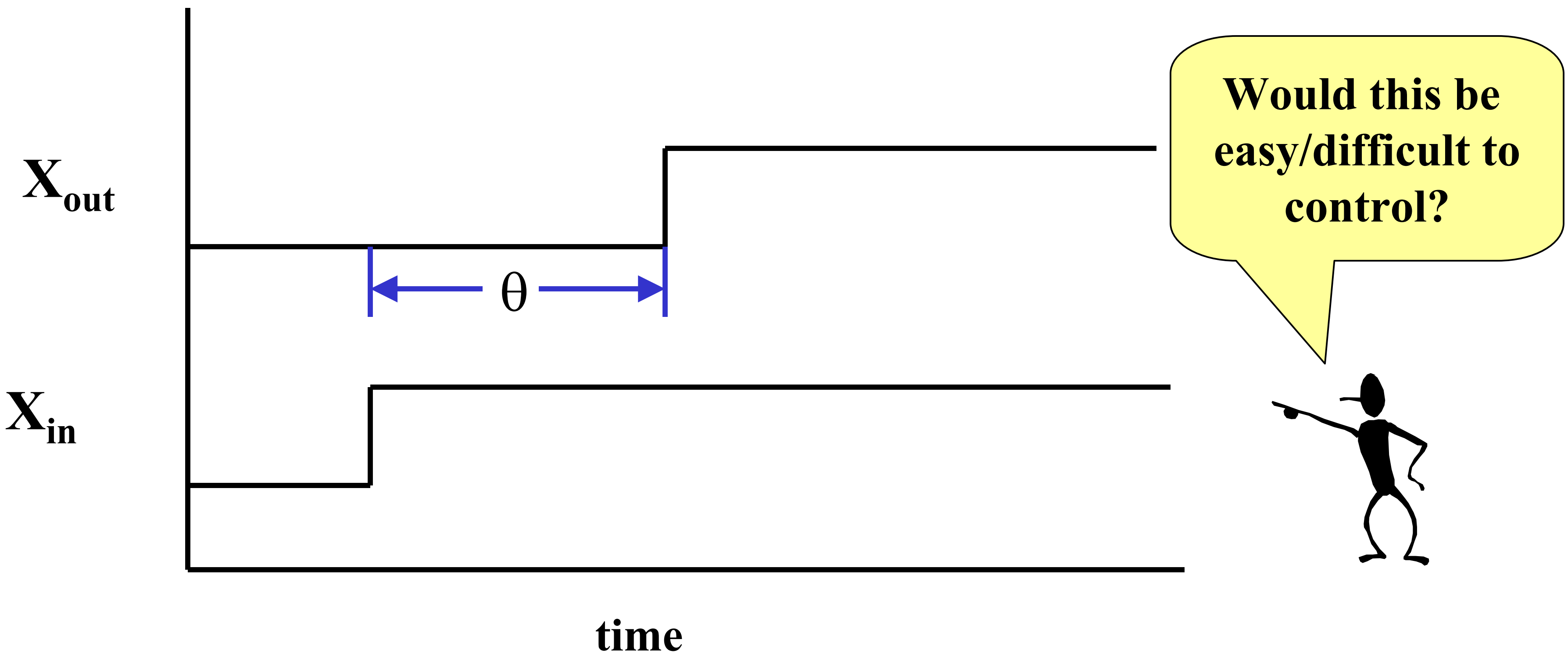


SIMPLE PROCESS SYSTEMS: DEAD TIME

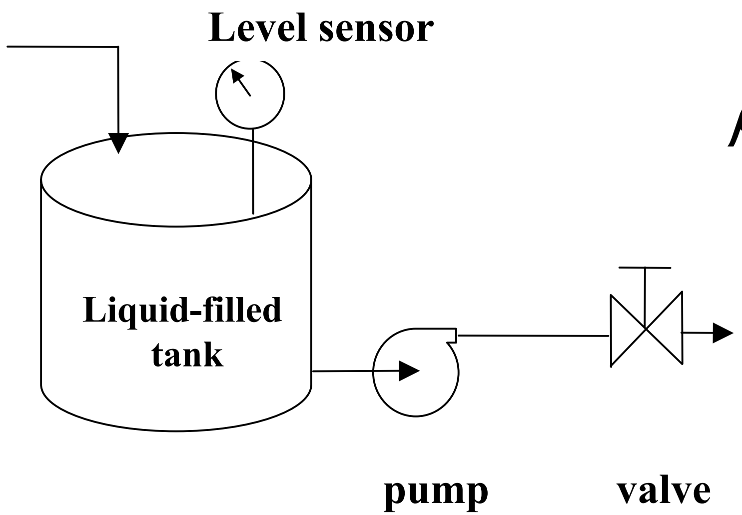


$$X_{out}(t) = X_{in}(t - \theta)$$

$$X_{out}(s) = e^{-\theta s} X_{in}(s)$$



SIMPLE PROCESS SYSTEMS: INTEGRATOR



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

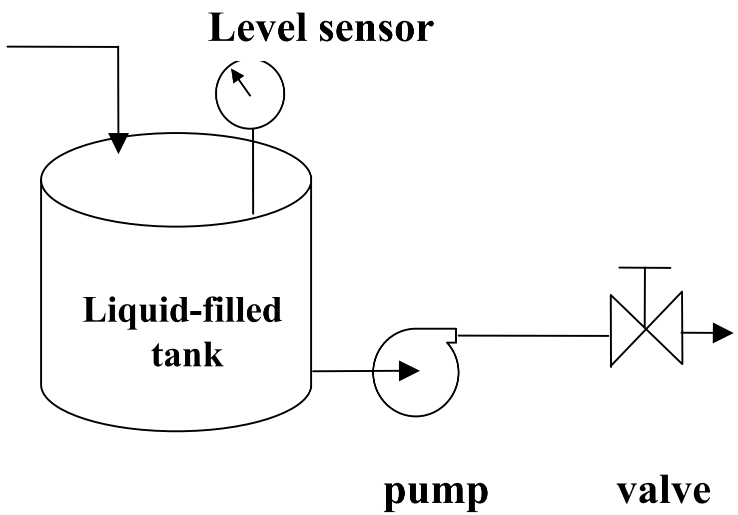
$$F_{in}(t) \neq f(L)$$

$$F_{out}(t) \neq f(L)$$

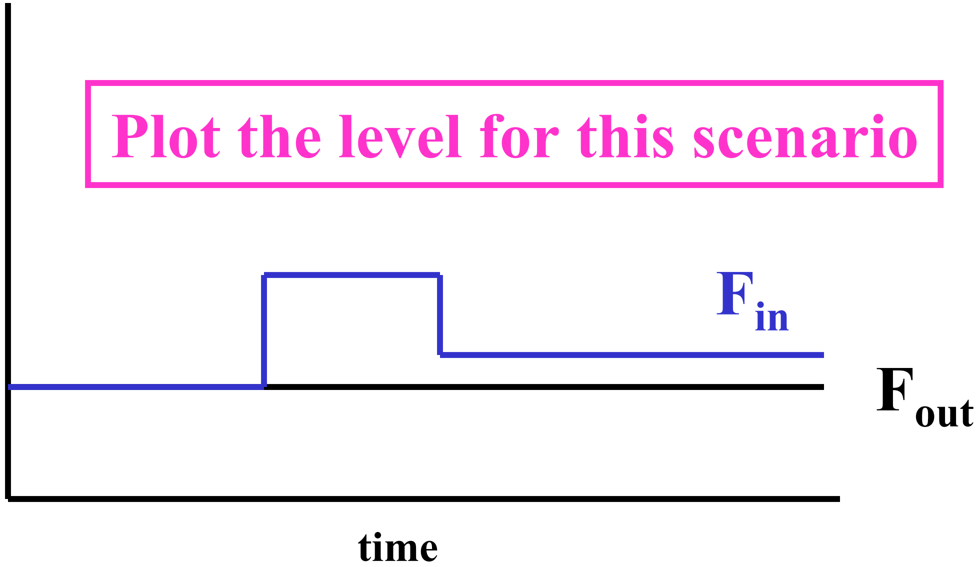
Plants have many inventories whose flows in and out do not depend on the inventory (when we apply no control or manual correction).

These systems are often termed "pure integrators" because they integrate the difference between in and out flows.

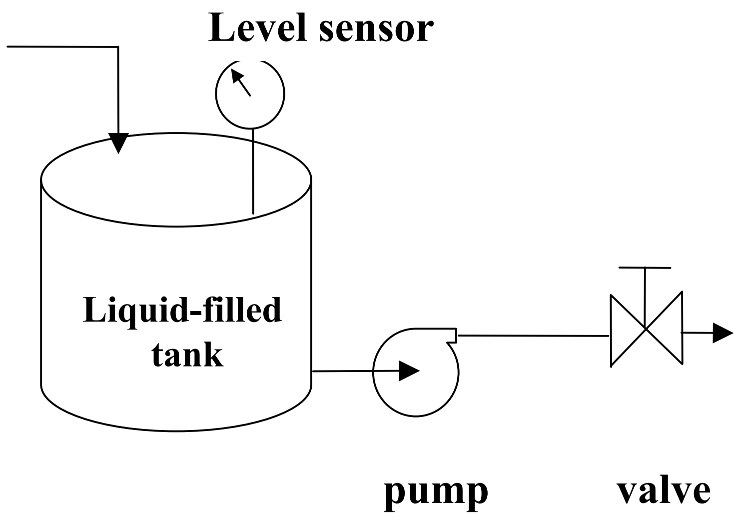
SIMPLE PROCESS SYSTEMS: INTEGRATOR



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



SIMPLE PROCESS SYSTEMS: INTEGRATOR



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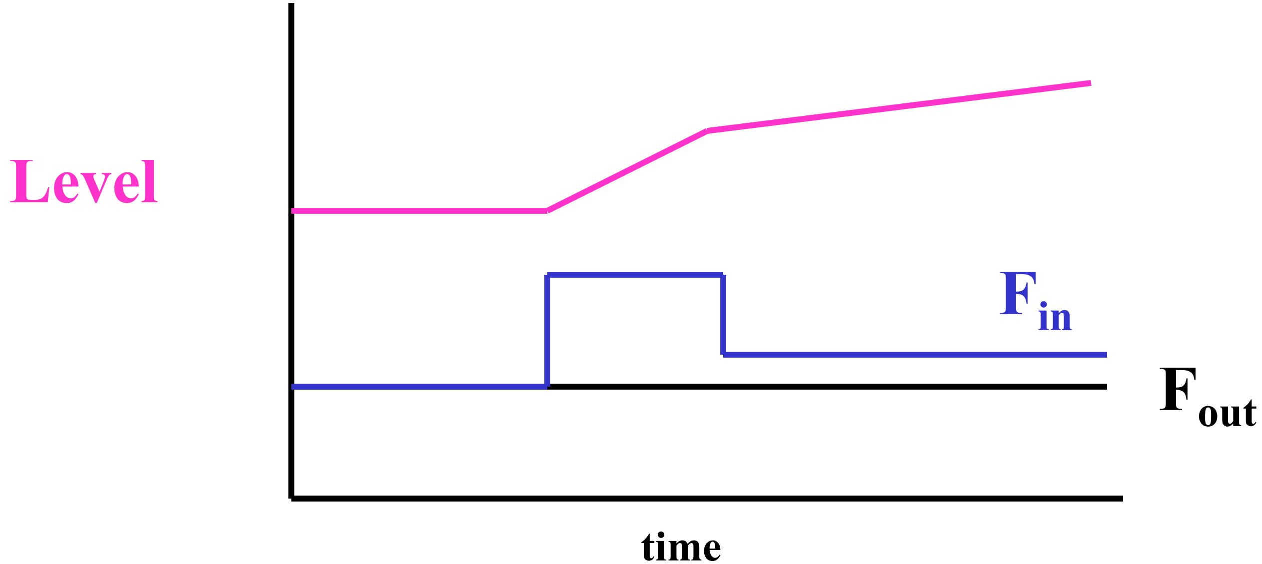
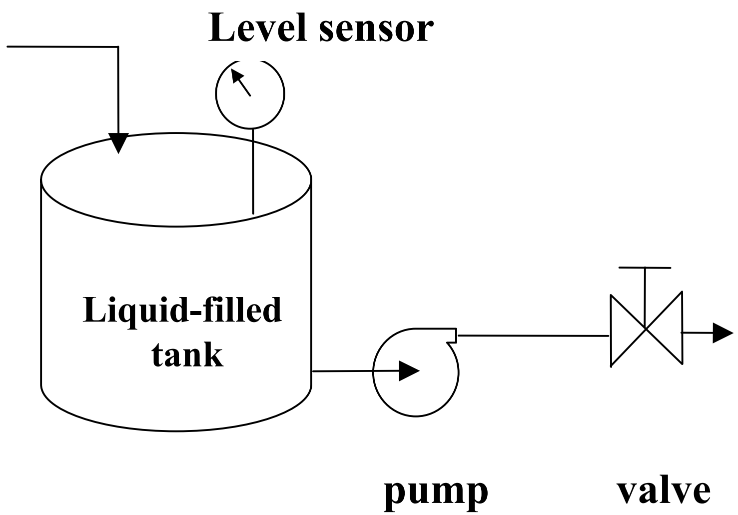
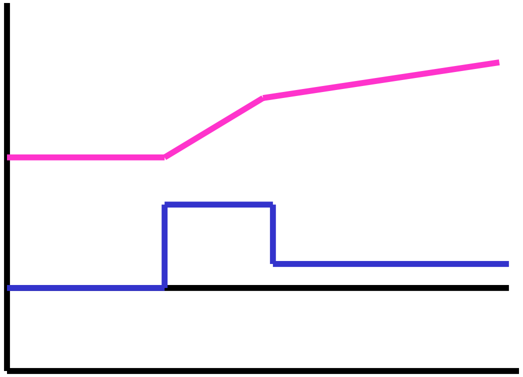


SIMPLE PROCESS SYSTEMS: INTEGRATOR



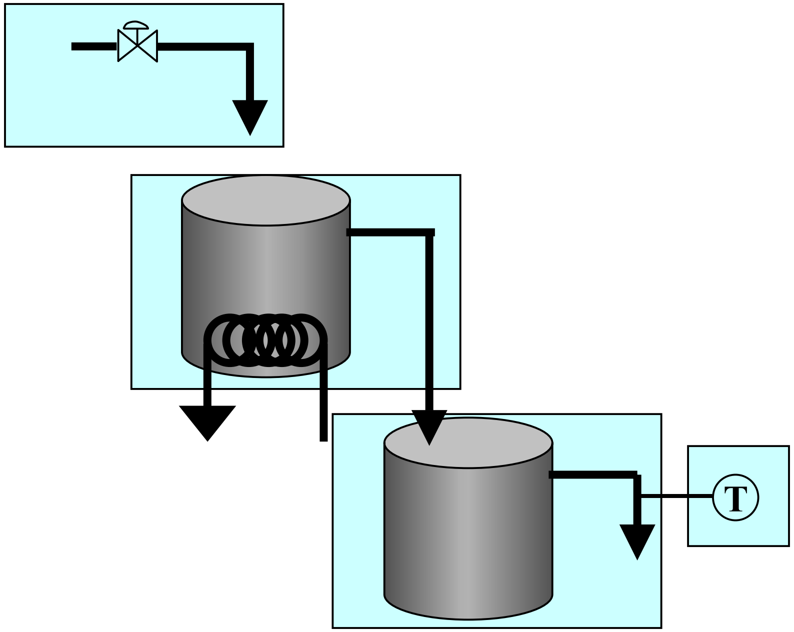


- Non-self-regulatory variables tend to "drift" far from desired values.
- We must control these variables.

STRUCTURES OF PROCESS SYSTEMS

NON-INTERACTING SERIES

- The output from an element does not influence the input to the same element
- Common example is tanks in series with pumped flow between
- Block diagram as shown



STRUCTURES OF PROCESS SYSTEMS

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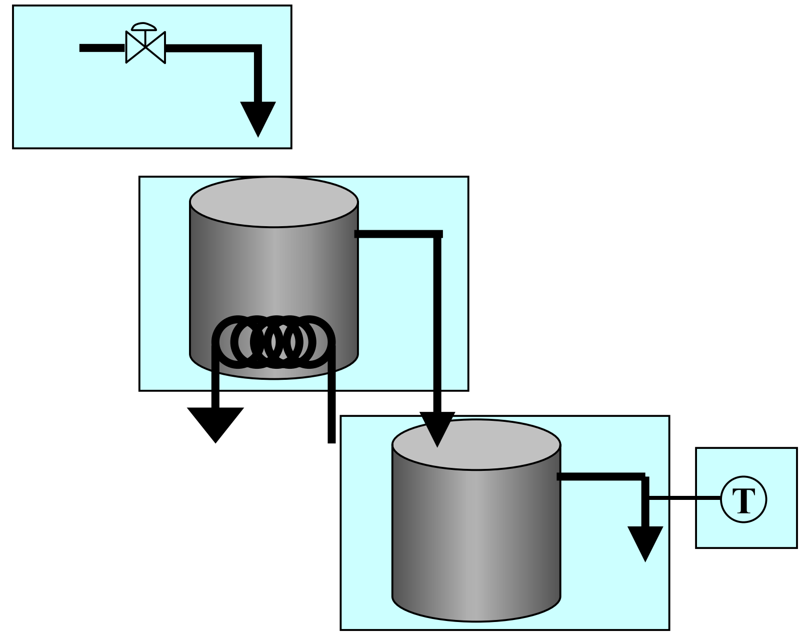
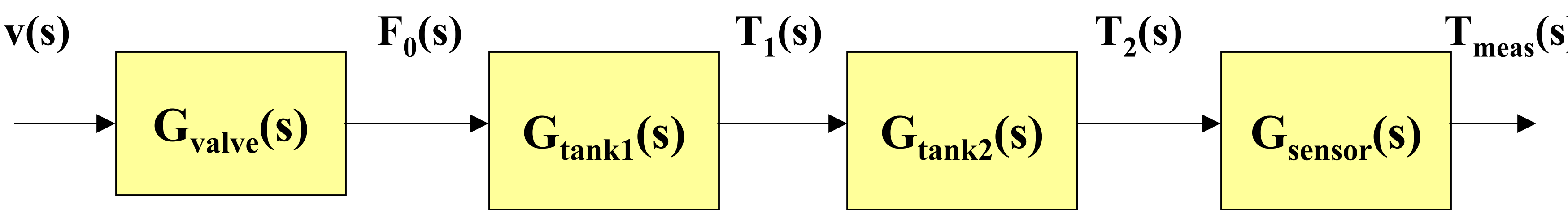
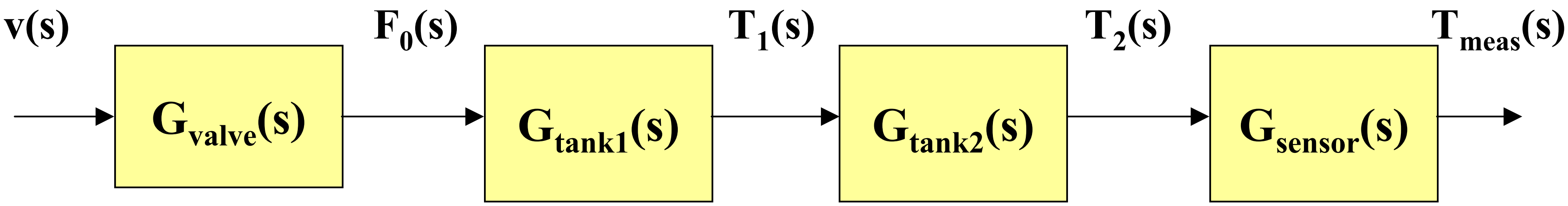




STRUCTURES OF PROCESS SYSTEMS

NON-INTERACTING SERIES



STRUCTURES OF PROCESS SYSTEMS

NON-INTERACTING SERIES

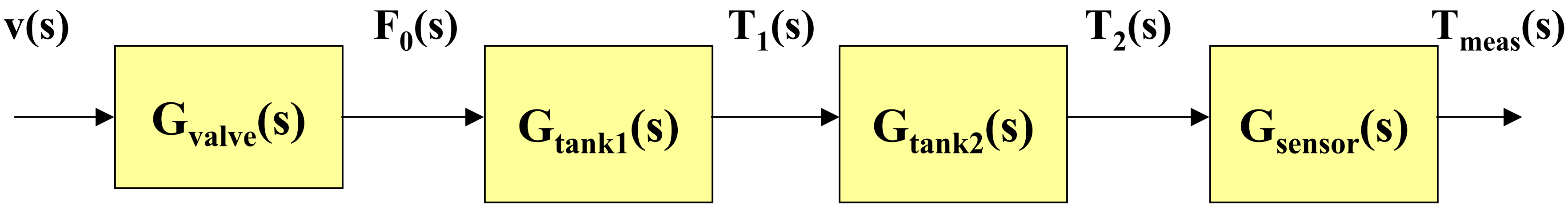
$$\xrightarrow{v(s)} \boxed{G_{valve}(s)} \xrightarrow{F_0(s)} \boxed{G_{tank1}(s)} \xrightarrow{T_1(s)} \boxed{G_{tank2}(s)} \xrightarrow{T_2(s)} \boxed{G_{sensor}(s)} \xrightarrow{T_{meas}(s)}$$

In general:

$$\frac{Y(s)}{X(s)} = \prod_{i=1}^{n} G_i(s)$$

STRUCTURES OF PROCESS SYSTEMS

NON-INTERACTING SERIES



In general:

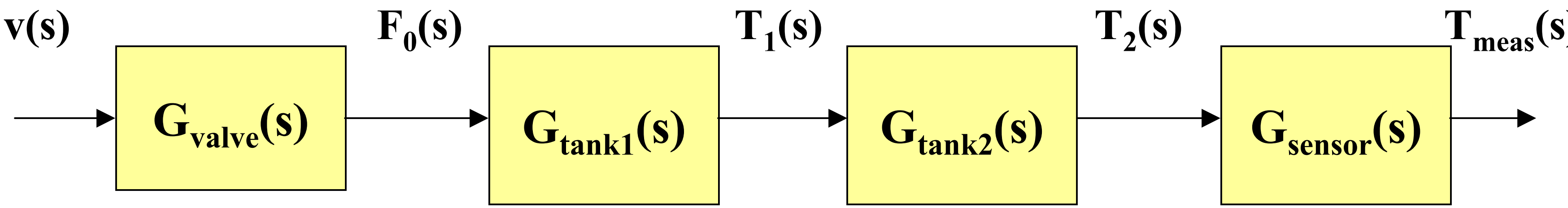
$$\frac{Y(s)}{X(s)} = \prod_{i=1}^{n} G_i(s)$$

With each element a first order system:

$$\frac{Y(s)}{X(s)} = \prod_{i=1}^{n} \frac{K_i}{(\tau_i s + 1)}$$

STRUCTURES OF PROCESS SYSTEMS

NON-INTERACTING SERIES



In general:

$$\frac{Y(s)}{X(s)} = \prod_{i=1}^{n} G_i(s)$$

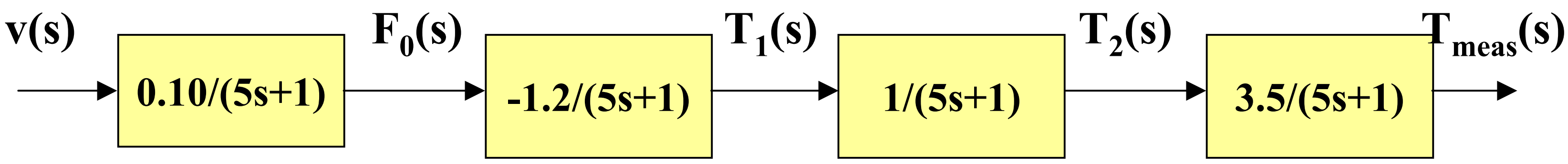
With each element a first order system:

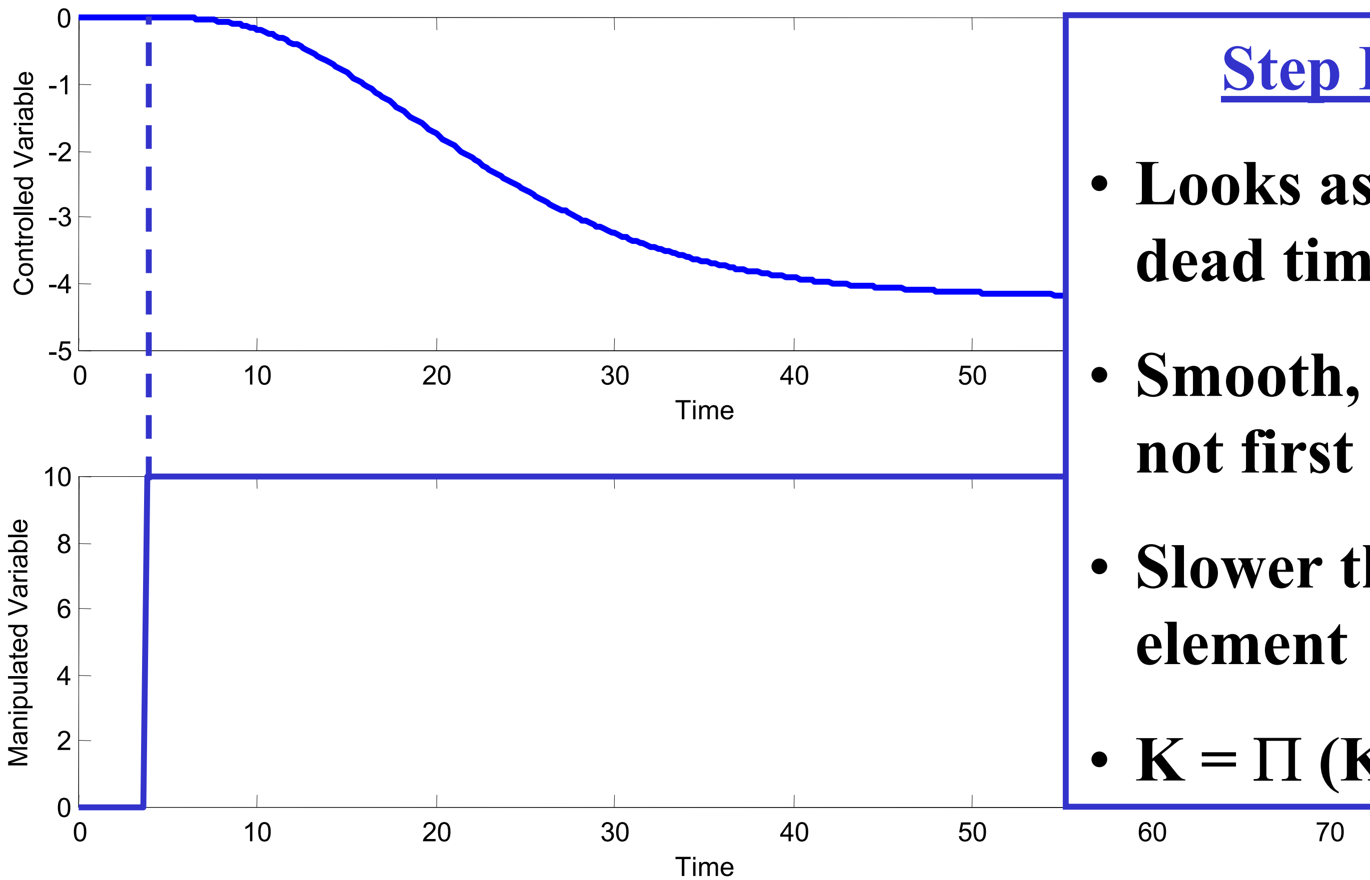
$$\frac{Y(s)}{X(s)} = \prod_{i=1}^{n} \frac{K_i}{(\tau_i s + 1)}$$

- overall gain is product of gains
- no longer first order system
- slower than any single element

STRUCTURES OF PROCESS SYSTEMS

NON-INTERACTING SERIES



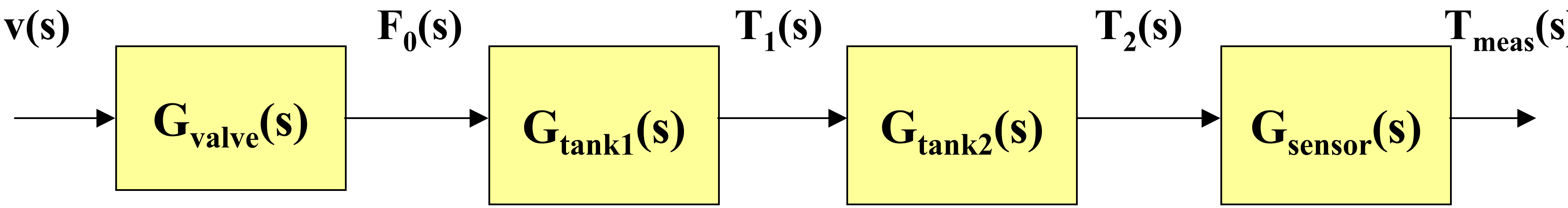


Step Response

- Looks as though some dead time occurs
- Smooth, monotonic, not first order
- Slower than any element
- $K = \Pi\ (K_i)$

STRUCTURES OF PROCESS SYSTEMS

NON-INTERACTING SERIES



With each element a first order system with dead time:

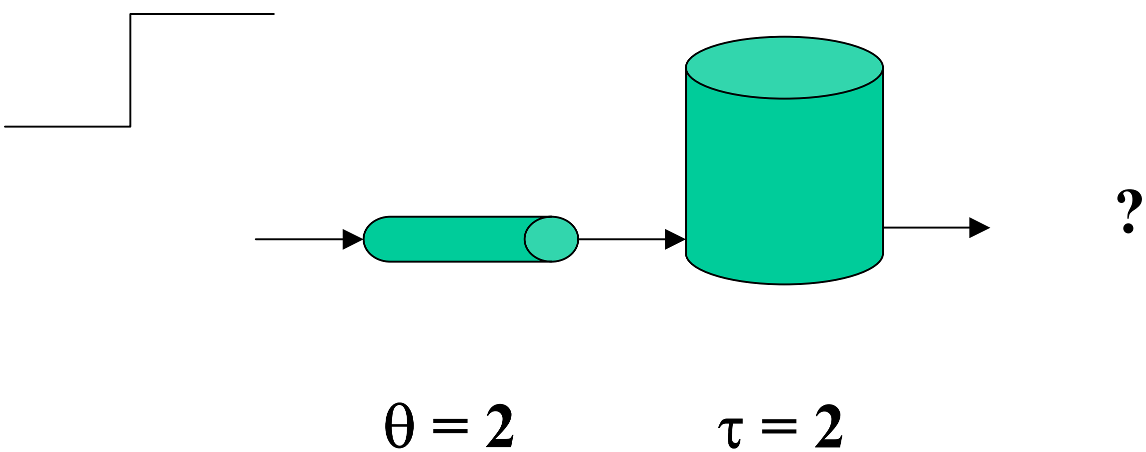
$$\frac{Y(s)}{X(s)} = \prod_{i=1}^{n} \frac{K_i e^{-\theta_i s}}{(\tau_i s + 1)}$$

Guidelines on step response

- **Sigmoidal ("S") shaped**
- $t_{63\%} \approx \Sigma\ (\theta_i + \tau_i)$ **[not rigorous!]**
- $K = \Pi\ (K_i)$ **[rigorous!]**
- **Usually, some "apparent dead time" occurs**

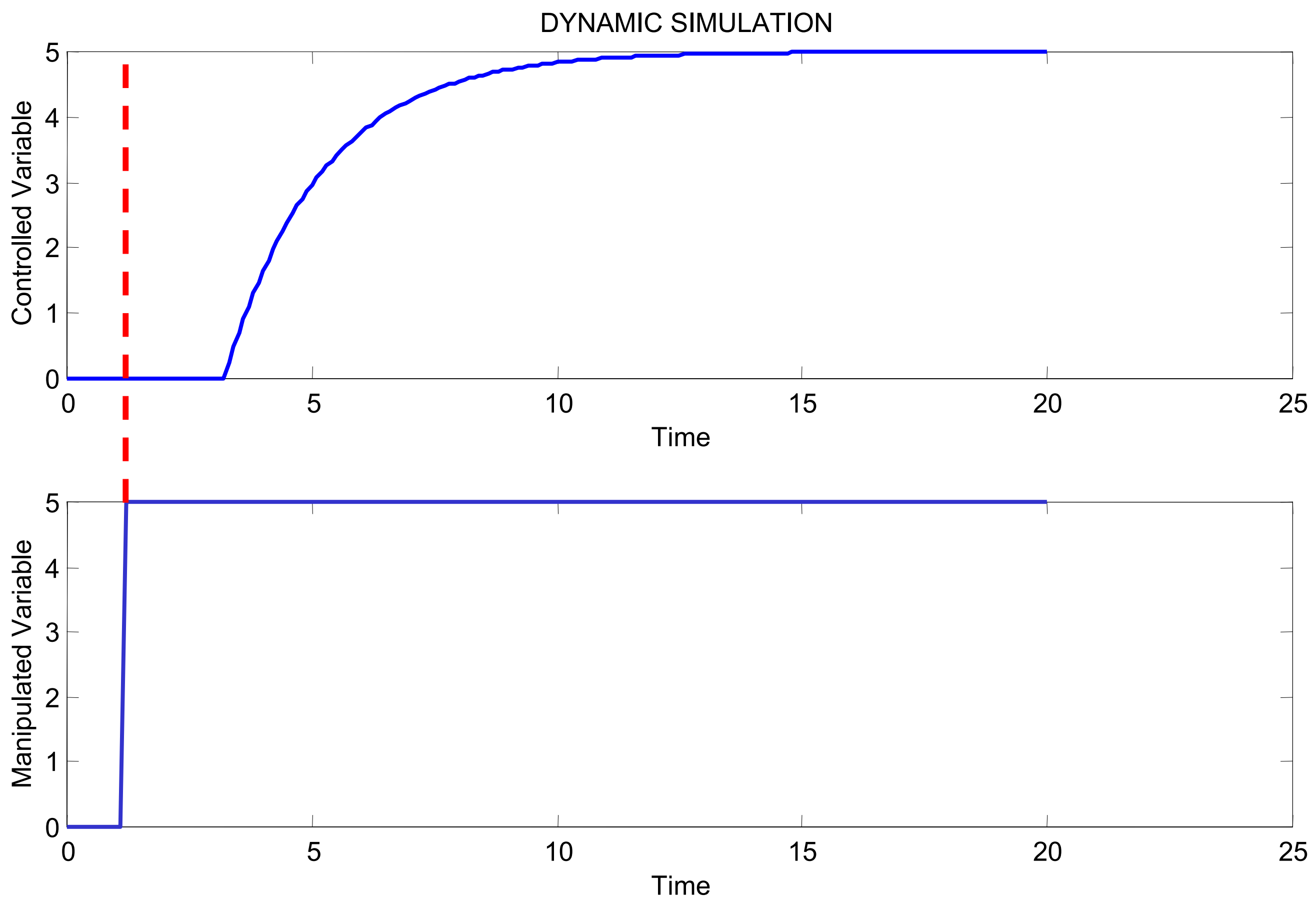
STRUCTURES OF PROCESS SYSTEMS

Class Exercise: Sketch the step response for the system below.



STRUCTURES OF PROCESS SYSTEMS

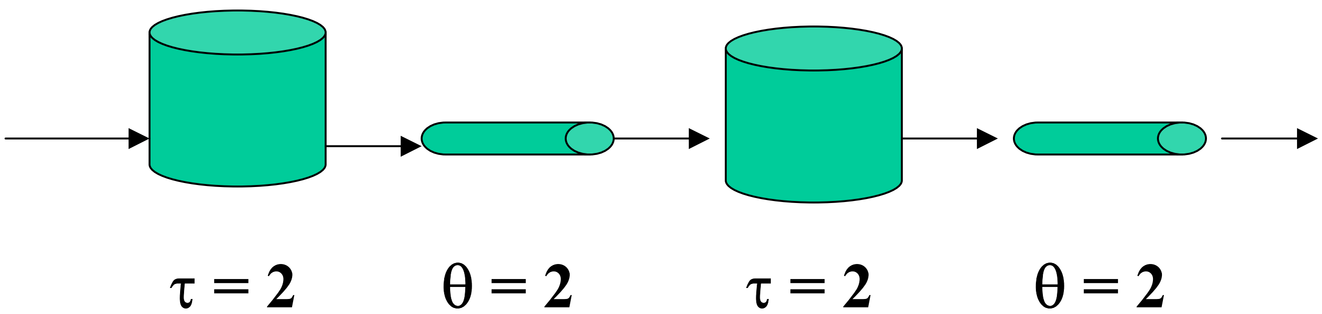
Class Exercise: **Sketch the step response for the system below.**



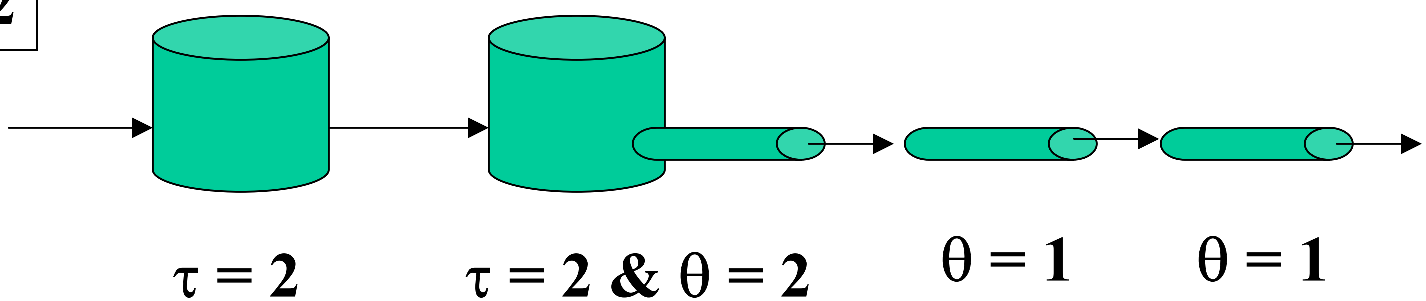
STRUCTURES OF PROCESS SYSTEMS

Class Exercise: Sketch the step response for each of the systems below and compare the results.

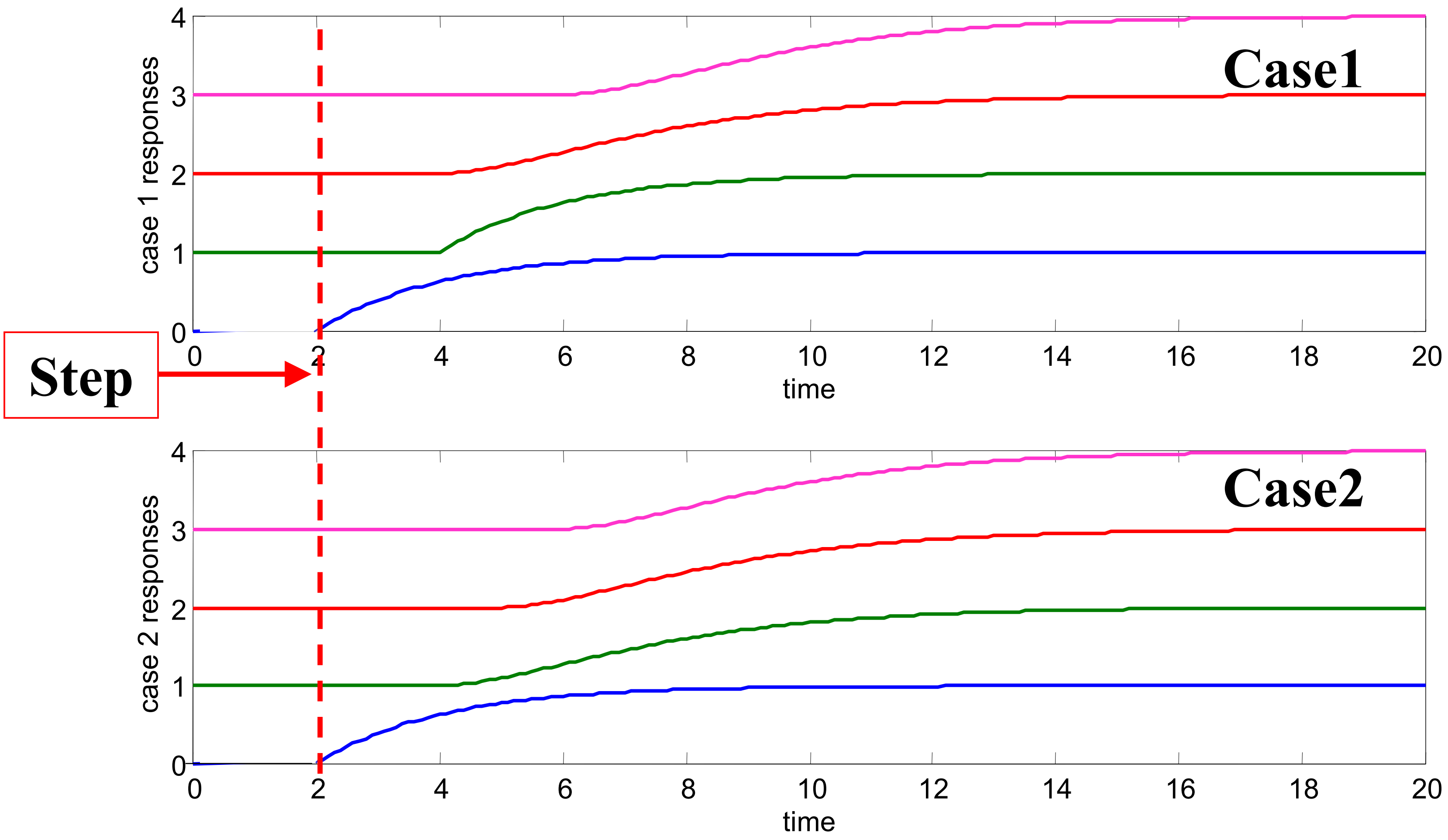
Case 1



Case 2



Two plants can have different intermediate variables and have the same input-output behavior!

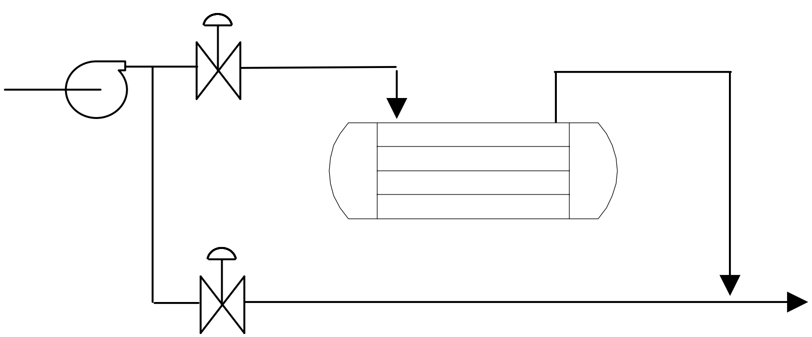


STRUCTURES OF PROCESS SYSTEMS

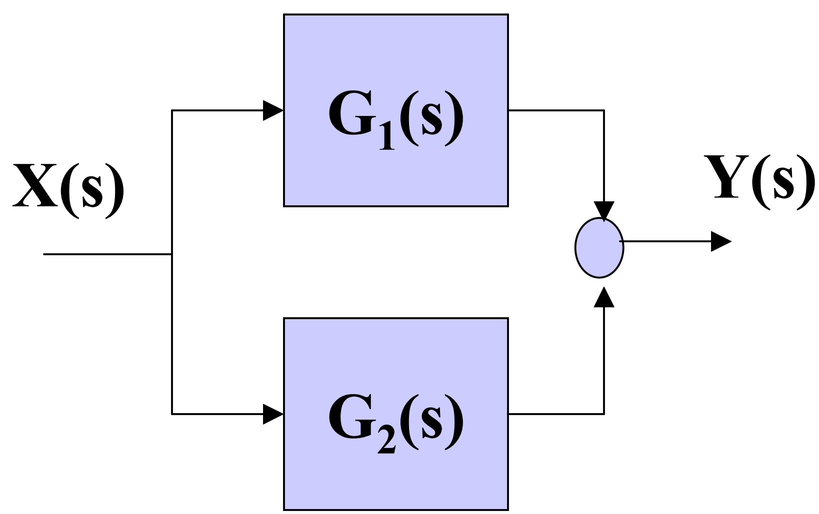
PARALLEL STRUCTURES **result from more than one causal path between the input and output. This can be a flow split, but it can be from other process relationships.**

Example process systems

$$A \rightarrow B \rightarrow C$$

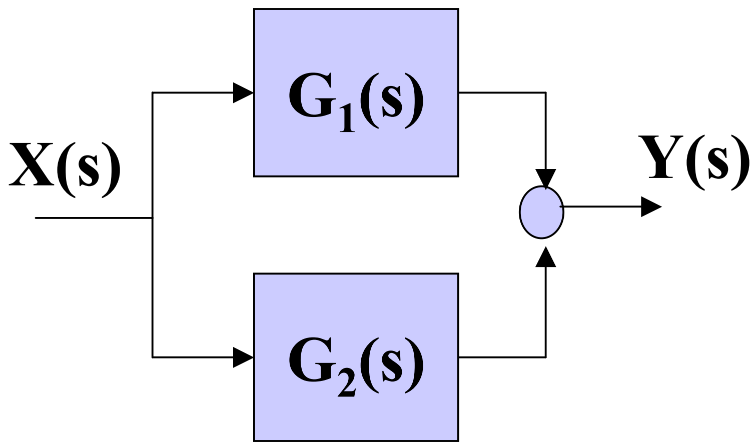


Block diagram



STRUCTURES OF PROCESS SYSTEMS

PARALLEL STRUCTURES



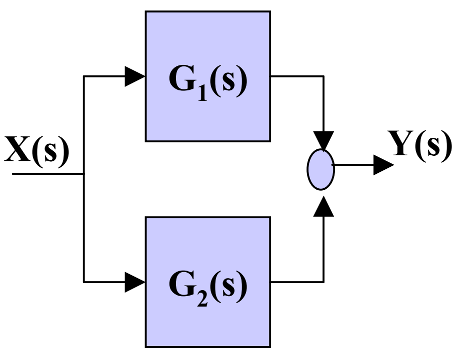
If both elements are first order, the overall model is

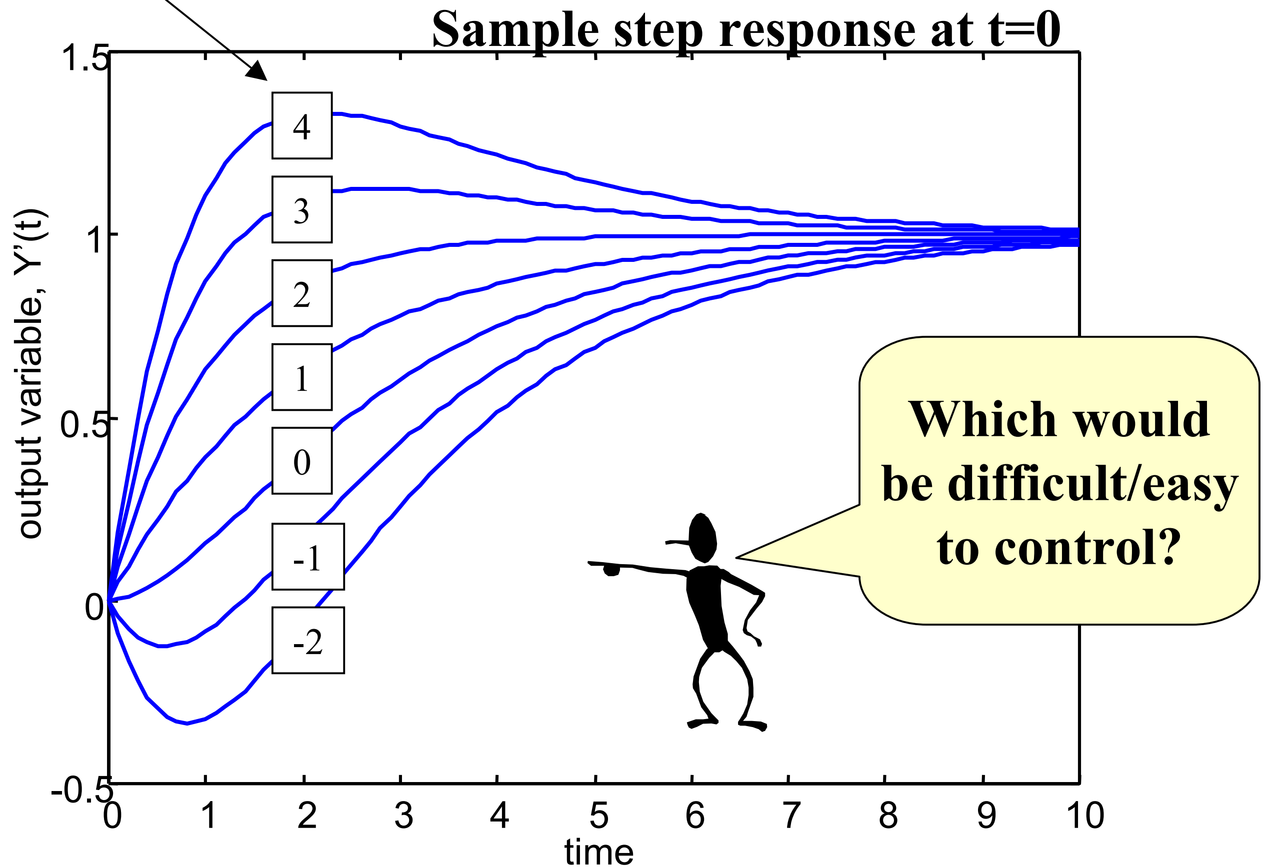
Class exercise: **Derive this transfer function**

$$\frac{Y(s)}{X(s)} = \frac{K_p(\tau_3 s + 1)}{(\tau_1 s + 1)(\tau_2 s + 1)}$$

STRUCTURES OF PROCESS SYSTEMS

PARALLEL STRUCTURES can experience complex dynamics. Parameter is the "zero" in the transfer function.

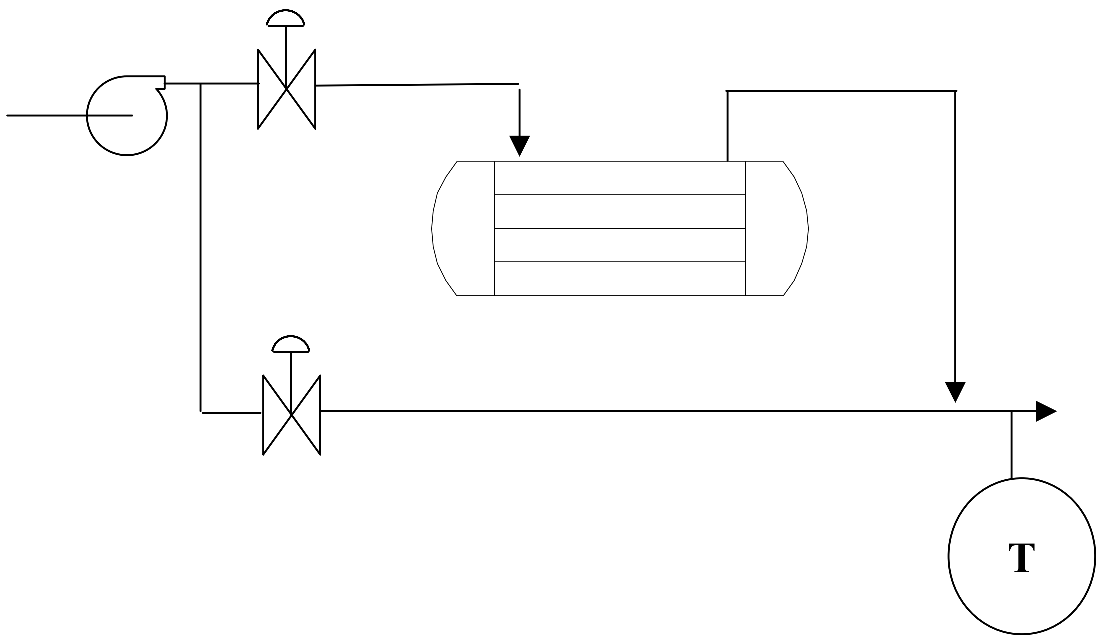




STRUCTURES OF PROCESS SYSTEMS

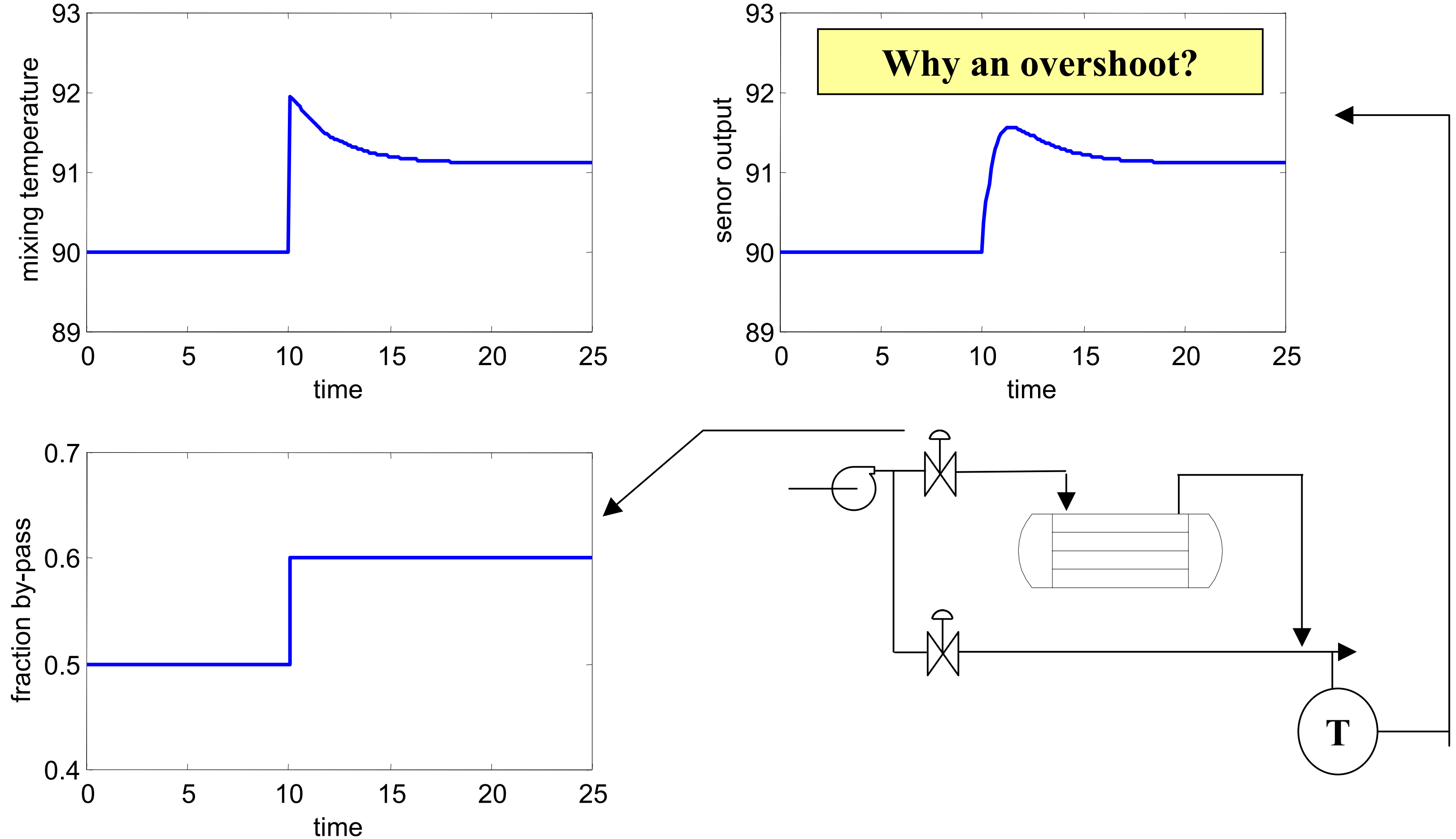
PARALLEL STRUCTURE

Class exercise: **Explain the dynamics of the outlet temperature after a change to the flow ratio, with the total flow rate constant.**



STRUCTURES OF PROCESS SYSTEMS

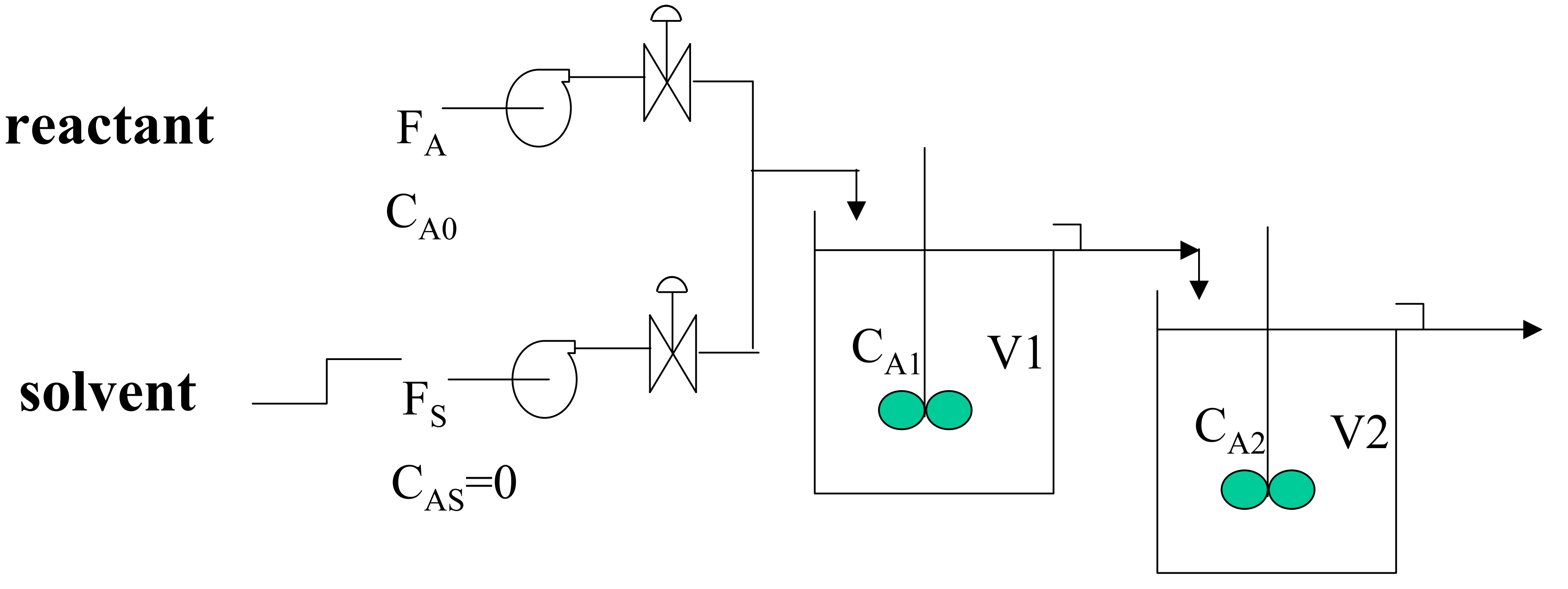
PARALLEL STRUCTURES: **Explain the dynamics of the outlet temperature after a step change to the flow ratio.**



STRUCTURES OF PROCESS SYSTEMS

PARALLEL STRUCTURE

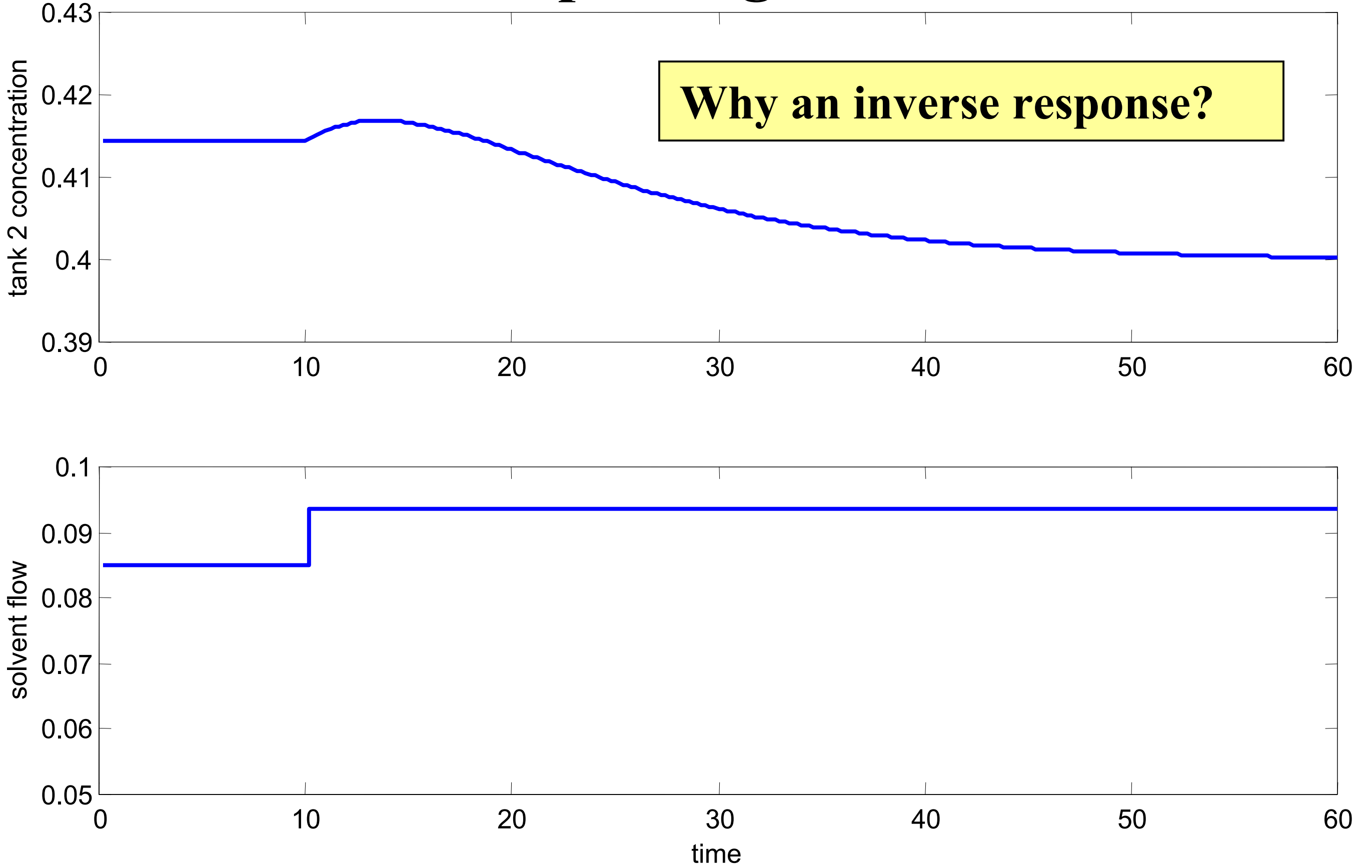
Class exercise: Explain the dynamics of the outlet concentration after a step change to the solvent flow rate.



STRUCTURES OF PROCESS SYSTEMS

PARALLEL STRUCTURE

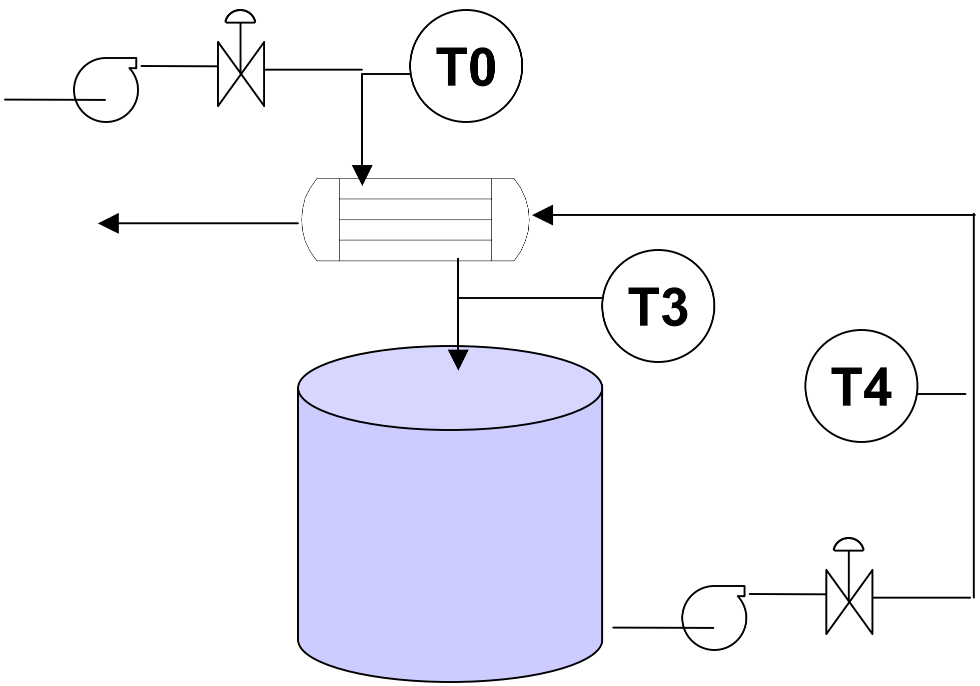
Class exercise: Explain the dynamics of the outlet concentration after a step change to the solvent flow rate.



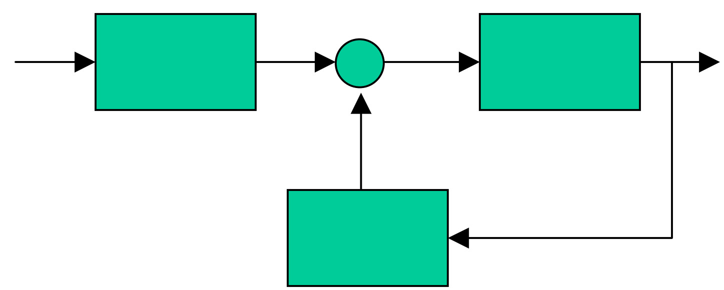
STRUCTURES OF PROCESS SYSTEMS

RECYCLE STRUCTURES result from recovery of material and energy. They are essential for profitable operation, but they strongly affect dynamics.

Process example

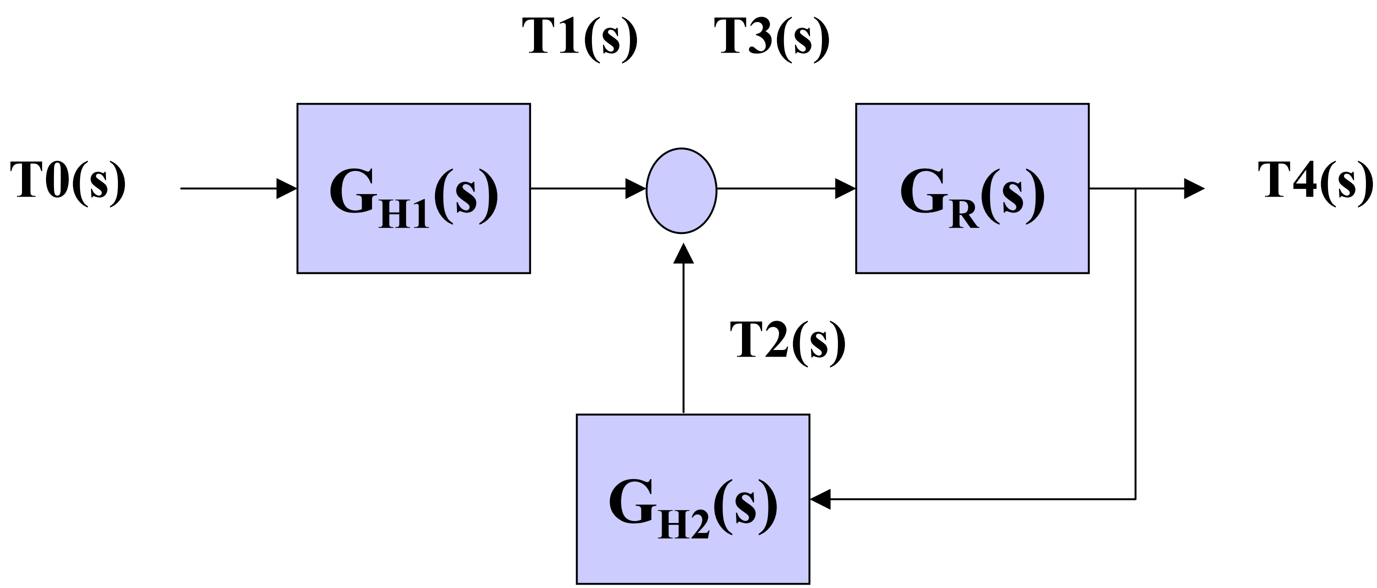


Block diagram



STRUCTURES OF PROCESS SYSTEMS

RECYCLE STRUCTURES

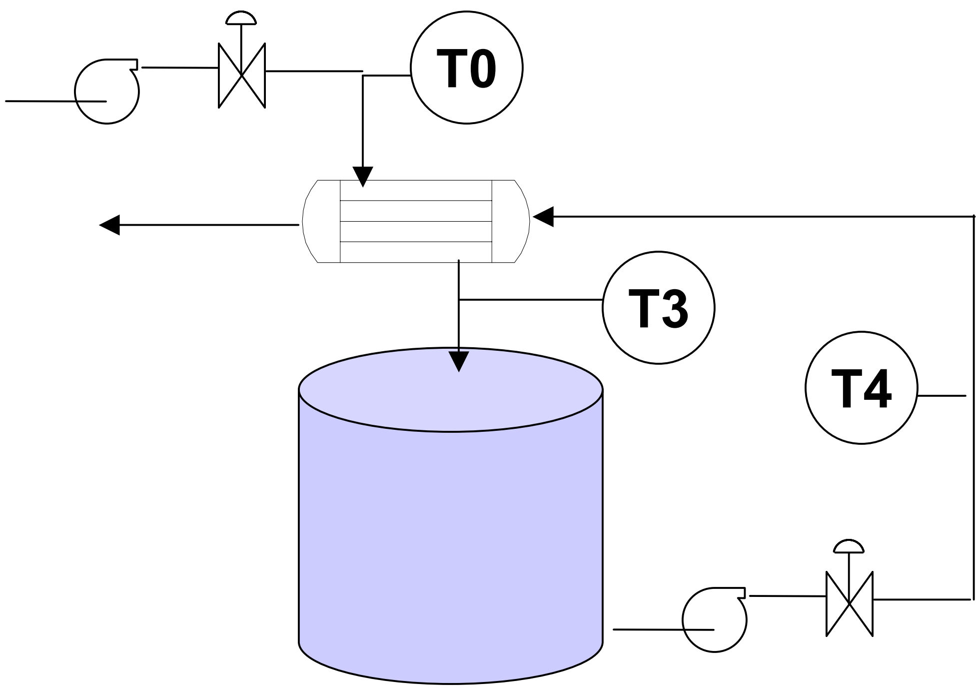


$$\frac{T4(s)}{T0(s)} = \frac{G_R(s)G_{H1}(s)}{1 - G_R(s)G_{H2}(s)}$$

STRUCTURES OF PROCESS SYSTEMS

RECYCLE STRUCTURES

Class exercise: Determine the effect of recycle on the dynamics of a chemical reactor (faster or slower?).



- Exothermic reaction
- feed/effluent preheater

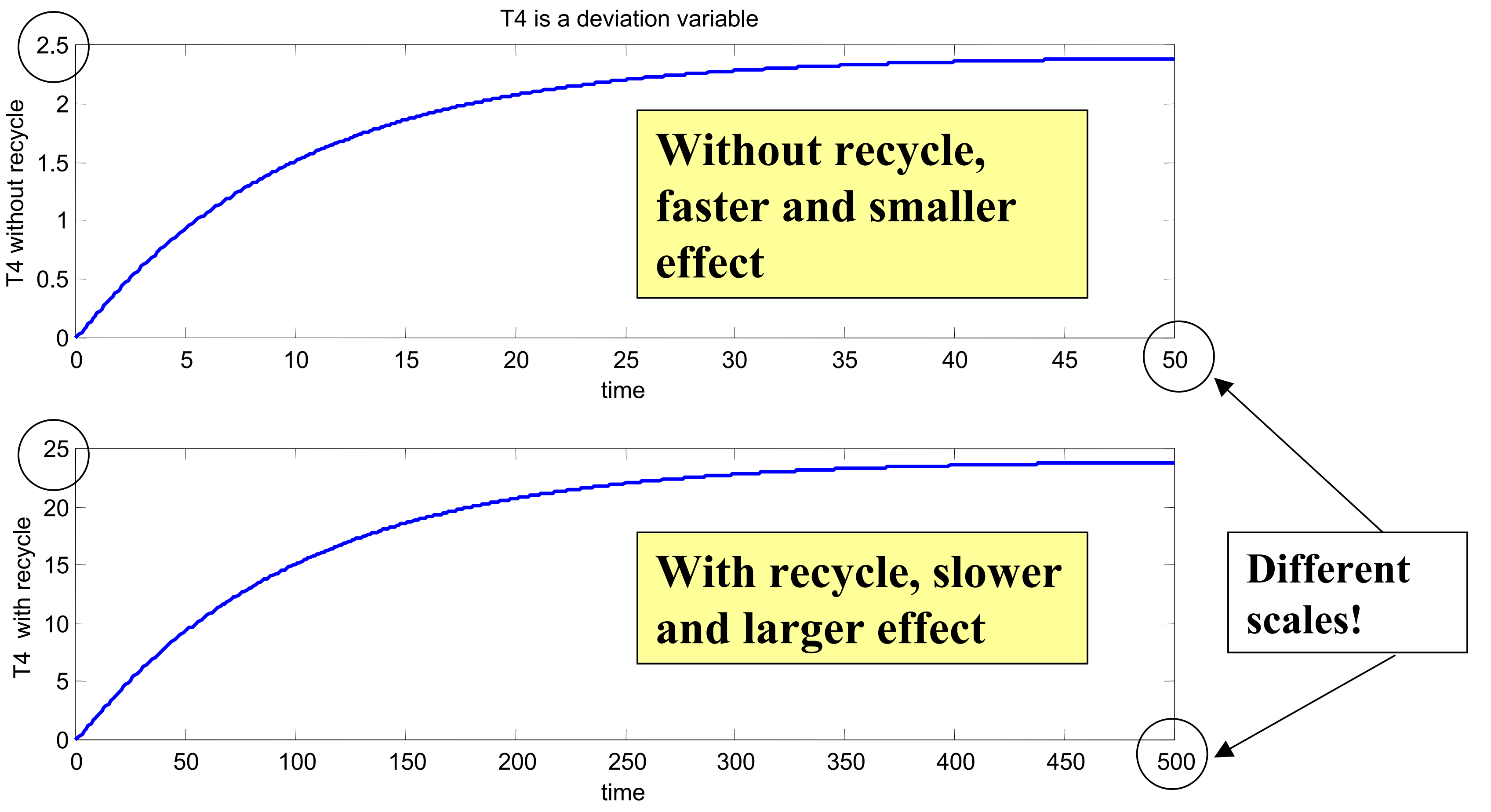
$$G_{H1}(s) = 0.40 \quad K/K$$

$$G_{H2}(s) = 0.30 \quad K/K$$

$$G_R(s) = 3/(10s+1)$$

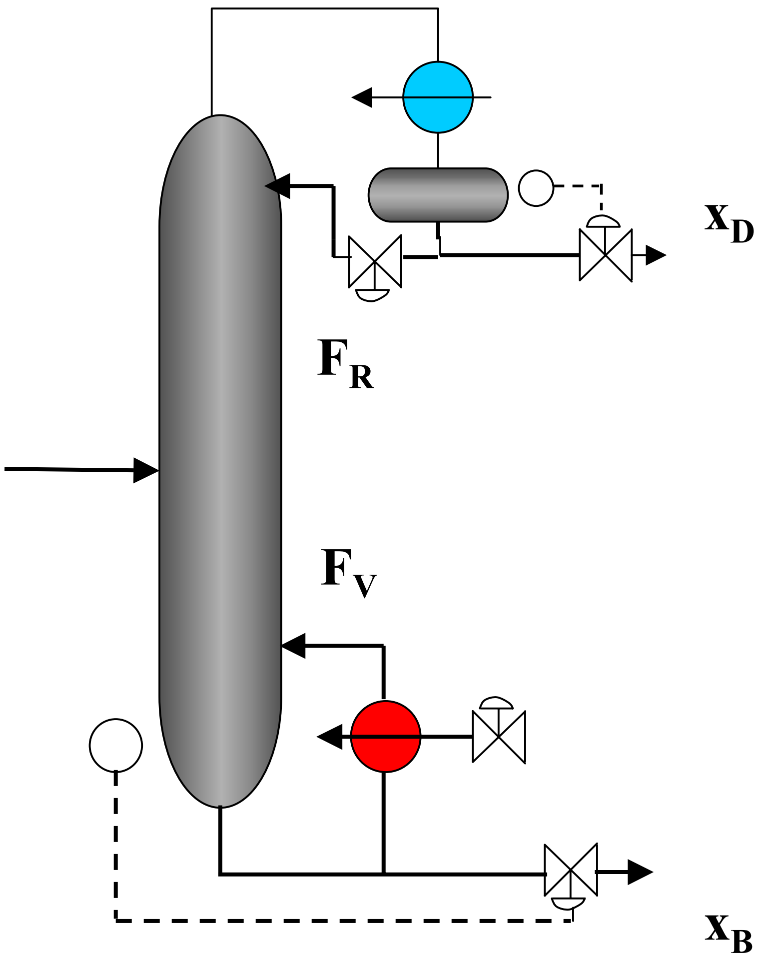
STRUCTURES OF PROCESS SYSTEMS

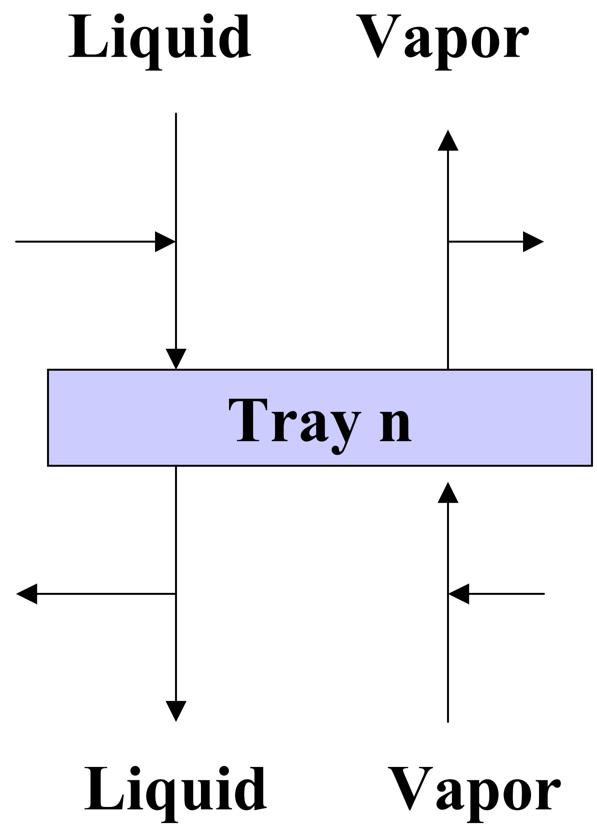
Class exercise: Determine the effect of recycle on the dynamics of a chemical reactor (faster or slower?).



STRUCTURES OF PROCESS SYSTEMS

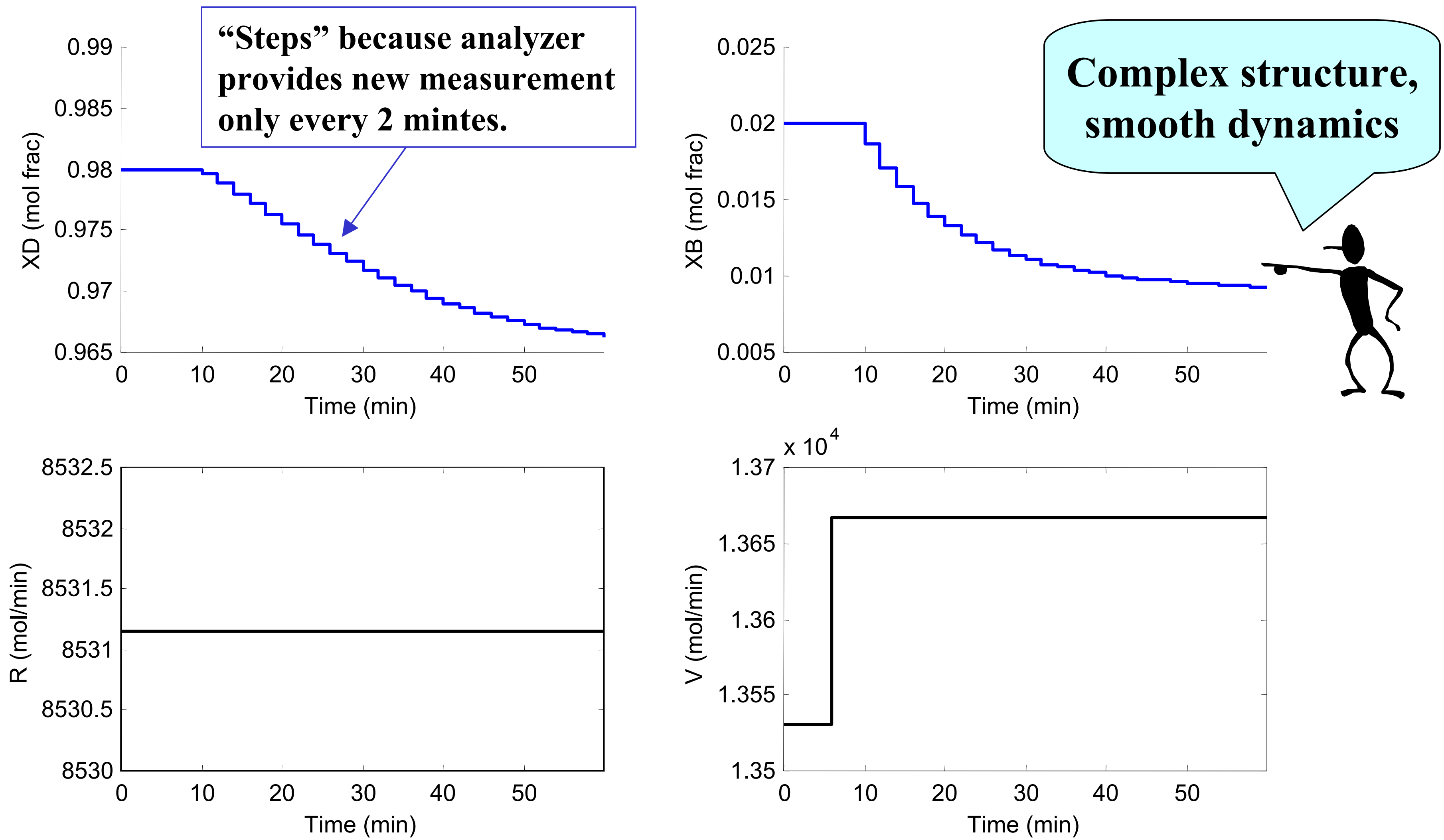
STAGED STRUCTURES





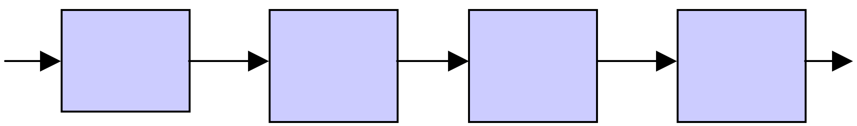
STRUCTURES OF PROCESS SYSTEMS

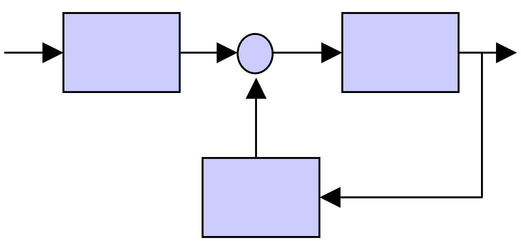
STAGED STRUCTURES

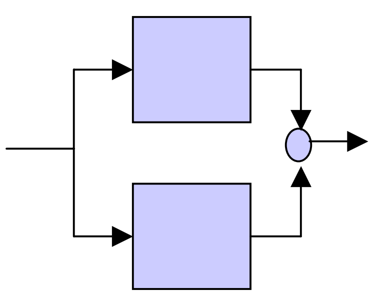


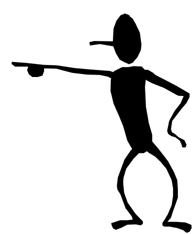
OVERVIEW OF PROCESS SYSTEMS

Even simple elements can yield complex dynamics when combined in typical process structures.







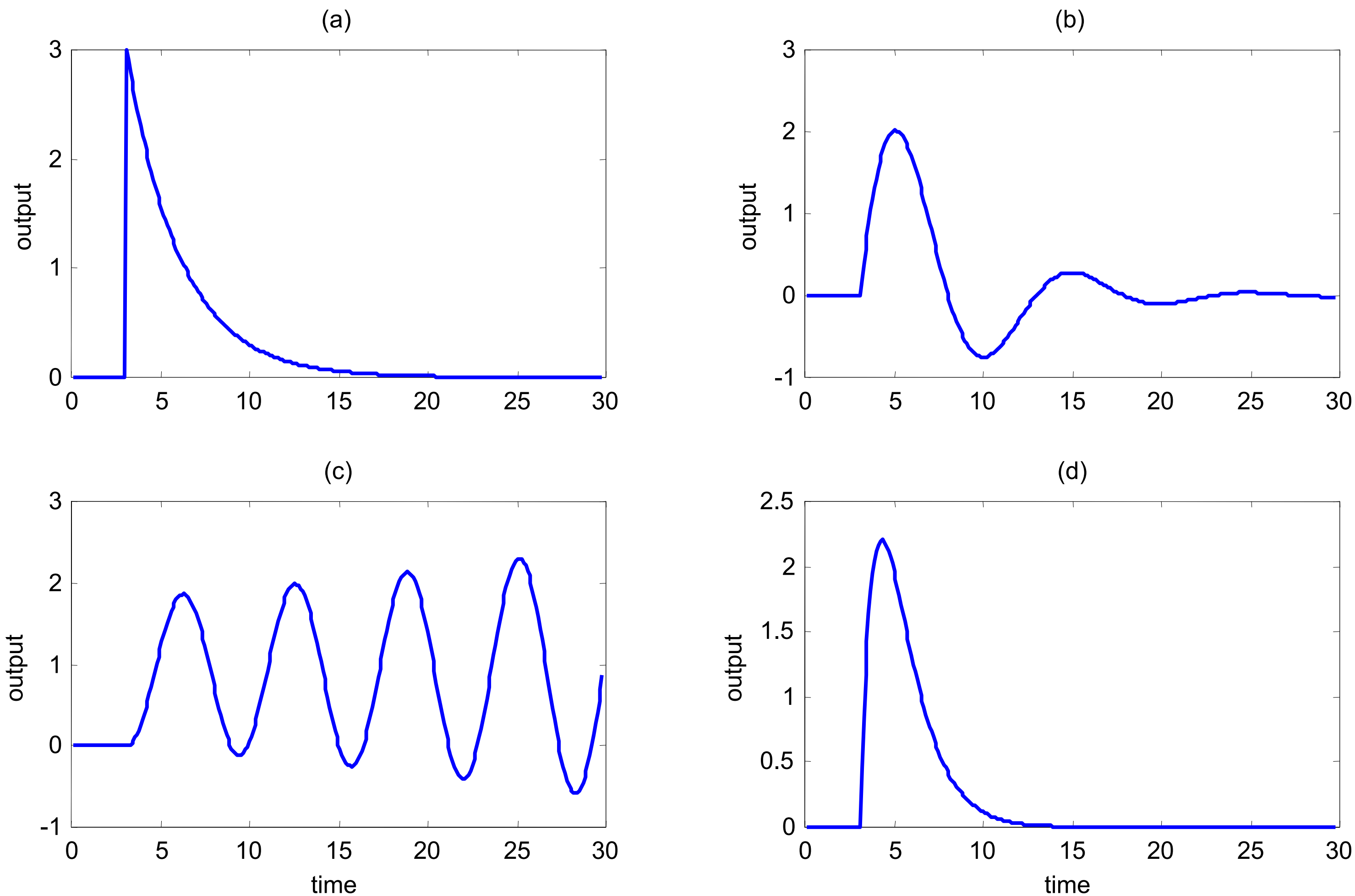


We can

- **Estimate the dynamic response based on elements and structure**
- **Recognize range of effects possible**
- **Apply analysis methods to yield dynamic model**

CHAPTER 5: PROCESS SYSTEMS WORKSHOP 1

Four systems experienced an impulse input at t=2. Explain what you can learn about each system (dynamic model) from the figures below.

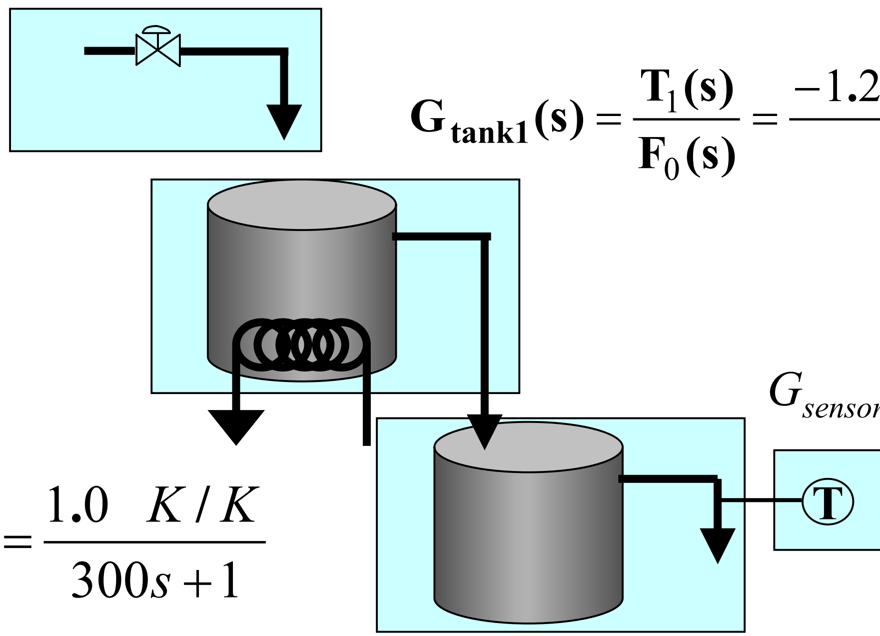


CHAPTER 5: PROCESS SYSTEMS WORKSHOP 2

Using the guidelines in this chapter, sketch the response of the measured temperature below to a +5% step to the valve.

$$G_{\text{valve}}(s) = \frac{F_0(s)}{v(s)} = .10 \ \ \mathrm{m^3/min} \big/ \%\ \text{open}$$

$$G_{\text{tank1}}(s) = \frac{T_1(s)}{F_0(s)} = \frac{-1.2 \ \ \mathrm{K/(m^3/min)}}{250s+1}$$



$$G_{\text{tank2}}(s) = \frac{T_2(s)}{T_1(s)} = \frac{1.0 \ \ K/K}{300s+1}$$

$$G_{sensor}(s) = \frac{T_{measured}(s)}{T_2(s)} = \frac{1.0 \ \ K/K}{10s+1}$$

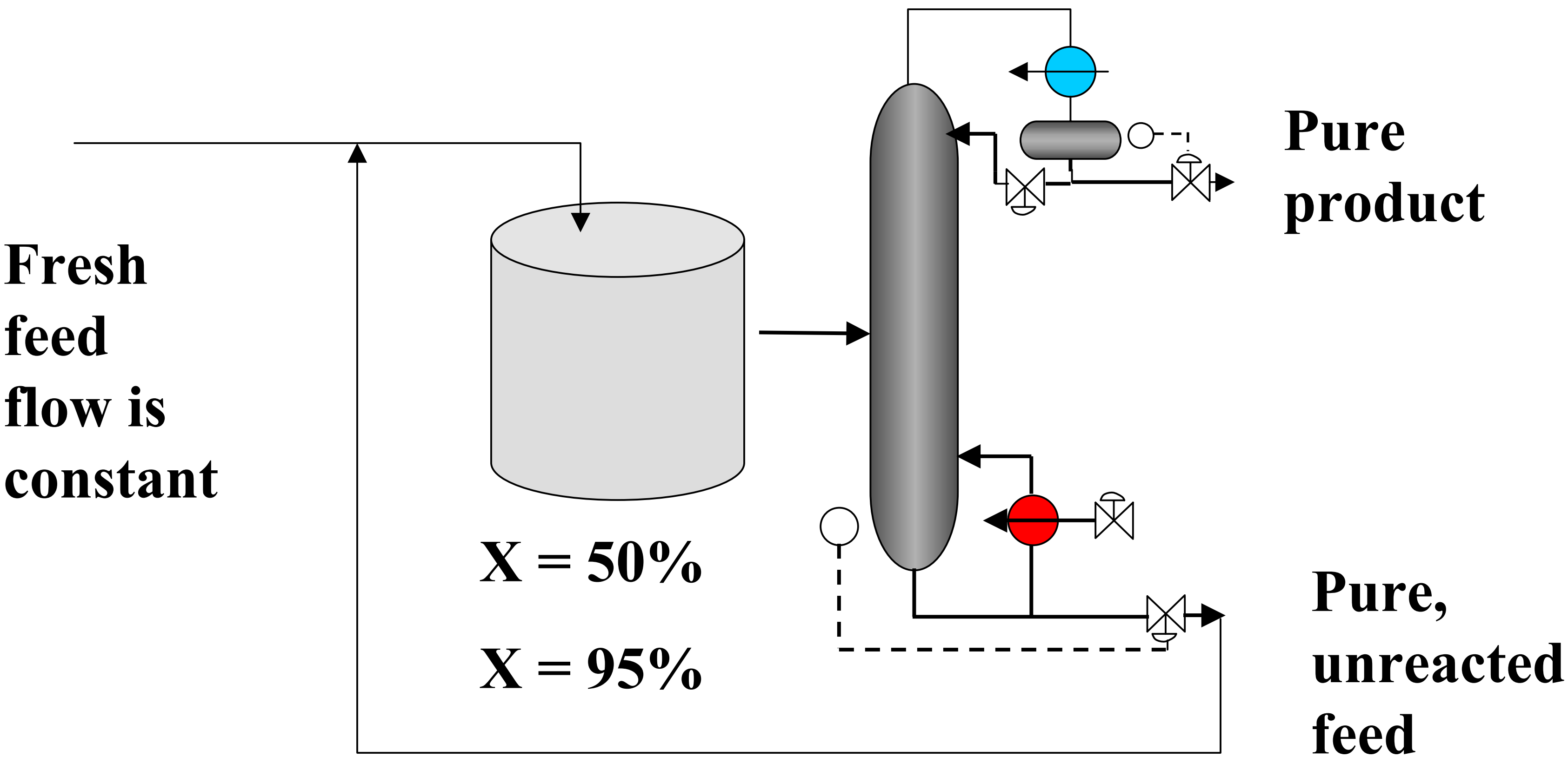
(Time in seconds)

CHAPTER 5: PROCESS SYSTEMS WORKSHOP 3

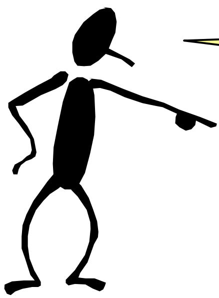
Sensors provide an estimate of the true process variable because the measurement is corrupted by errors.

- **Discuss sources of noise in a measurement.**
- **Define the following terms for a sensor**
  - Accuracy
  - Reproducibility
- **Explain some process measurements needing (a) good accuracy and (b) good reproducibility**
- **Suggest an approach for operating a process when a key material property (composition, etc.) cannot be measured using an onstream analyzer.**

We are designing the following reactor with recycle. We have two choices for the conversion in the reactor. Will the plant dynamics be affected by the selection?

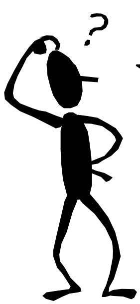


CHAPTER 5 : TYPICAL PROCESS SYSTEMS



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

- **Predict output for typical inputs for common dynamic systems**
- **Derive the dynamics for important structures of simple dynamic systems**
- **Recognize the strong effects on process dynamics caused by process structures**



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 5: LEARNING RESOURCES

- **<u>SITE PC-EDUCATION WEB</u>**
  - Instrumentation Notes
  - Interactive Learning Module (Chapter 5)
  - Tutorials (Chapter 5)

- **Software Laboratory**
  - S_LOOP program

- **Textbook**
  - Chapter 18 on level modelling and control
  - Appendix I on parallel structures

CHAPTER 5: SUGGESTIONS FOR SELF-STUDY

1. Extend textbook Figure 5.1 for new input functions (additional rows): impulse and ramp.
2. Determine which of the systems in textbook Figure 5.3 can be underdamped.
3. Explain the shape of the amplitude ratio as frequency increases for each system in textbook Figure 5.1.
4. Discuss the similarity/dissimilarity between self regulation and feedback.
5. Explain textbook Figure 5.5.
6. Discuss the similarity between recycle and feedback.

CHAPTER 5: SUGGESTIONS FOR SELF-STUDY

7. Discuss how the dynamics of the typical process elements and structures would affect our ability to control a process. Think about driving an automobile with each of the dynamics between the steering wheel and the direction that the auto travels.

8. Formulate one question in each of three categories (T/F, multiple choice, and modelling) with solution and exchange them with friends in your study group.