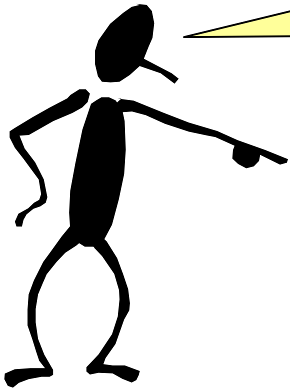
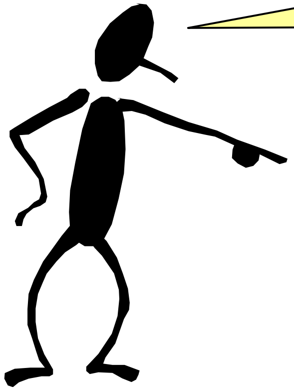
CHAPTER 19: Single-Loop IMC Control



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

- Recognize that other feedback algorithms are possible
- Understand the IMC structure and how it provides the essential control features
- Tune an IMC controller
- Correctly select between PID and IMC

CHAPTER 19: Single-Loop IMC Control



Outline of the lesson.

- **Thought exercise for model-based control**
- **IMC structure**
- **Desired control features**
- **IMC algorithm and tuning**
- **Application guidelines**

CHAPTER 19: Single-Loop IMC Control

Let's quickly review the PID algorithm

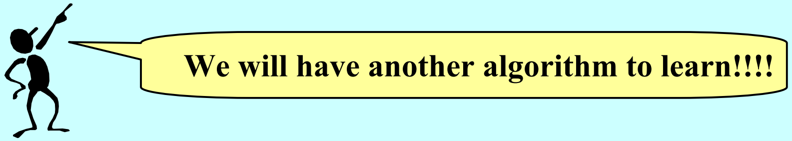
$$E(t) = SP(t) - CV(t)$$

$$MV(t) = K_c \left[E(t) + \frac{1}{T_I} \int_0^{\infty} E(t')dt' - T_d \frac{d\,CV}{dt} \right] + I$$

- PID was developed in **1940's**
- PID is not the only **feedback** algorithm
- PID gives good balance of **performance and robustness**
- PID does not always give the best performance
- **Multiple PIDs** are used for multivariable systems

CHAPTER 19: Single-Loop IMC Control

Let's look ahead to the IMC structure and algorithm

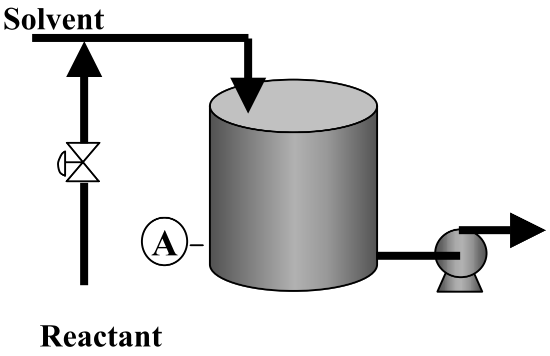


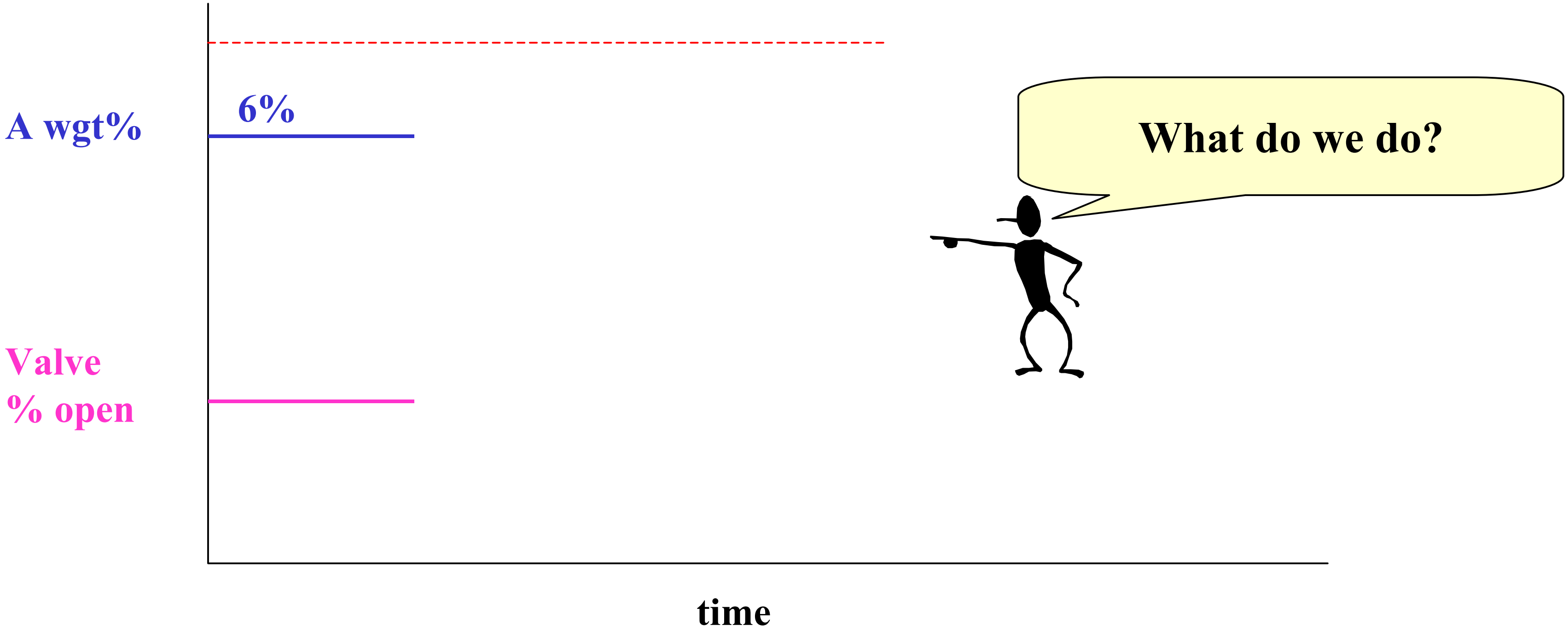
- **IMC was developed formally in 1980's, but the ideas began in 1950's**
- **IMC uses a process model *explicitly***
- **IMC involves a different structure and controller**
- **IMC could replace PID, but we chose to retain PID unless an advantage exists**
- **A single "IMC" can be used for multivariable systems**

CHAPTER 19: Single-Loop IMC Control

Let's do a thought experiment:

1. We want to control the concentration in the tank.
2. Initially, A = 6 wgt%
   We want A = 7 wgt%
3. From data, we know that
   $\Delta A/\Delta v$ = 0.5 wgt%/% open





CHAPTER 19: Single-Loop IMC Control

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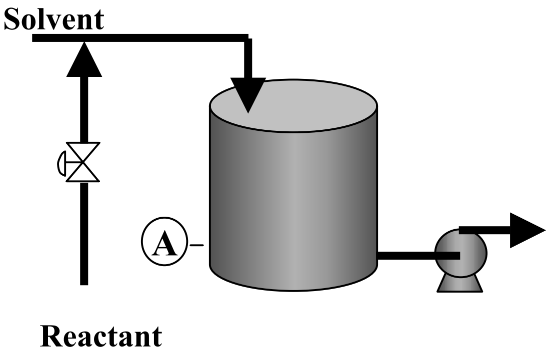

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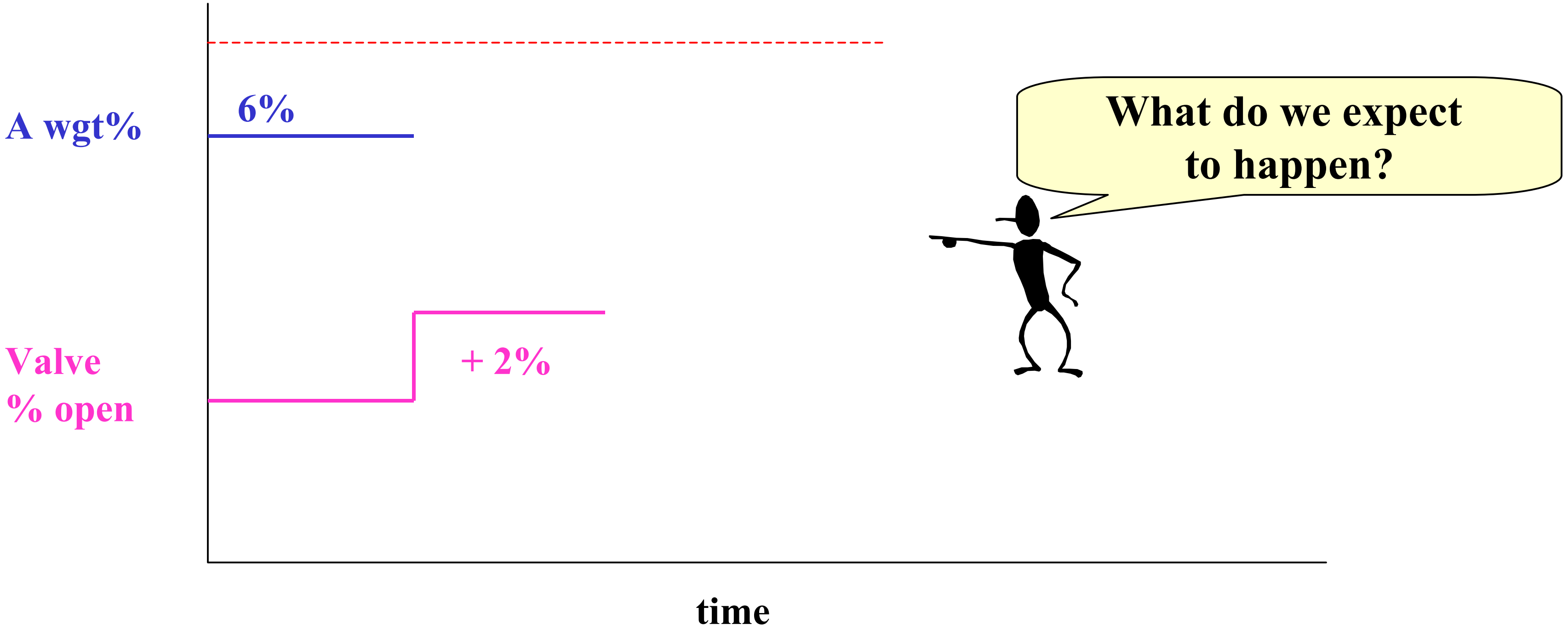

CHAPTER 19: Single-Loop IMC Control

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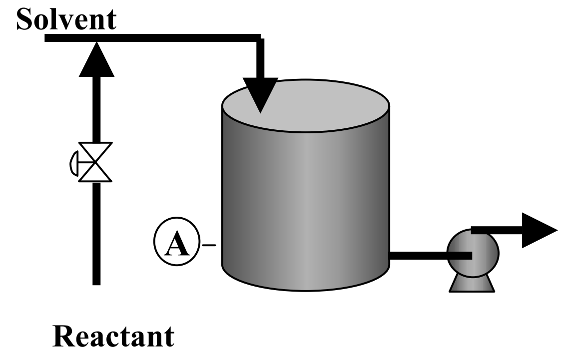
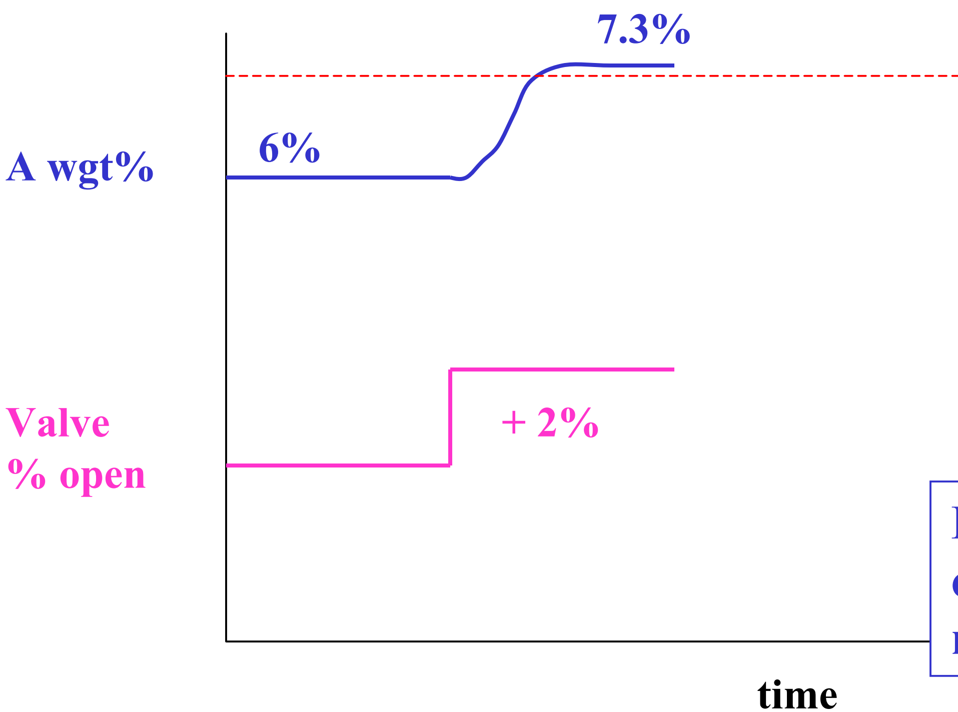
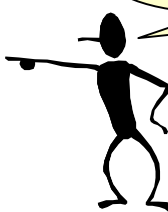




- Should we be surprised?
- What do we do now?
- Devise 2 different responses



Hint: We used a model for the first calculation. What do we do if the model is in error?

CHAPTER 19: Single-Loop IMC Control

Let's do a thought experiment:

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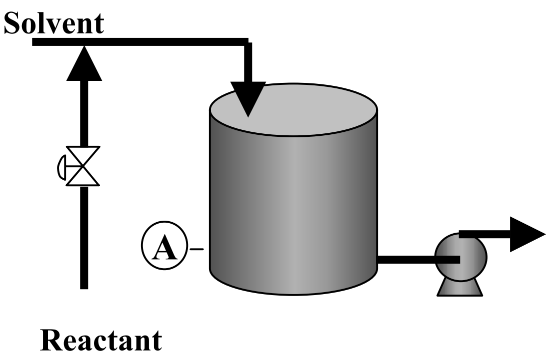
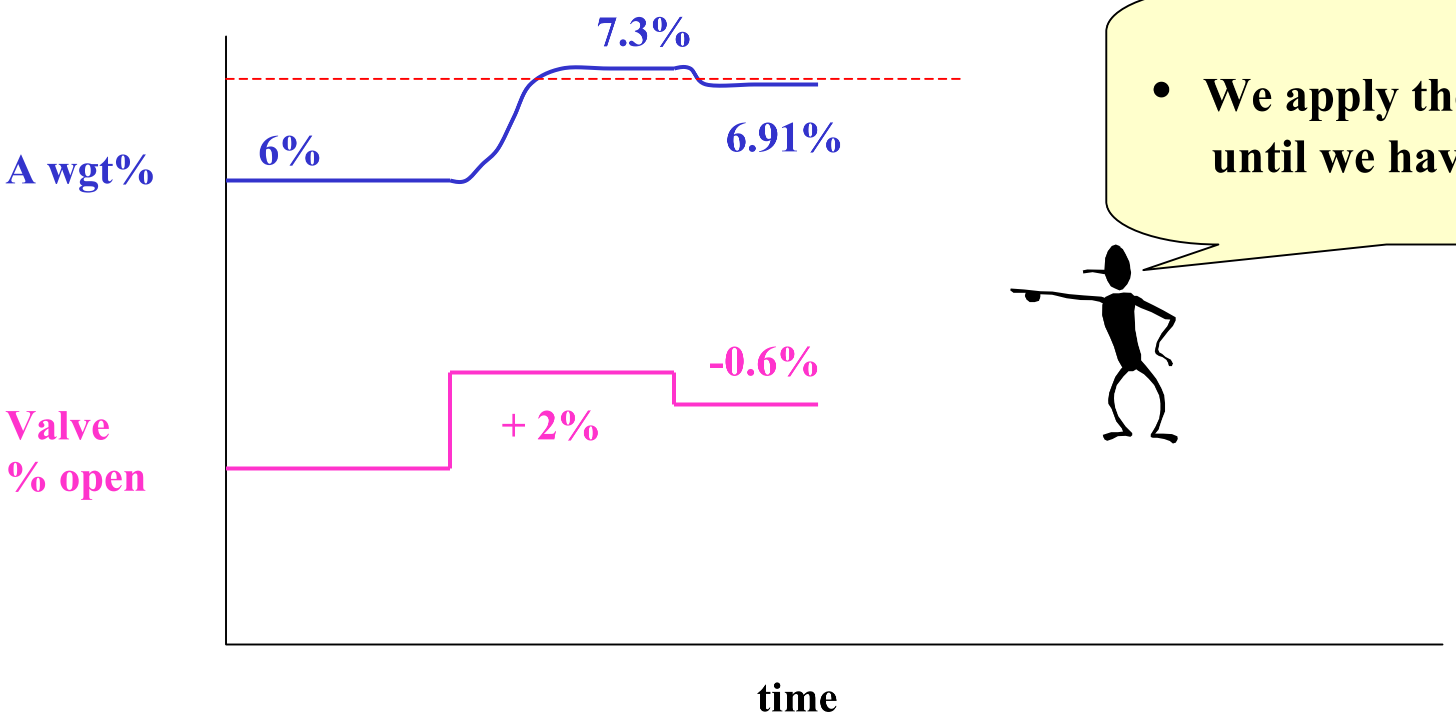
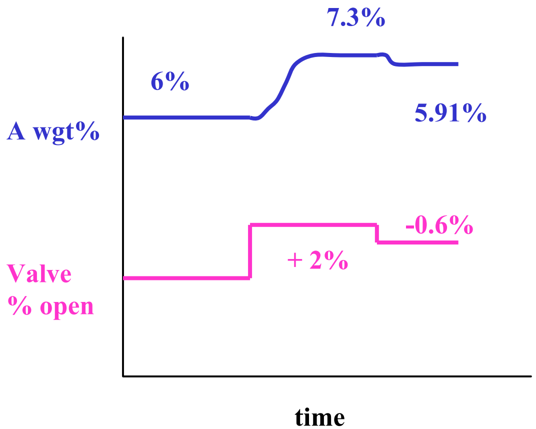
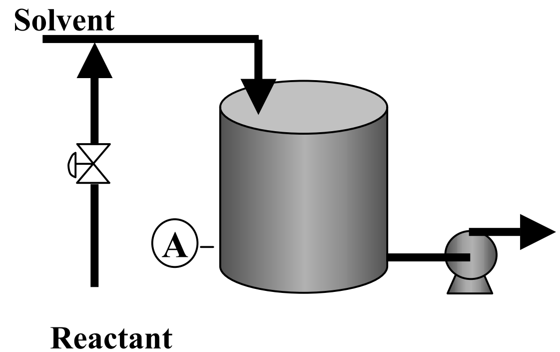


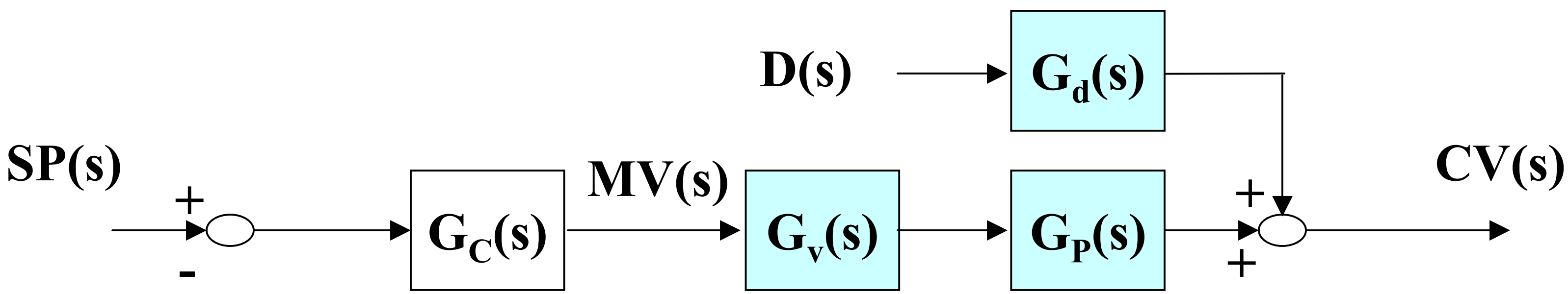


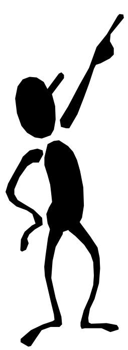
- We apply the feedback until we have converged.

CHAPTER 19: Single-Loop IMC Control



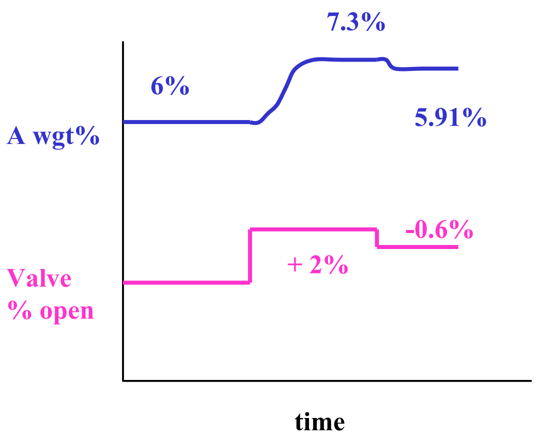


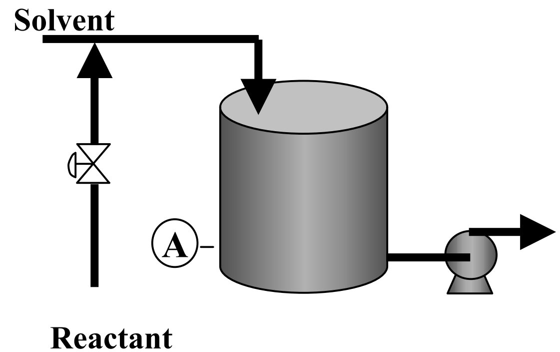


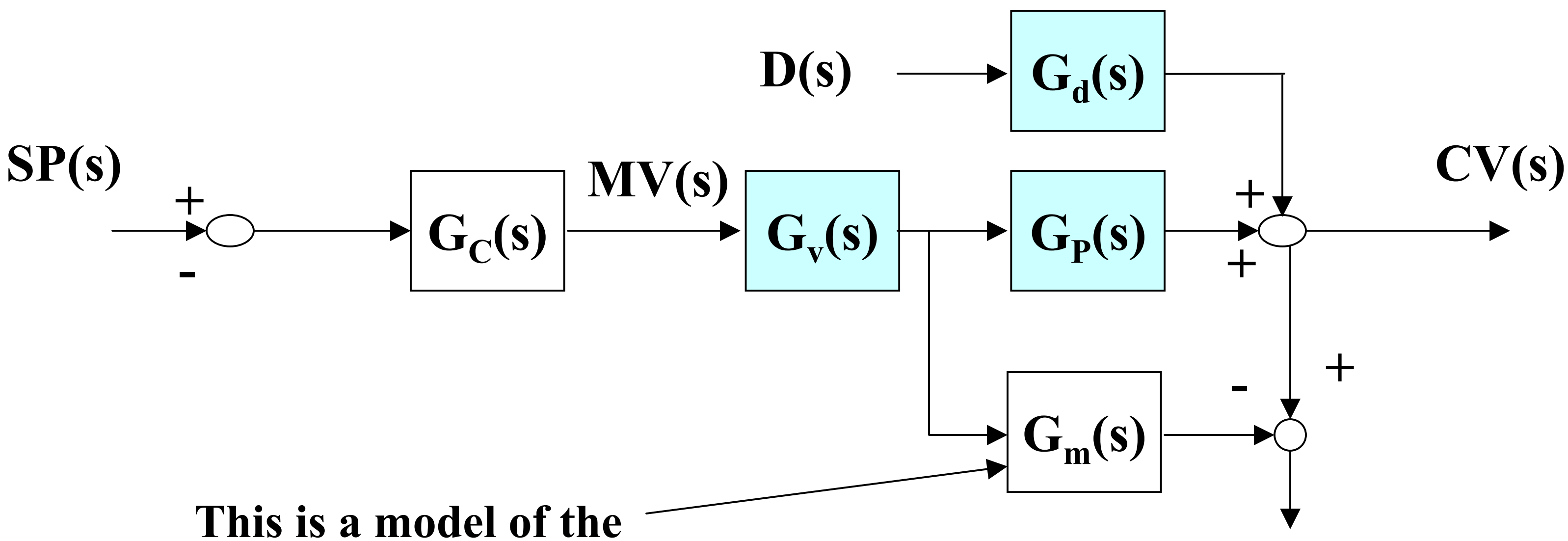


Discuss this diagram and complete the closed-loop block diagram for the IMC concept.

CHAPTER 19: Single-Loop IMC Control



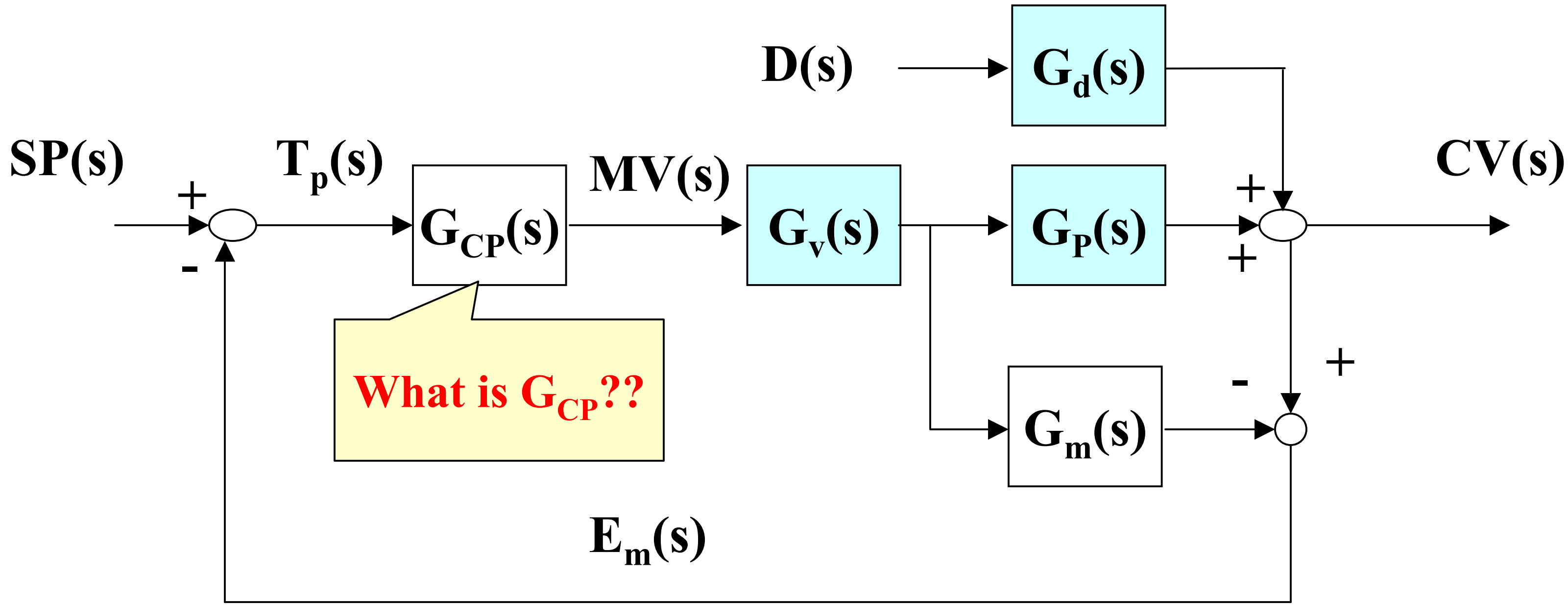




This is a model of the feedback process.

"Model error" = $E_m(s)$

CHAPTER 19: Single-Loop IMC Control



Transfer functions

$G_{CP}(s)$ = controller
$G_v(s)$ = valve
$G_P(s)$ = feedback process
$G_m(s)$ = model
$G_d(s)$ = disturbance process

Variables

CV(s) = controlled variable
$CV_m(s)$ = measured value of CV(s)
D(s) = disturbance
$E_m(s)$ = model error
MV(s) = manipulated variable
SP(s) = set point
$T_p(s)$ = set point corrected for model error

CHAPTER 19: Single-Loop IMC Control

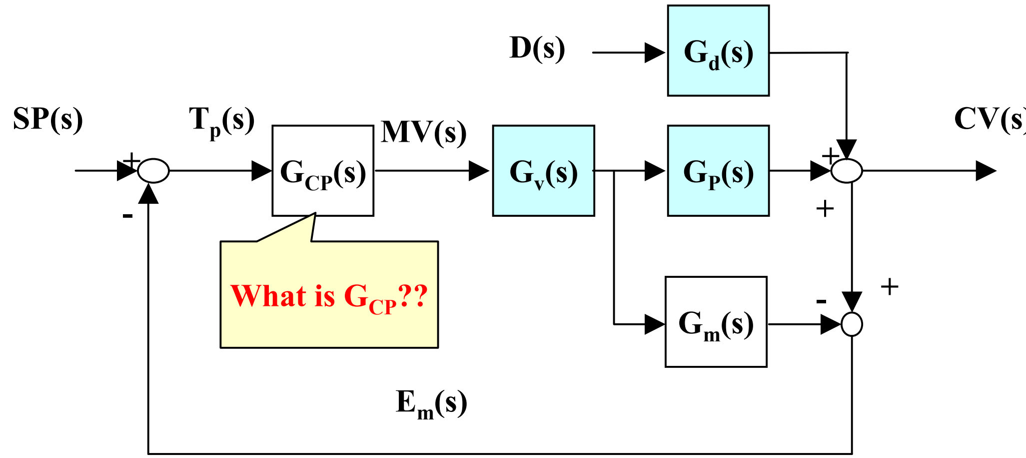
What controller calculation gives good performance?

- It is **NOT** a PID algorithm
- Let's set some key features and determine what G_{cp} will achieve these features

1. Zero steady-state offset for "step-like" inputs
2. Perfect control (CV=SP for all time)
3. Moderate manipulated variable adjustments
4. Robustness to model mismatch
5. Anti-reset-windup

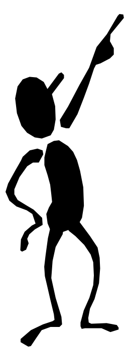
CHAPTER 19: Single-Loop IMC Control

What controller calculation gives good performance?



1. Zero steady-state offset:

$$\frac{CV(s)}{D(s)} = \frac{(1 - G_{cp}(s)G_m(s))G_d(s)}{1 + G_{CP}(s)\left(G_v(s)G_p(s)G_S(s) - G_m(s)\right)}$$

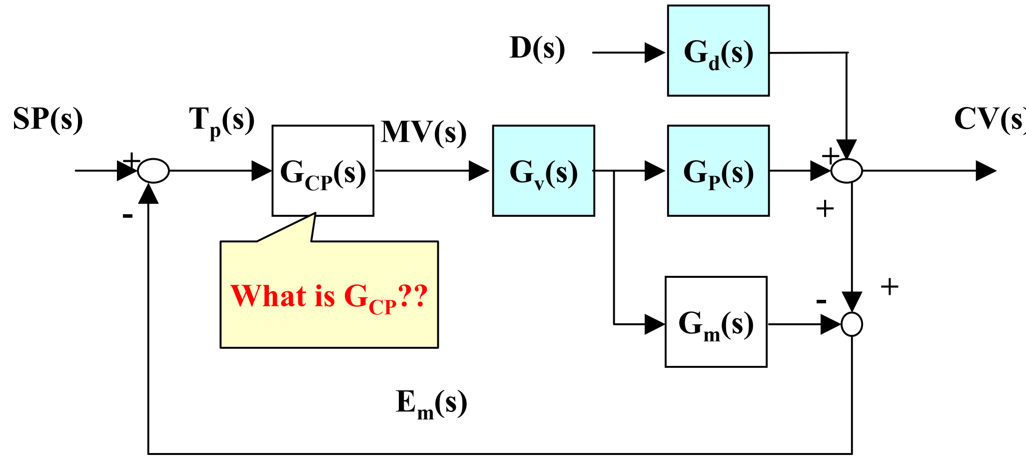


What condition for $G_{cp}(s)$ ensures zero steady-state offset for a step disturbance?

Hint: Steady-state is at $t = \infty$.

CHAPTER 19: Single-Loop IMC Control

What controller calculation gives good performance?



1. Zero steady-state offset:

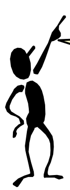
$$\frac{CV(s)}{D(s)} = \frac{(1 - G_{cp}(s) G_m(s)) G_d(s)}{1 + G_{CP}(s)\left(G_v(s) G_p(s) G_S(s) - G_m(s)\right)}$$

$$\boxed{\lim_{t \to \infty} CV(t) = \lim_{s \to 0} s \frac{\Delta D}{s} \frac{(1 - K_{cp} K_m) K_d}{1 + K_{cp}(K_p - K_m)} = 0}$$

CONCLUSION

$$\mathbf{K_{cp} = (K_m)^{-1}}$$

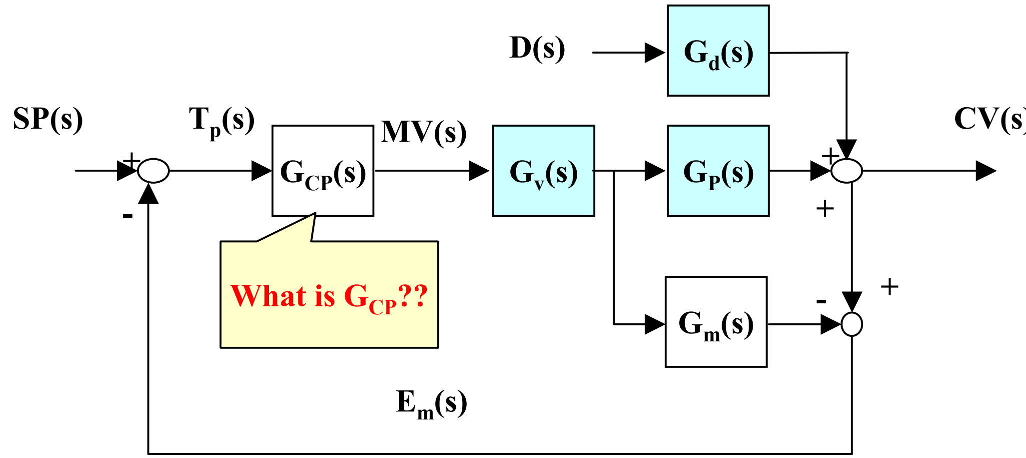
Easily achieved because both are in computer!



Oh yeah, the final value theorem!

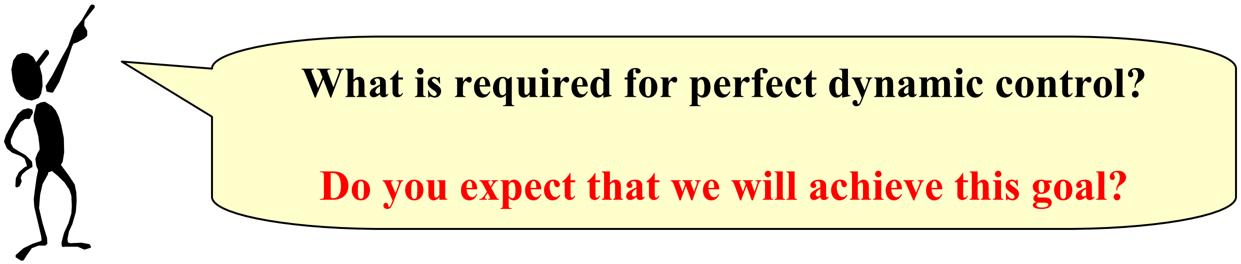
CHAPTER 19: Single-Loop IMC Control

What controller calculation gives good performance?



2. Perfect dynamic control:

$$\frac{CV(s)}{D(s)} = \frac{(1 - G_{cp}(s)G_m(s))G_d(s)}{1 + G_{CP}(s)\left(G_v(s)G_p(s)G_S(s) - G_m(s)\right)}$$



CHAPTER 19: Single-Loop IMC Control

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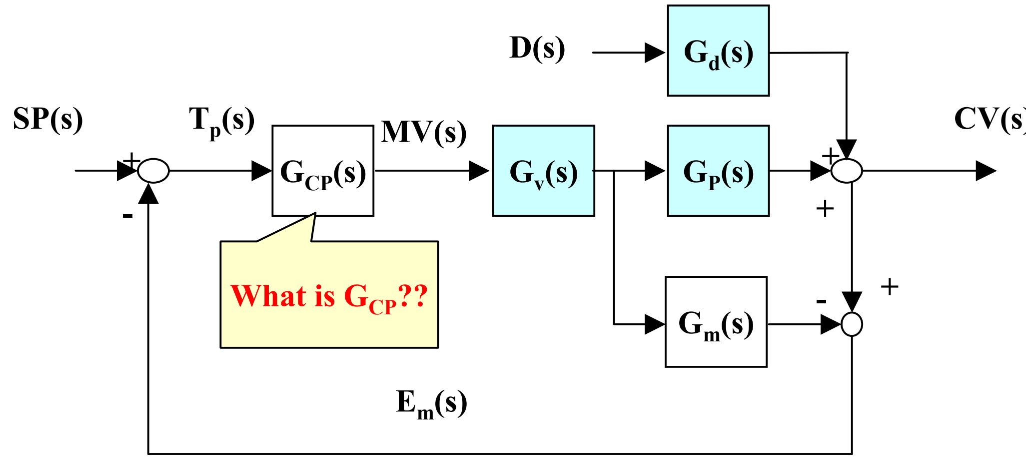

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$$\boxed{CV(s) = \frac{(1 - G_{cp}(s) G_m(s)) G_d(s)}{1 + G_{CP}(s)\left(G_v(s) G_p(s) G_S(s) - G_m(s)\right)} D(s) = 0}$$

CONCLUSION

$$G_{cp}(s) = (G_m(s))^{-1}$$

Controller is inverse of model!

Can we achieve this?

2. Perfect dynamic control:

3. Moderate manipulated variable adjustments

$$G_m(s) = \frac{K_m e^{-\theta s}}{(\tau s + 1)} \quad \text{then} \quad G_{cp}(s) = \frac{(\tau s + 1) e^{\theta s}}{K_m}$$

This is a pure derivative, which will lead to excessive manipulated variable moves

This is a prediction into the future, which is not possible

CONCLUSION

$$G_{cp}(s) = (G_m(s))^{-1}$$

Controller is inverse of model!

Can we achieve this?

Conclusion: Perfect control is not possible!

(See other examples in the workshops.)

CHAPTER 19: Single-Loop IMC Control

2. Perfect dynamic control:

3. Moderate manipulated variable adjustments

$$G_m(s) = \frac{K_m(\tau_1 s + 1)}{(\tau_2 s + 1)(\tau_3 s + 1)} \quad \text{then} \quad G_{cp}(s) = \frac{(\tau_2 s + 1)(\tau_3 s + 1)}{K_m(\tau_1 s + 1)}$$

CONCLUSION

$$G_{cp}(s) = (G_m(s))^{-1}$$

Controller is inverse of model!

Can we achieve this?

This has a second derivative, which will lead to excessive manipulated variable moves

This could have an unstable controller, if τ_1 is negative. This is unacceptable.

Conclusion: Perfect control is not possible!

(See other examples in the workshops.)

CHAPTER 19: Single-Loop IMC Control

Let's begin our IMC design with the results so far.

CONCLUSION

$$K_{cp} = (K_m)^{-1}$$

Easily achieved because both are in computer!

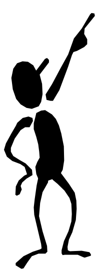
CONCLUSION

$$G_{cp}(s) \approx (G_m(s))^{-1}$$

Controller is inverse of model!

We have loosened the restriction to a condition that can be achieved.

Now, what does "approximate" mean?



How can we define the meaning of approximate so that we have a useful design approach?

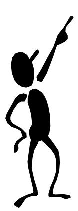
CHAPTER 19: Single-Loop IMC Control

Separate the model into two factors, one invertible and the other with all non-invertible terms.

$$G_m(s) = \underline{G_m^-(s)}\ \underline{G_m^+(s)}$$

The "invertible" factor has an inverse that is causal and stable, which results in an acceptable controller. The gain is the model gain, K_m.

The "non-invertible" factor has an inverse that is non-causal or unstable. The factor contains models elements with dead times and positive numerator zeros. The gain is the 1.0.



What do we use for the controller?

CHAPTER 19: Single-Loop IMC Control

Separate the model into two factors, one invertible and the other with all non-invertible terms.

$$G_m(s) = G_m^-(s)\ G_m^+(s)$$

The IMC controller eliminates all non-invertible elements in the feedback process model by inverting $G^-_m(s)$.

$$G_{cp}(s) = \left[G_m^-(s)\right]^{-1}$$

Looks easy, but I need some practice.

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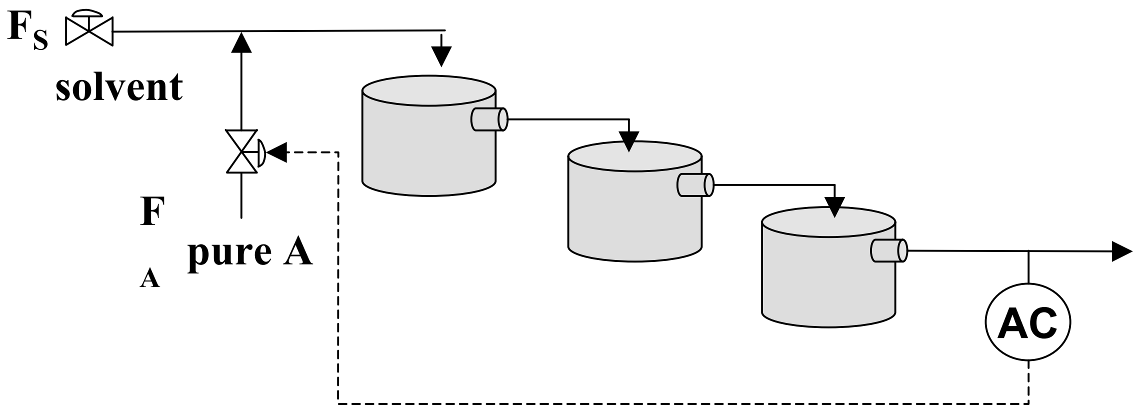


Class exercise: **We have two models for the feedback dynamics for the 3-tank mixer. Determine $G_{cp}(s)$ for each.**

Empirical model

$$G_m(s) = \frac{0.039e^{-5.5s}}{(1+10.5s)}$$

Fundamental model

$$G_m(s) = \frac{0.039}{(1+5s)^3}$$

CHAPTER 19: Single-Loop IMC Control

Empirical model

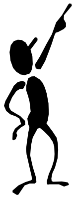
$$G_m(s) = \frac{0.039e^{-5.5s}}{(1+10.5s)}$$

$$G_{cp}(s) = \frac{(1+10.5s)}{0.039}$$

Fundamental model

$$G_m(s) = \frac{0.039}{(1+5s)^3}$$

$$G_{cp}(s) = \frac{(1+5s)^3}{0.039}$$



Discuss these results.

- **Do they "make sense"?**
- **Are there any shortcomings?**

(Hint: Look at other desirable features.)

CHAPTER 19: Single-Loop IMC Control

$$G_{cp}(s) = \frac{(1+10.5s)}{0.039}$$

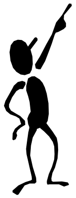
First derivative

$$G_{cp}(s) = \frac{(1+5s)^3}{0.039}$$

Third derivative!

3. Moderate manipulated variable adjustments

4. Robustness to model mismatch



To achieve these features, we must be able to "slow down" the controller.

We chose to include a filter in the feedback path.

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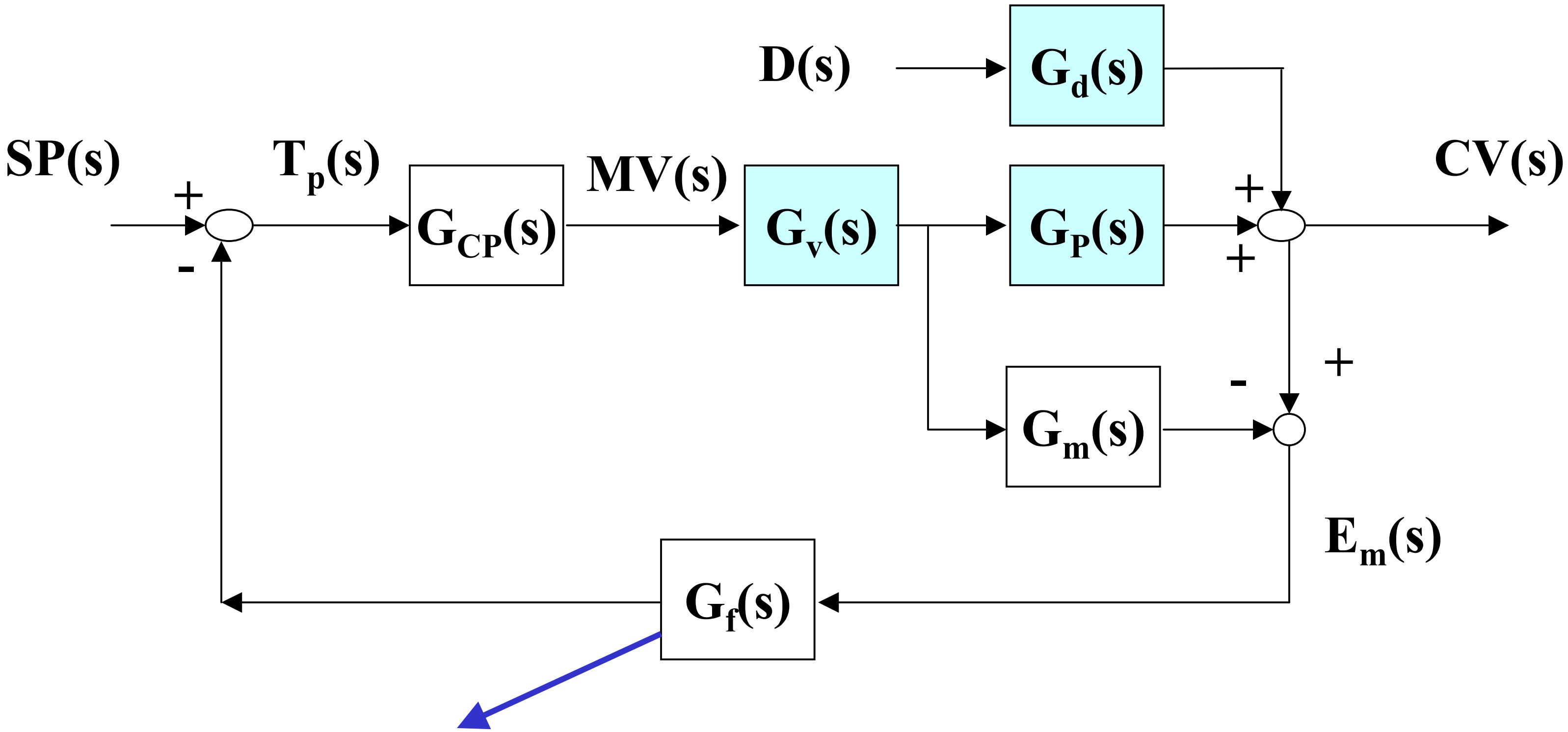

$$G_f(s) = \left[\frac{1}{\tau_f s + 1} \right]^{N_f}$$

The value of N_f is selected so that the product of the controller and filter has a polynomial in "s" with a denominator order ≥ the numerator order.

The filter is designed to prevent pure derivatives and the filter constant is tuned to achieve "robust performance".

CHAPTER 19: Single-Loop IMC Control

Class exercise: Determine the structure of the filter for the two possible controllers we just designed for the three tank mixing process.

Empirical model

$$G_m(s) = \frac{0.039e^{-5.5s}}{(1+10.5s)}$$

$$G_{cp}(s) = \frac{(1+10.5s)}{0.039}$$

Fundamental model

$$G_m(s) = \frac{0.039}{(1+5s)^3}$$

$$G_{cp}(s) = \frac{(1+5s)^3}{0.039}$$

CHAPTER 19: Single-Loop IMC Control

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$$G_f(s) = \left[\frac{1}{\tau_f s + 1}\right]^1$$

Fundamental model

$$G_m(s) = \frac{0.039}{(1+5s)^3}$$

$$G_{cp}(s) = \frac{(1+5s)^3}{0.039}$$

$$G_f(s) = \left[\frac{1}{\tau_f s + 1}\right]^3$$

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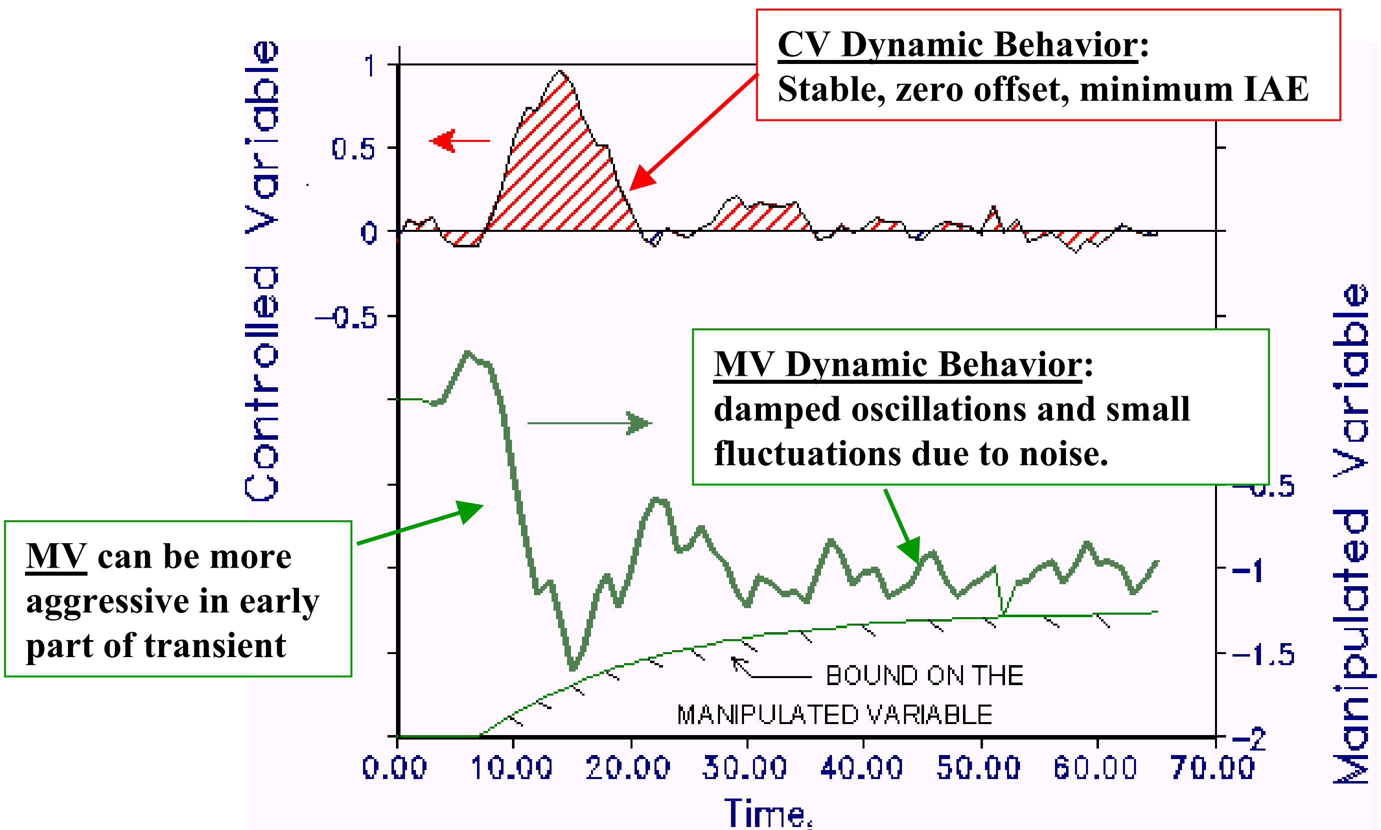
Now, we must determine the proper value for the filter time constant - this is controller tuning again!

We know how to set the goals from experience with PID.



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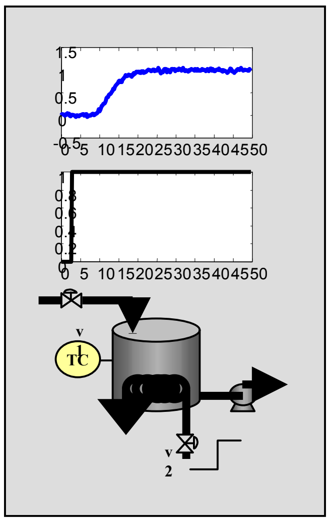
We can tune using a simulation and optimization or

Process reaction curve



Km = 1

θm = 5

τm = 5

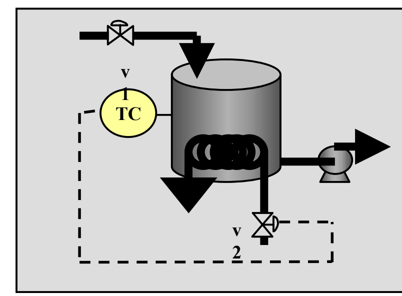
Solve the tuning problem. Requires a computer program.

COMBINED DEFINITION OF TUNING

- **First order with dead time process model**
- **Noisy measurement signal**
- **± 25% parameters errors between model/plant**
- **IMC controller: determine K_f**
- **Minimize IAE with MV inside bound**

τ_f =???

Apply, and fine tune.



We can develop tuning correlations. These are available for a lead-lag controller, $G_{cp}(s)G_f(s)$.

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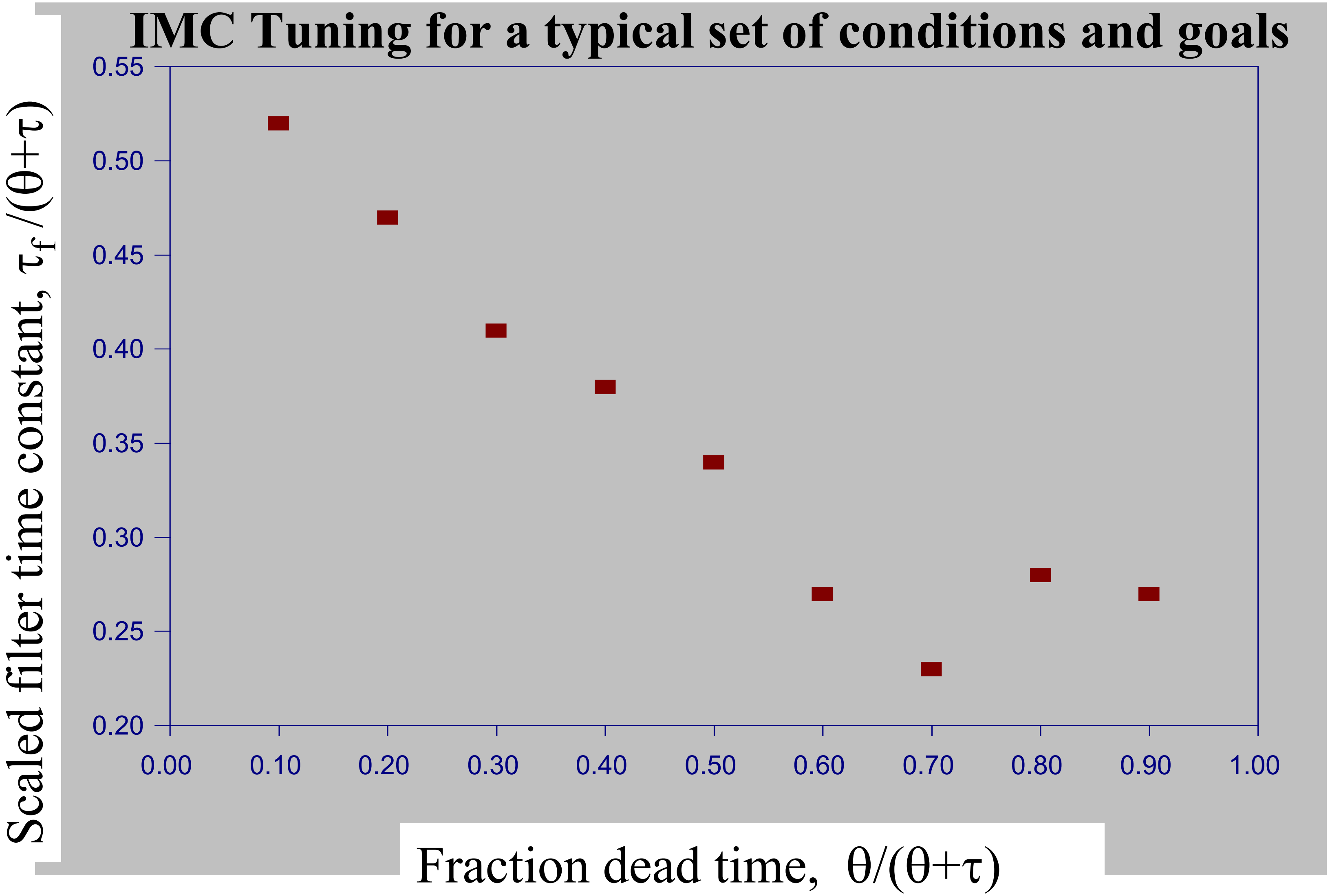

CHAPTER 19: Single-Loop IMC Control

Class exercise: Determine the filter time constant for the IMC controller that we just designed for the three tank mixing process.

Empirical model

$$G_m(s) = \frac{0.039e^{-5.5s}}{(1+10.5s)}$$

$$\boxed{G_{cp}(s) = \frac{(1+10.5s)}{0.039}}$$

$$G_f(s) = \left[\frac{1}{\tau_f s + 1}\right]^1$$

CHAPTER 19: Single-Loop IMC Control

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$$\boxed{G_{cp}(s) = \frac{(1+10.5s)}{0.039}}$$

$$G_f(s) = \left[\frac{1}{\tau_f s + 1}\right]^1$$

1. The controller is lead-lag, so we can use the correlation.

2. $\theta/(\theta+\tau) = 5.5/16.0 = 0.34$

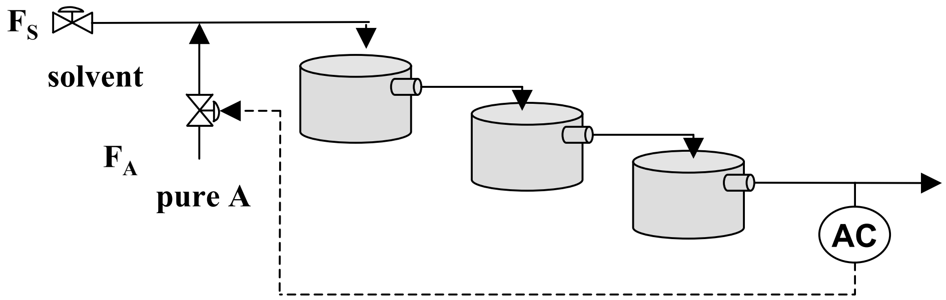
3. $\tau_f /(\theta+\tau) = 0.38$;

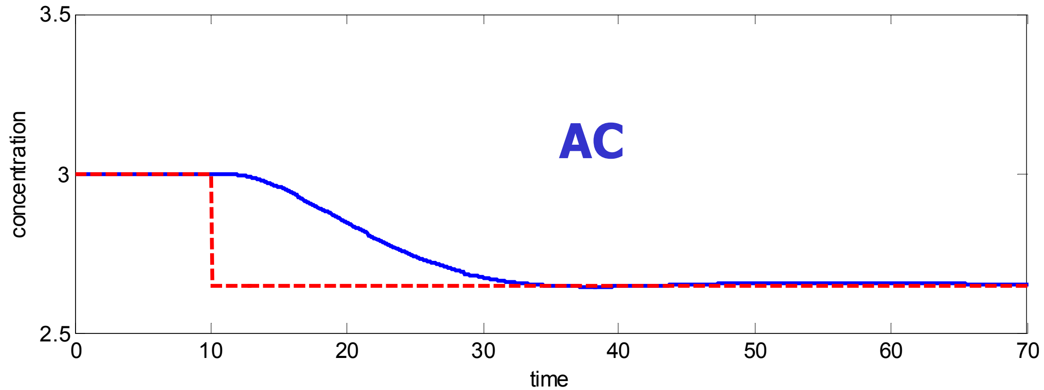
$\tau_f = (0.38)(15.5) = 6.1$ minutes

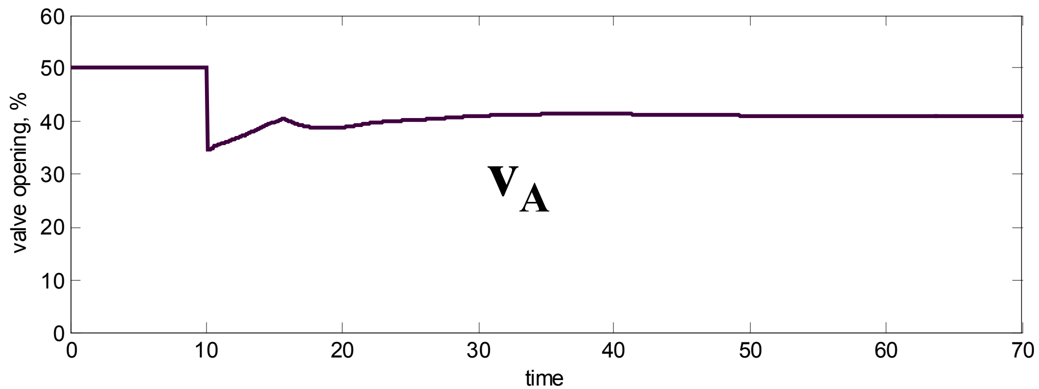
4. See the next slide for the dynamic response.

5. We can fine tune to achieve the desired CV and MV behavior.

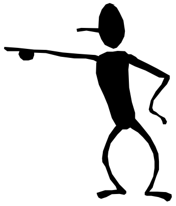
CHAPTER 19: Single-Loop IMC Control







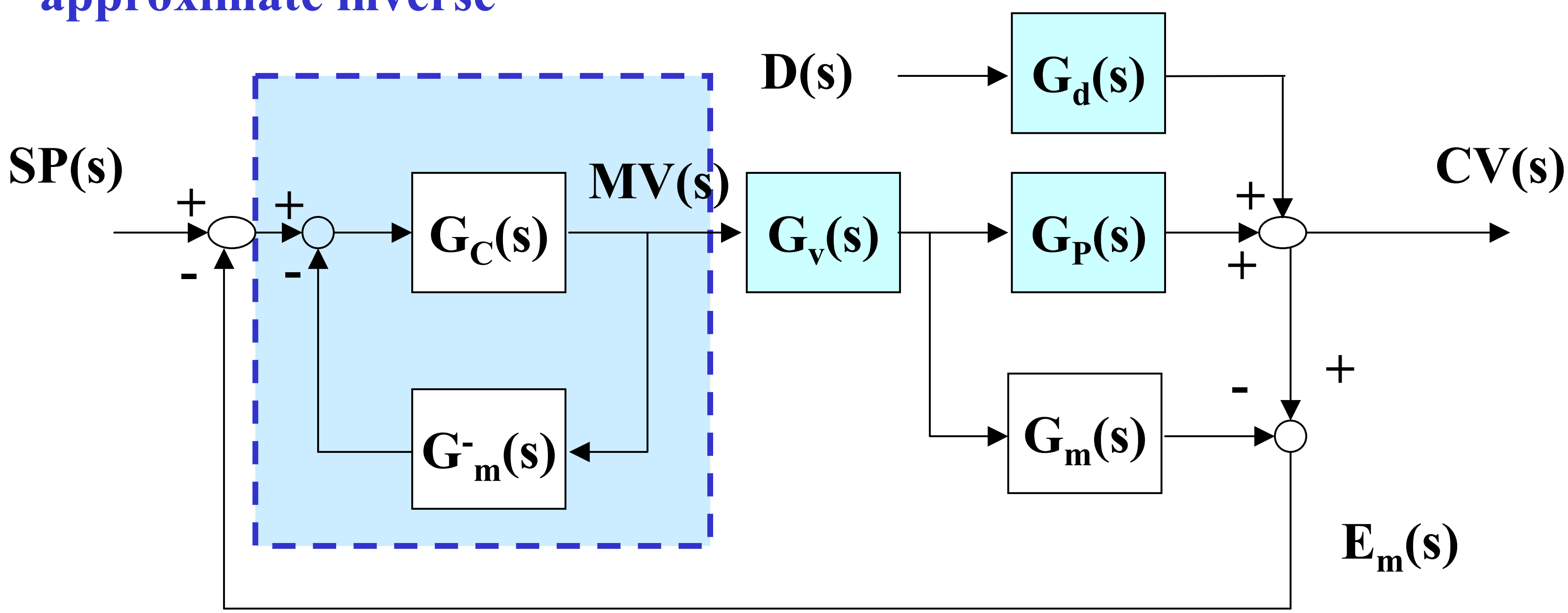
Discuss the control performance.



CHAPTER 19: Single-Loop IMC Control

Smith Predictor: A smart fellow named Smith saw the benefit for an explicit model in the late 1950's. He invented the Smith Predictor, using the PI controller.

The elements in the box calculate an approximate inverse



Notes: $G_c(s)$ is a PI controller; $G^-_m(s)$ is the invertible factor.

CHAPTER 19: Single-Loop IMC Control

When do we select an IMC over a PID?

1. Very high fraction dead time, $\theta/(\theta+\tau) > 0.7$.
2. Very strong inverse responses.
3. Cascade primary controller with slow secondary (inner) dynamics
4. Feedforward with disturbance dead time less than feedback dead time.

See the textbook for further discussion.

CHAPTER 19: IMC CONTROL WORKSHOP 1

Trouble shooting: You have determined the model below empirically and have tuned the IMC controller using the correlations. The closed-loop performance is not acceptable. What do you do?

Empirical model

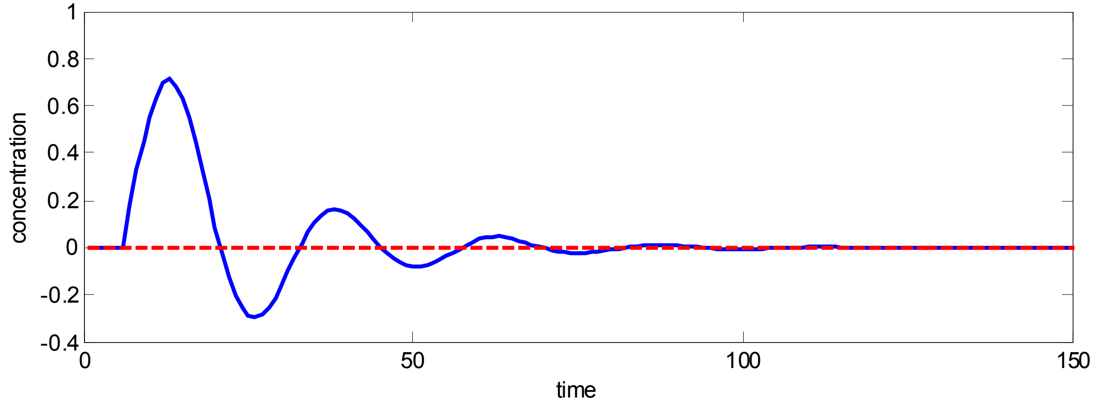
Km = 1

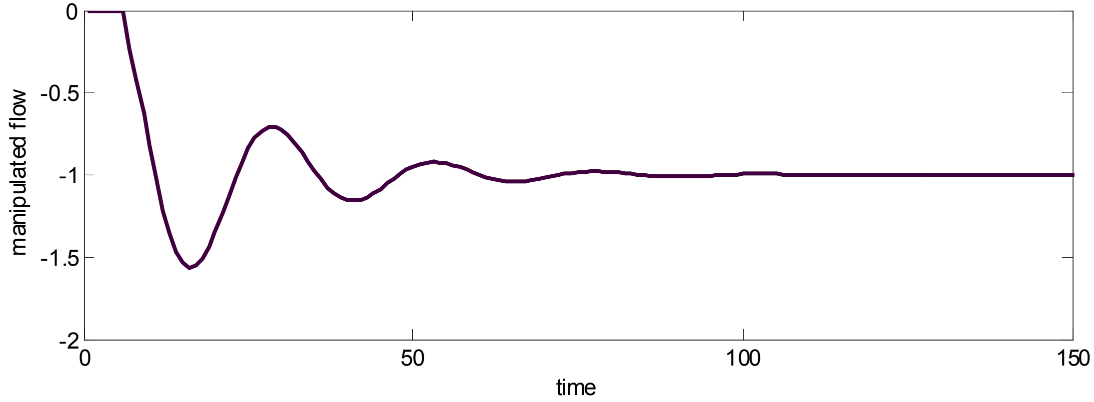
θm = 5

τm = 5

IMC filter

$\tau_f = 3.5$

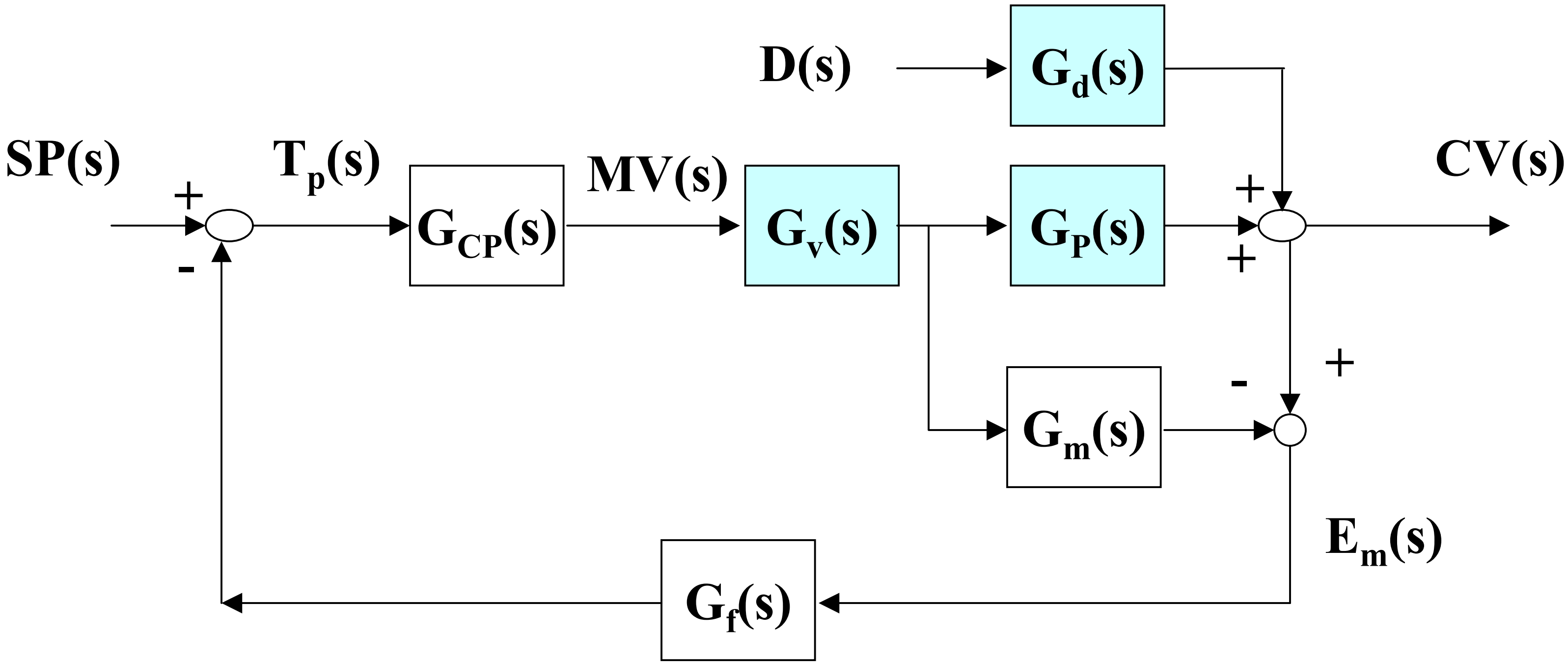




CHAPTER 19: IMC CONTROL WORKSHOP 2

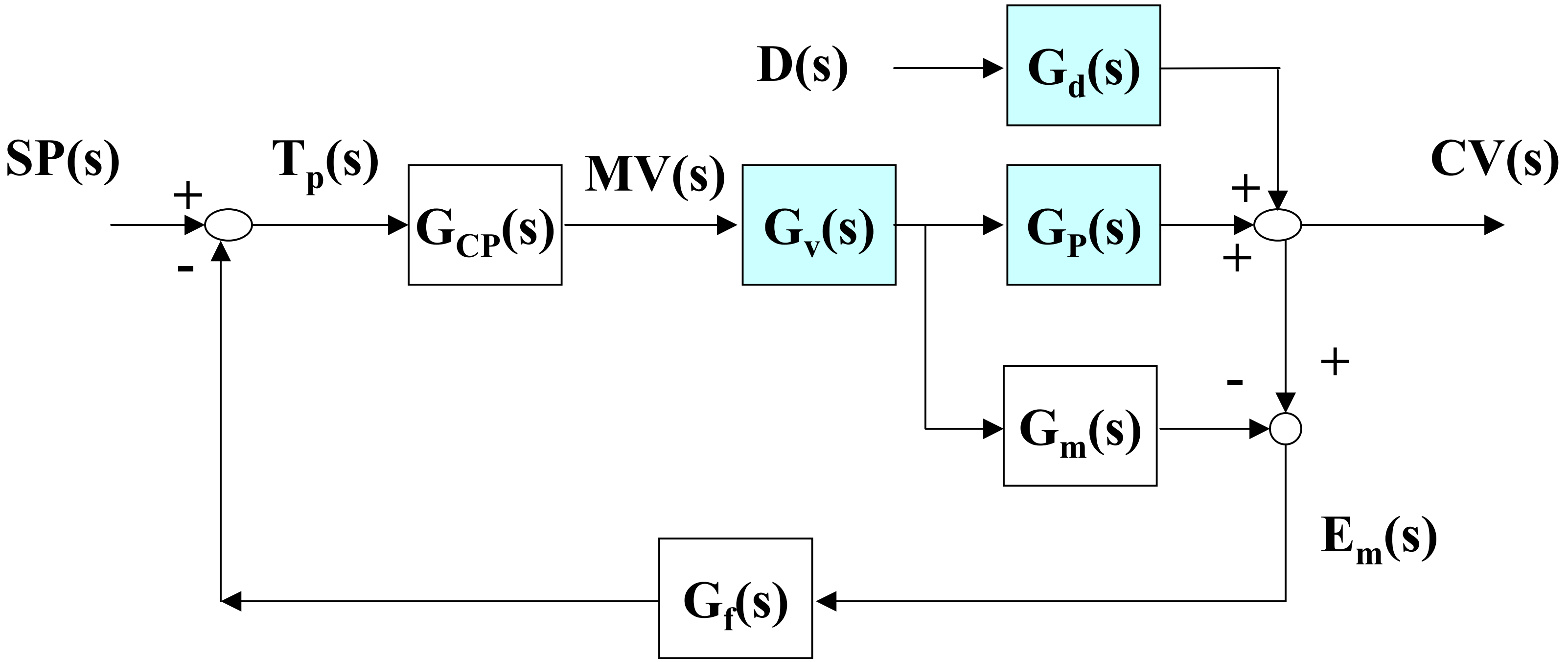
Design features: We want to avoid integral windup.

1. Describe integral windup and why it is undesirable.
2. Modify the structure to provide anti-reset windup.



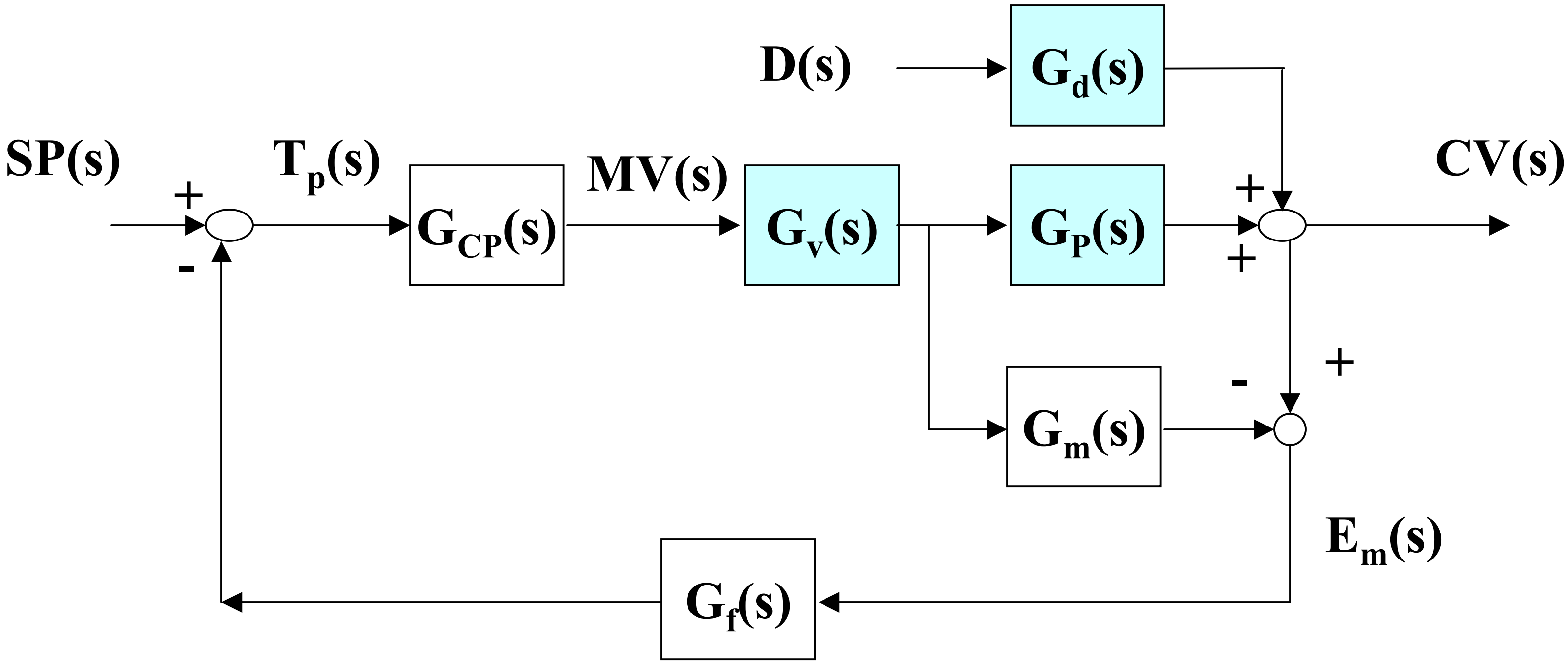
CHAPTER 19: IMC CONTROL WORKSHOP 3

Design features: We want to obtain good performance for set point changes and disturbances. The filter below affects disturbances. Introduce a modification that enables us to influence set point responses independently.

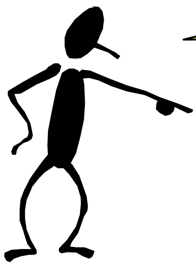


CHAPTER 19: IMC CONTROL WORKSHOP 4

Design features: We discussed two reasons why we cannot achieve perfect feedback control. Identify other reasons and explain how they affect the IMC structure design.

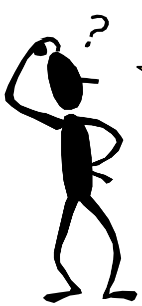


CHAPTER 19: Single-Loop IMC Control



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

- Recognize that other feedback algorithms are possible
- Understand the IMC structure and how it provides the essential control features
- Tune an IMC controller
- Correctly select between PID and IMC



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 19: LEARNING RESOURCES

- **SITE PC-EDUCATION WEB**
  - Tutorials (Chapter 19)

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

- **Addition information on IMC control is given in the following reference.**

  Brosilow, C. and B. Joseph, *Techniques of Model-Based Control*, Prentice-Hall, Upper Saddle River, 2002

CHAPTER 19: SUGGESTIONS FOR SELF-STUDY

1. Discuss the similarities and differences between IMC and Smith Predictor algorithms

2. Develop the equations that would be solved for a digital implementation of the IMC controller for the three-tank mixer.

3. Select a feedback control example in the textbook and determine the IMC tuning for this process.

4. Find a feedback control example in the textbook for which IMC is a better choice than PID.

5. Explain how you would implement a digital algorithm to provide good control for the process in Example 19.8 experiencing the flow variation described.