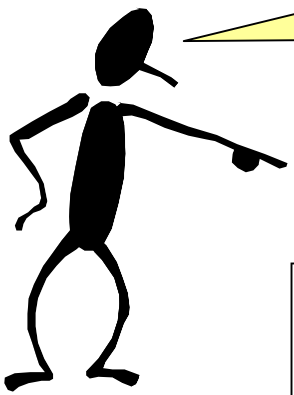
CHAPTER 12: PRACTICAL ISSUES

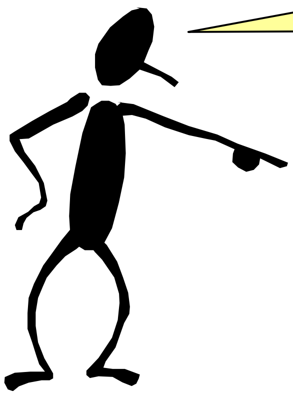


When I complete this chapter, I want to be able to do the following.

Make PID work in practice!

- Select proper field instrumentation
- Use power of digital computation to validate and correct measurements
- Use & tune various industrial PID algorithms
- Improve performance of "simple" PID

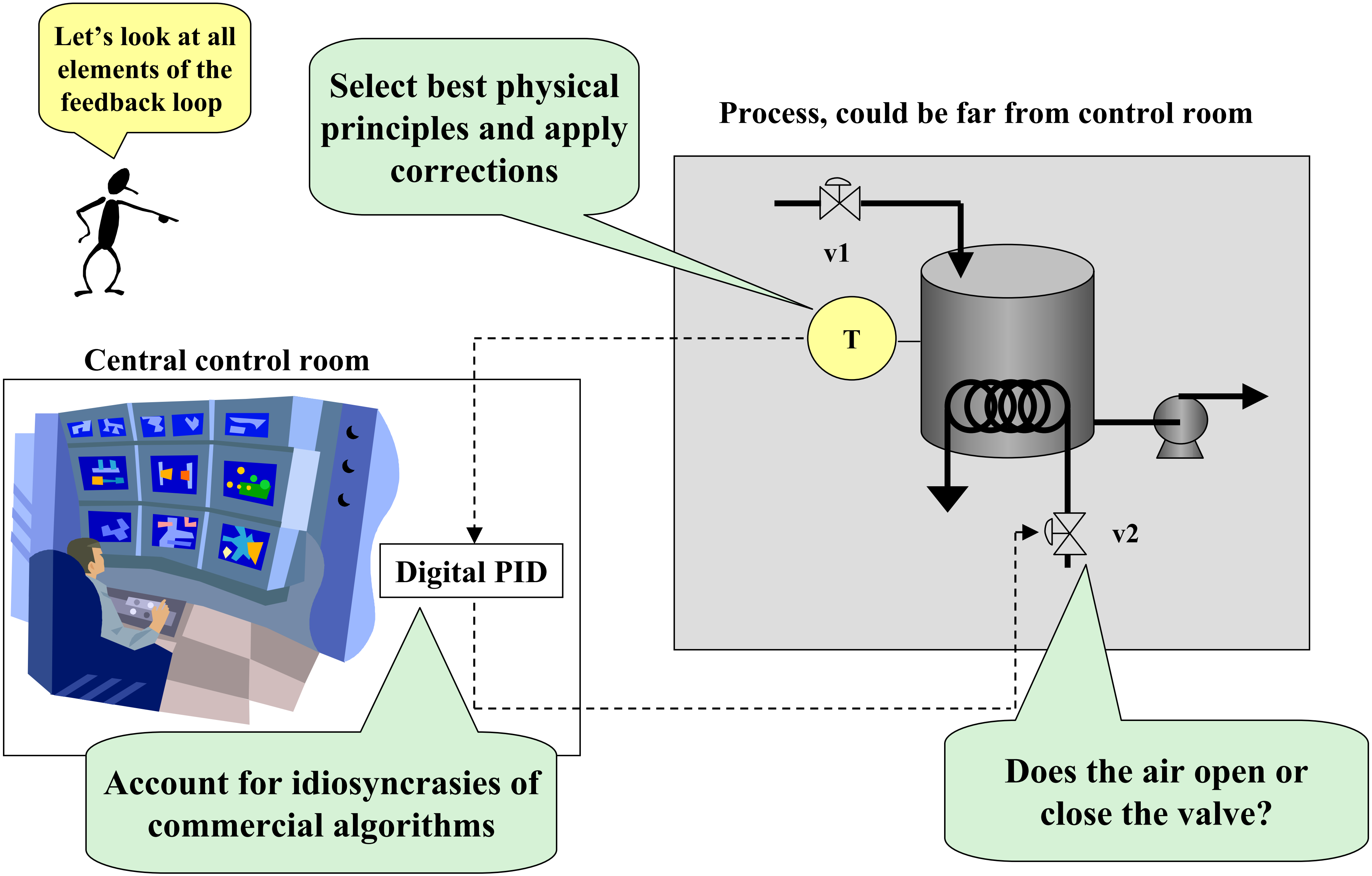
CHAPTER 12: PRACTICAL ISSUES



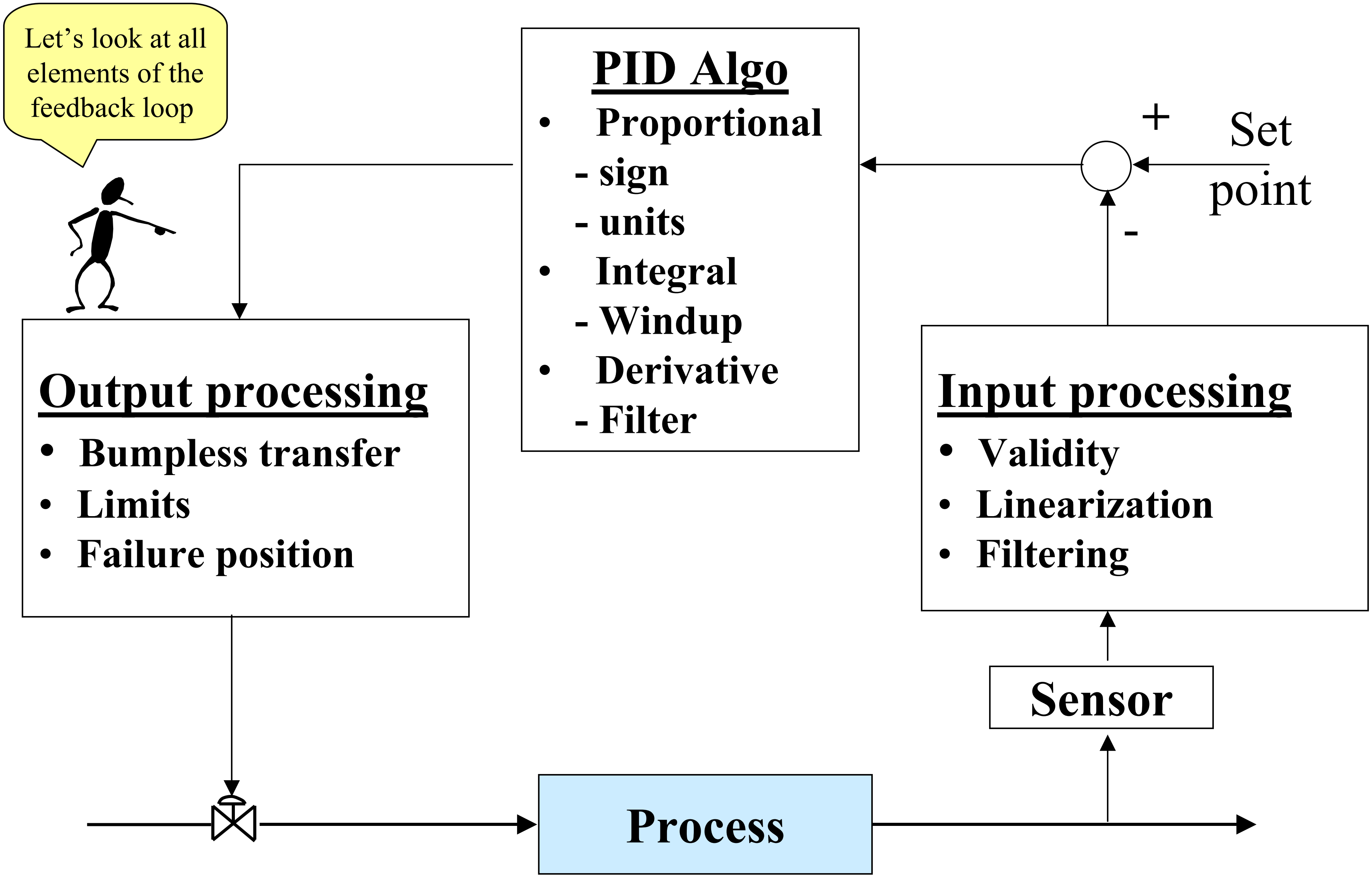
Outline of the lesson.

- **Select appropriate sensors and valves**
- **Determine the controller parameters for commercial systems**
- **Tuning methods for noise reduction**
- **Enhance the simple PID for shortcomings (windup, bumpless)**

CHAPTER 12: PRACTICAL ISSUES

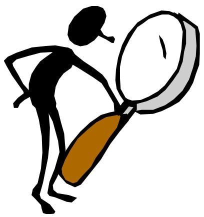


CHAPTER 12: PRACTICAL ISSUES



CHAPTER 12: PRACTICAL ISSUES

Input - Sensor and Precalculations



Sensors - We must "see" key variables to apply control

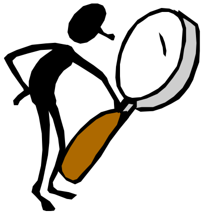
Please define the following terms

Accuracy =

Reproducibility =

CHAPTER 12: PRACTICAL ISSUES

Input - Sensor and Pre-calculations



Sensors - We must "see" key variables to apply control

Please define the following terms

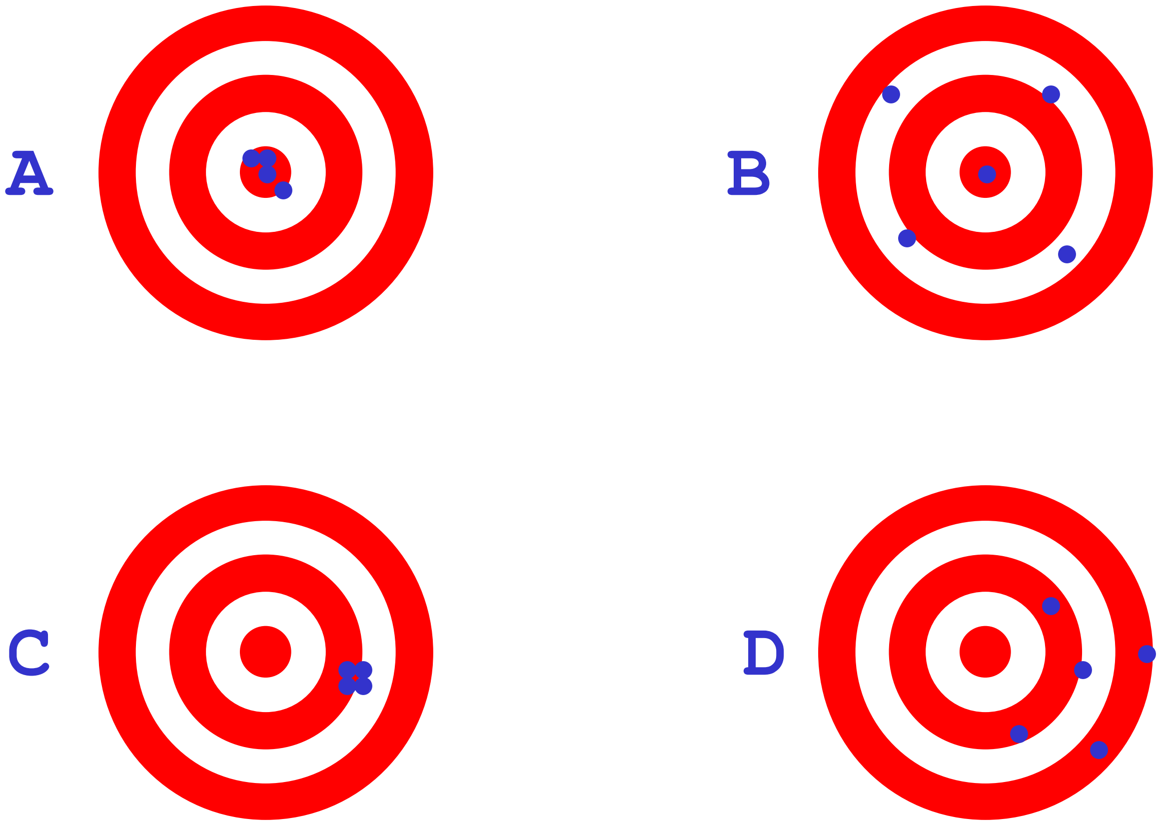
Accuracy = Degree of conformity to a standard (or true) value when a sensor is operated under specified conditions.

Reproducibility = Closeness of agreement among repeated sensor outputs for the same process variable.

CHAPTER 12: PRACTICAL ISSUES

Input - Sensor and Pre-calculations

Discuss the accuracy and reproducibility in these cases



CHAPTER 12: PRACTICAL ISSUES

Input - Sensor and Pre-calculations

Sensor range - The values over which the sensor can record the process variable. We need to "cover" expected range, but typically, the sensor accuracy decreases with increasing sensor range.

Temperature: Usually, the normal operating range

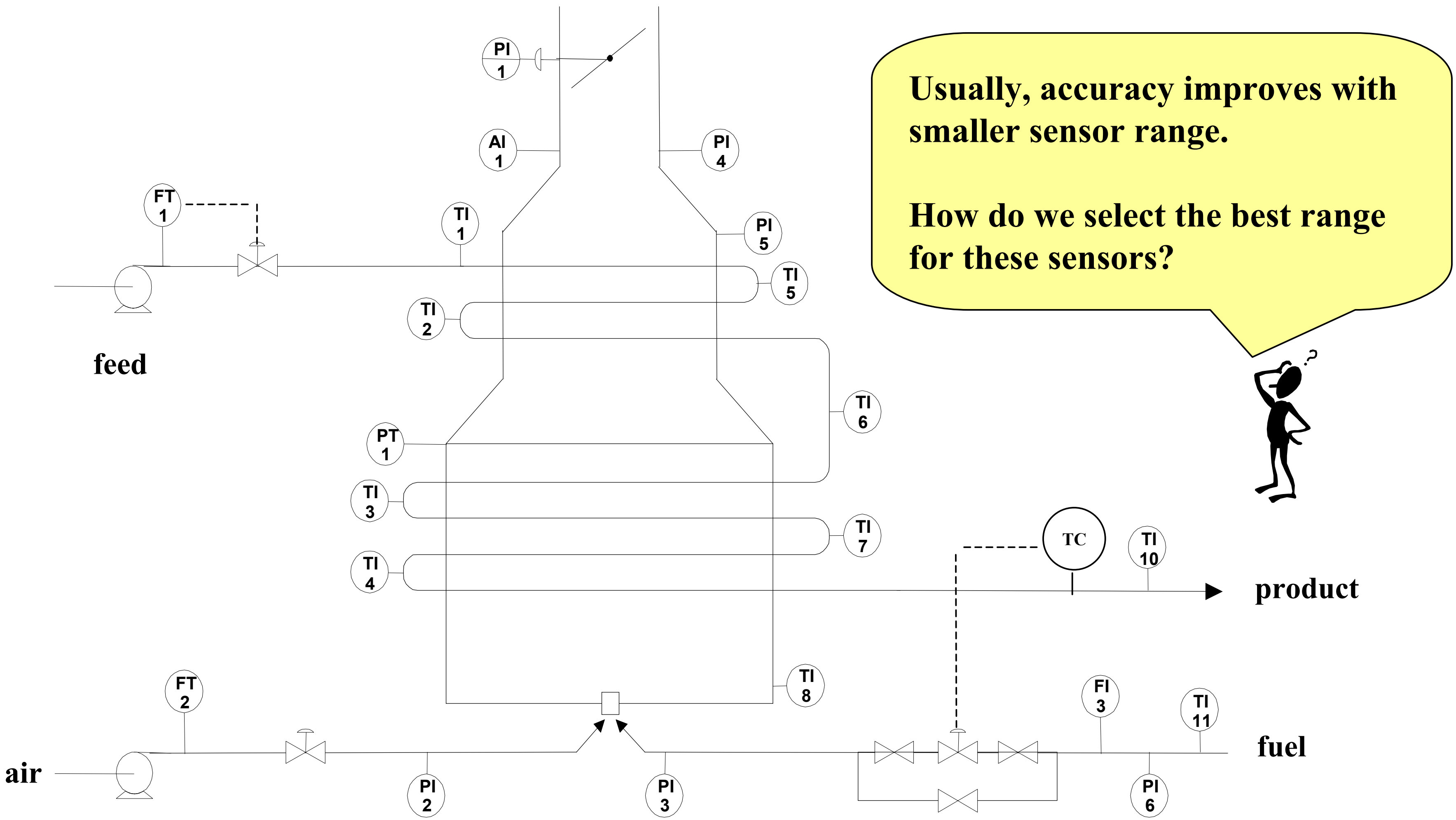
Flow: Usually, 0.0 to the maximum expected flow

Pressure: Usually, the normal operating range

Level: 0 - 100% (not meters, don't have to memorize the height of every vessel)

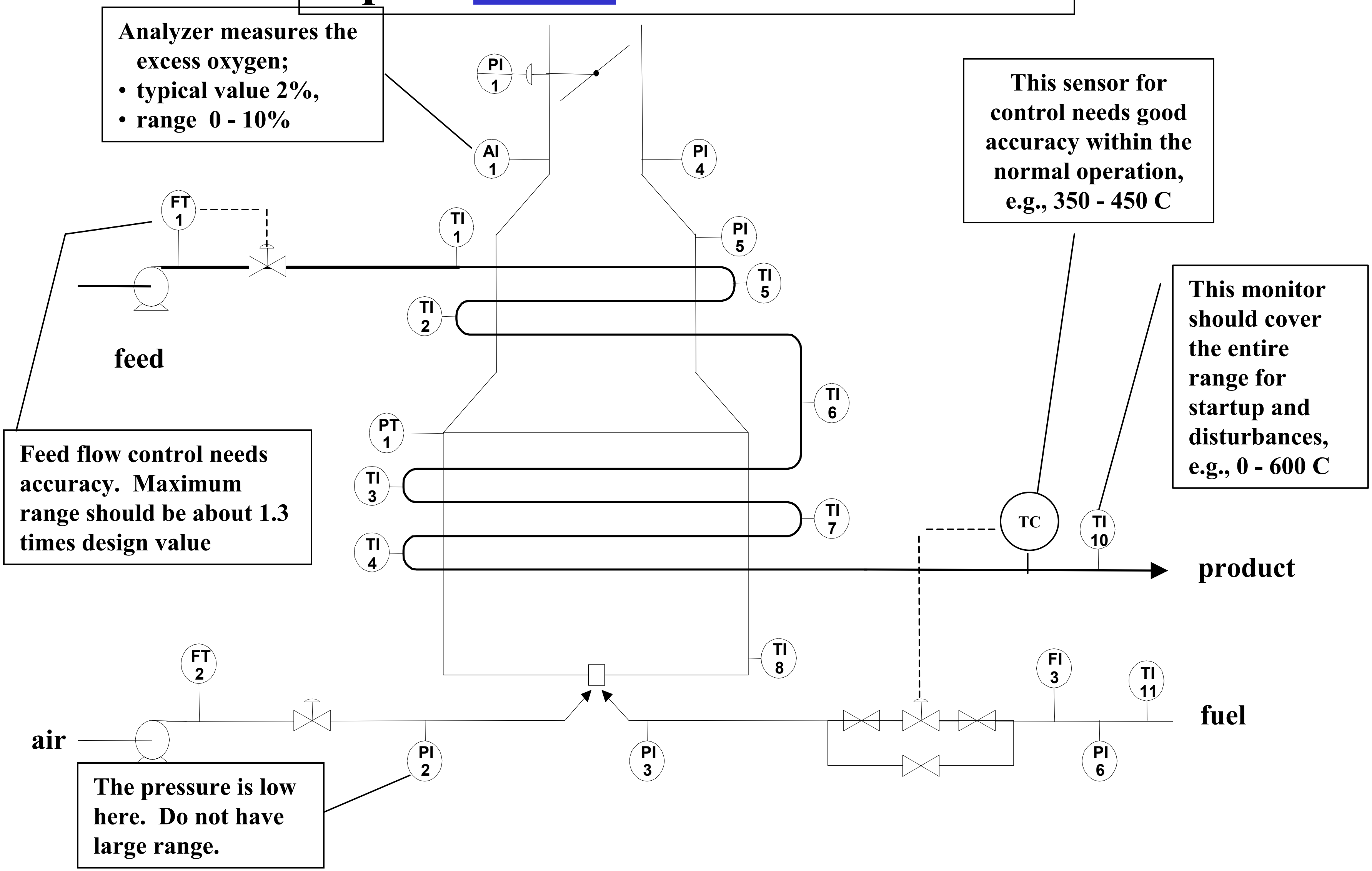
CHAPTER 12: PRACTICAL ISSUES

Input - Sensor and Pre-calculations



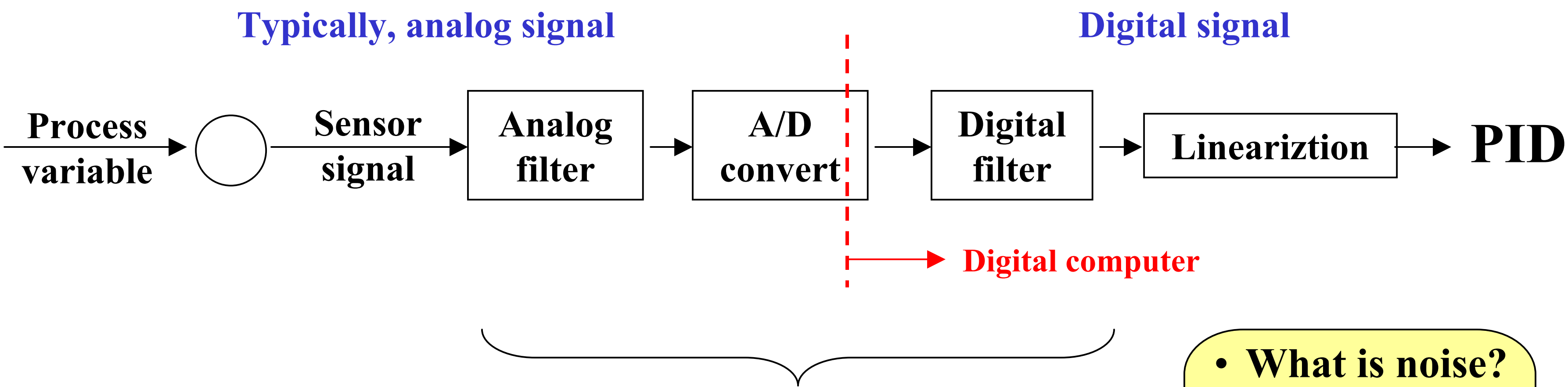
CHAPTER 12: PRACTICAL ISSUES

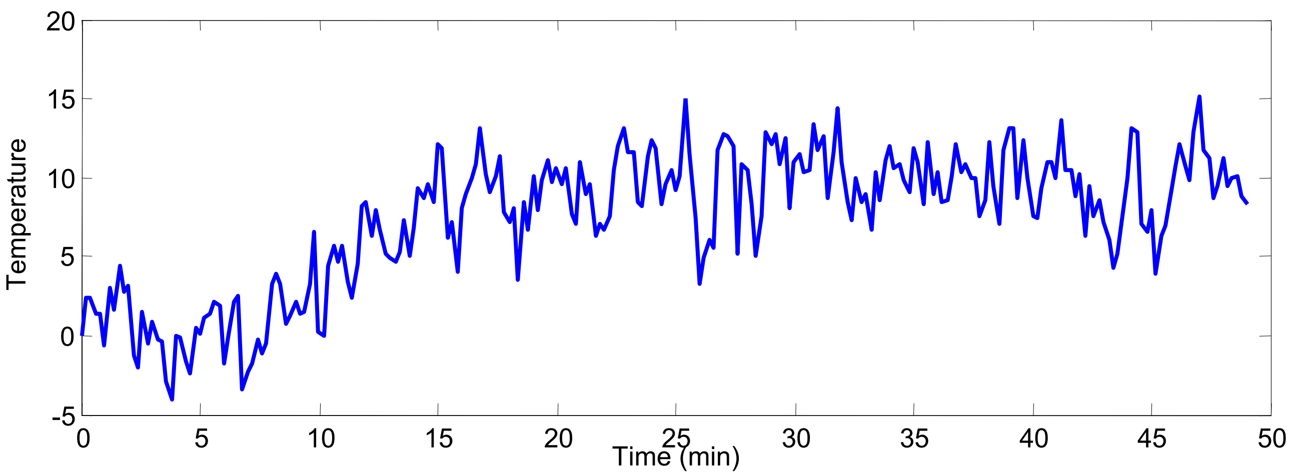
Input - Sensor and Pre-calculations



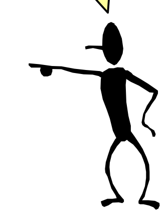
CHAPTER 12: PRACTICAL ISSUES

Input - Sensor and Pre-calculations



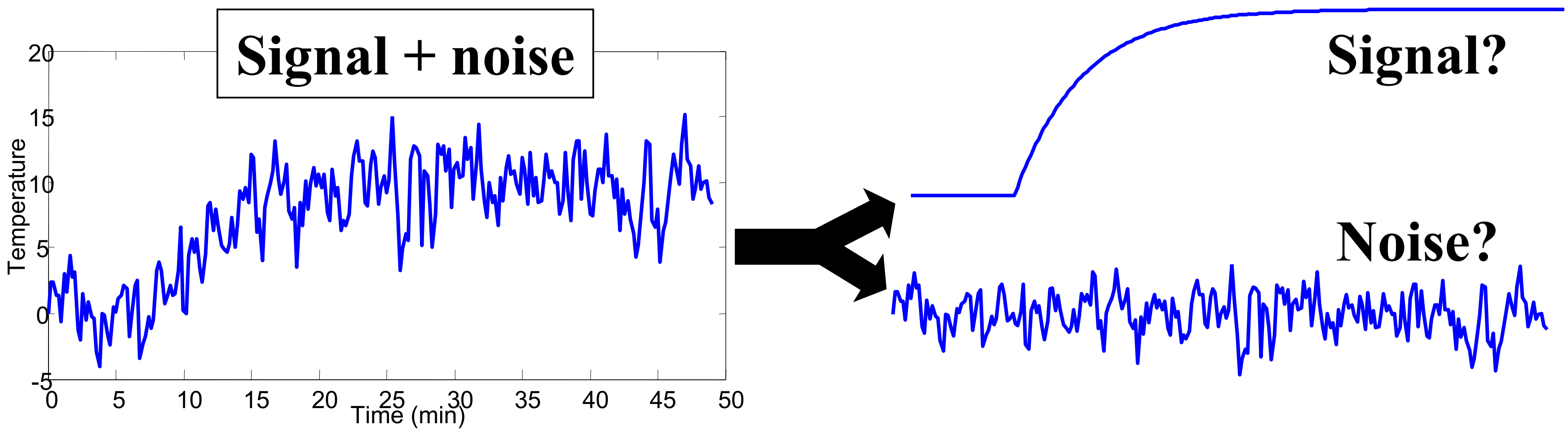


- What is noise?
- Why reduce noise using a filter?



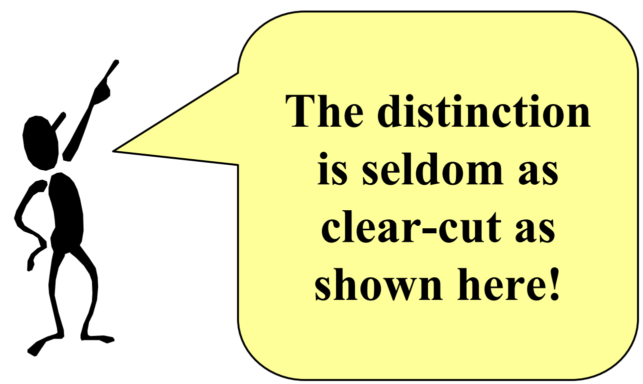
CHAPTER 12: PRACTICAL ISSUES

Input - Sensor and Pre-calculations



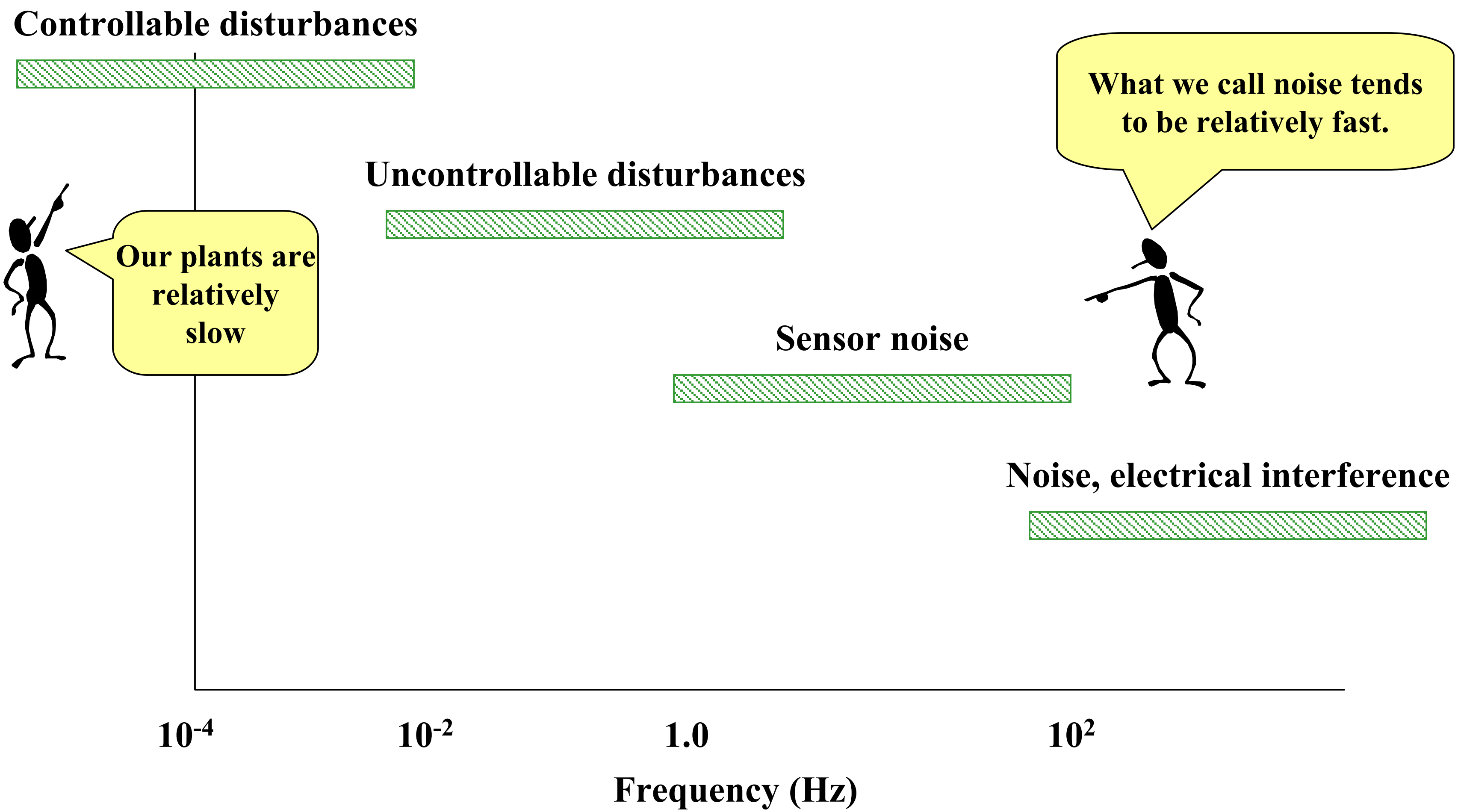
Noise: We think of noise as the non-repeatable component of the measurement.

Causes: Electrical interference, imperfect mixing, turbulence, ...



CHAPTER 12: PRACTICAL ISSUES

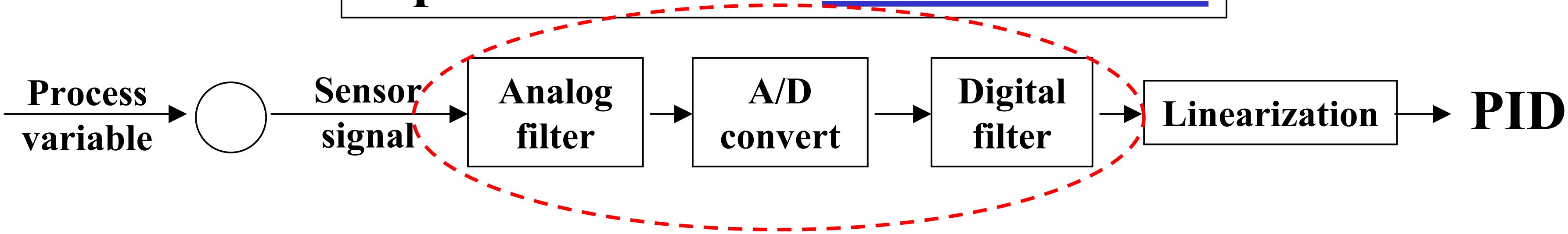
Input - Sensor and Pre-calculations



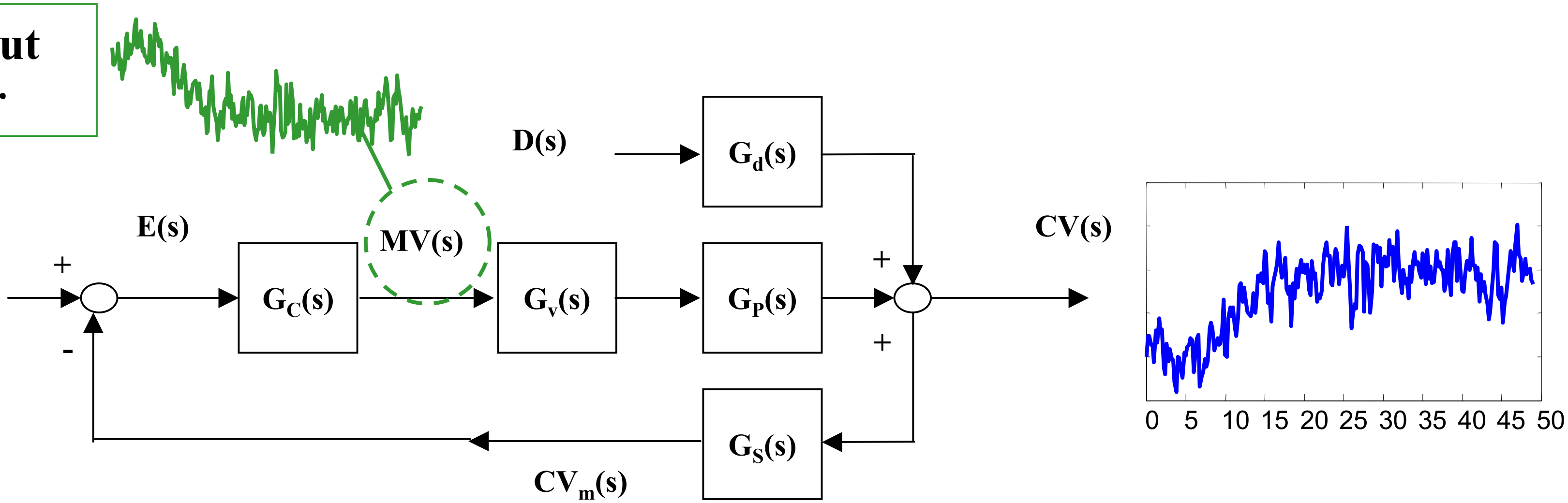
[Values are typical for chemical processes, but vary over a wide range]

CHAPTER 12: PRACTICAL ISSUES

Input - Sensor and Pre-calculations



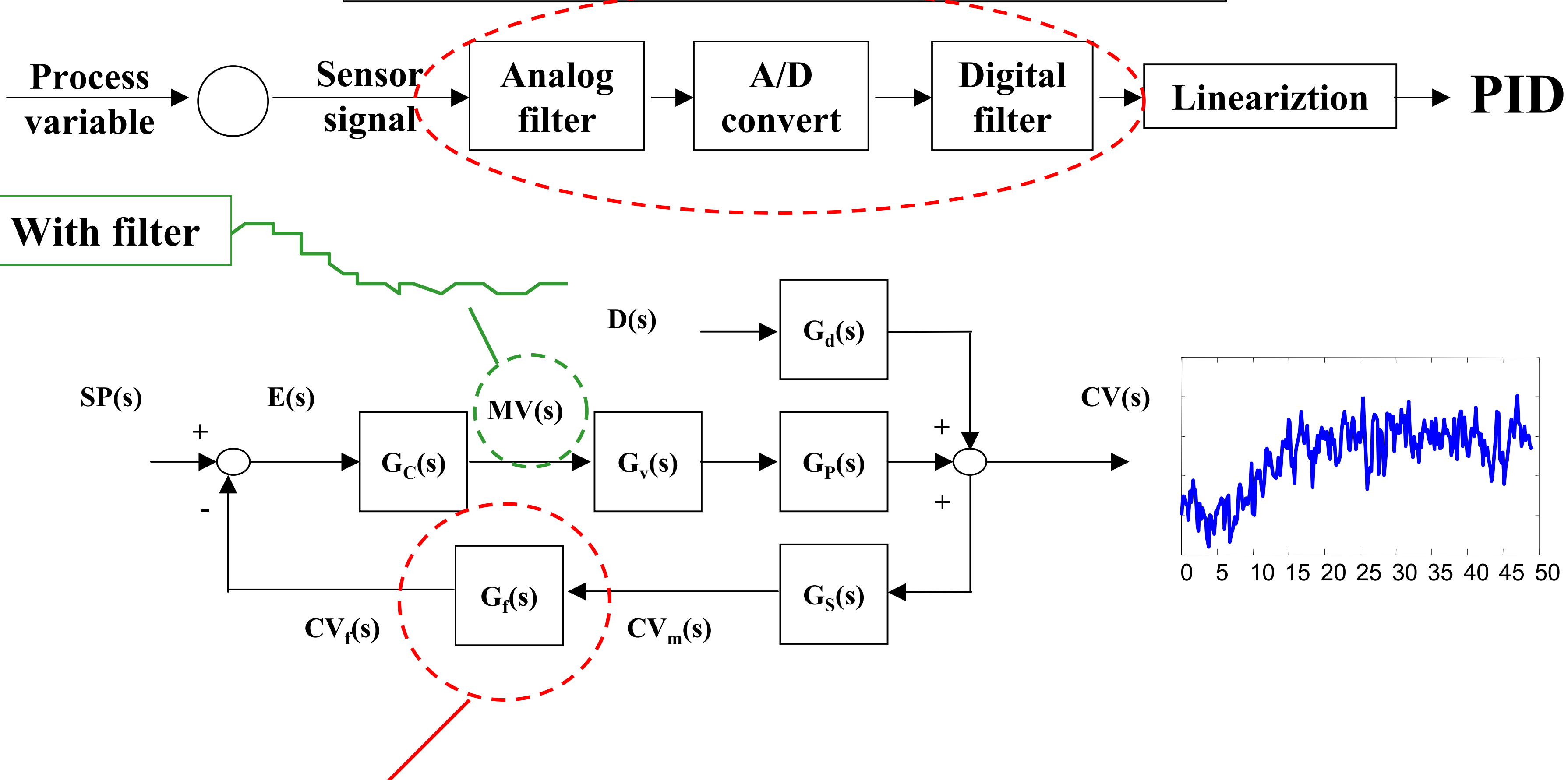
Without filter



Noise goes "around and around" in the feedback loop!

CHAPTER 12: PRACTICAL ISSUES

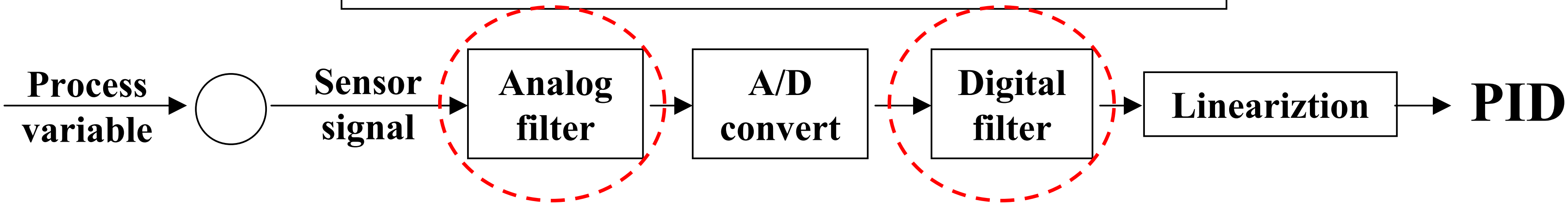
Input - Sensor and Pre-calculations

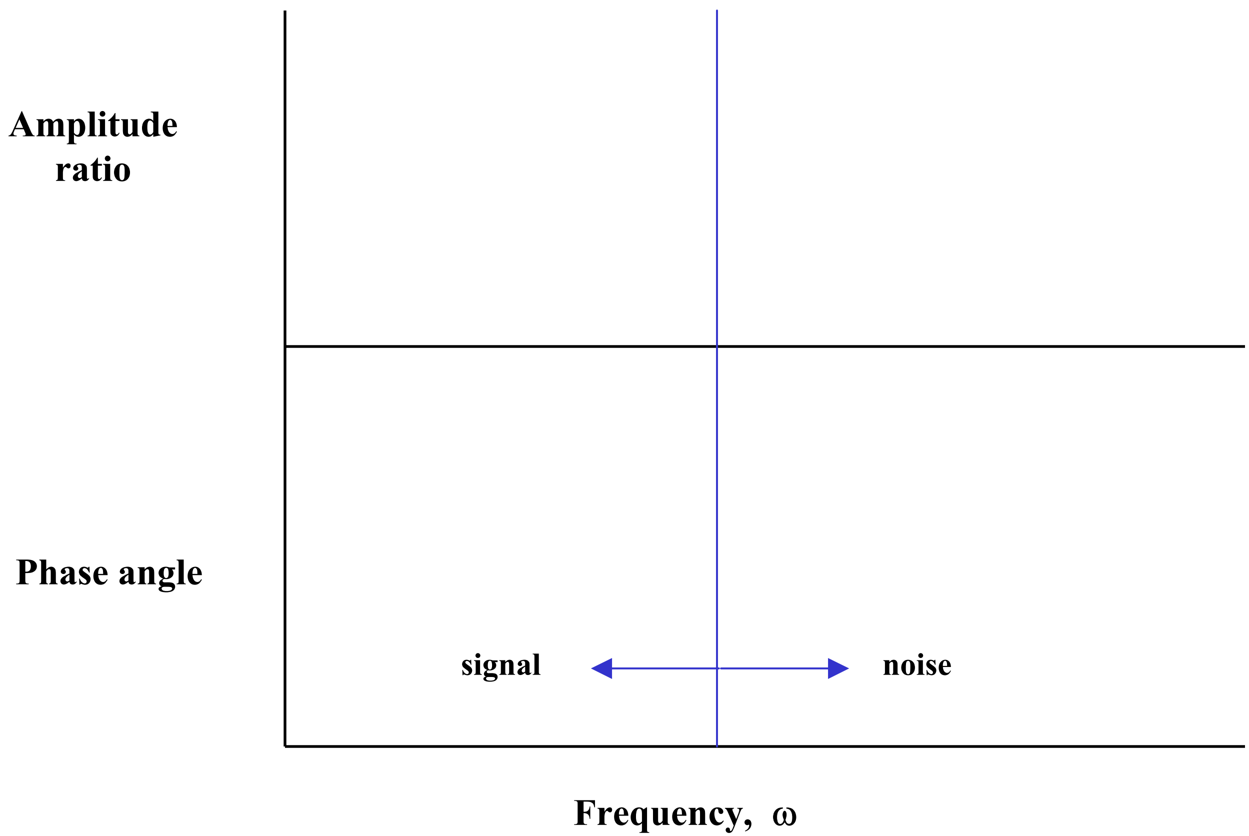


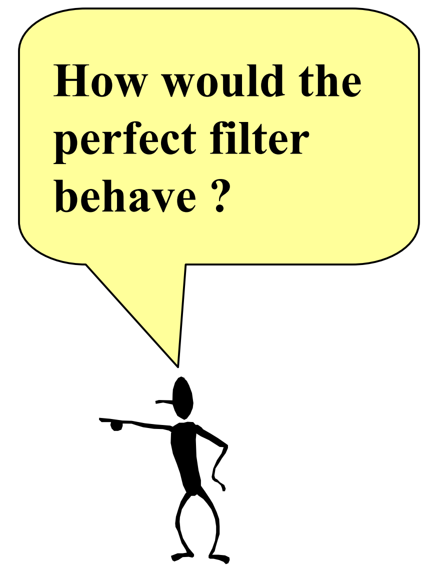
The filter is in the feedback loop. What do we conclude about the favorable filter dynamics?

CHAPTER 12: PRACTICAL ISSUES

Input - Sensor and Pre-calculations

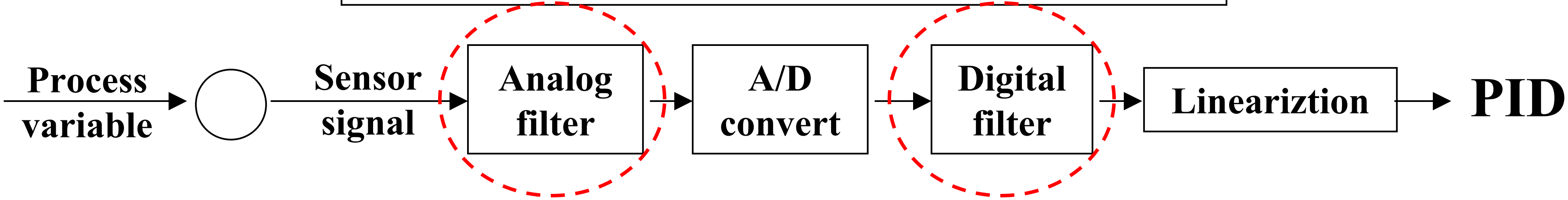


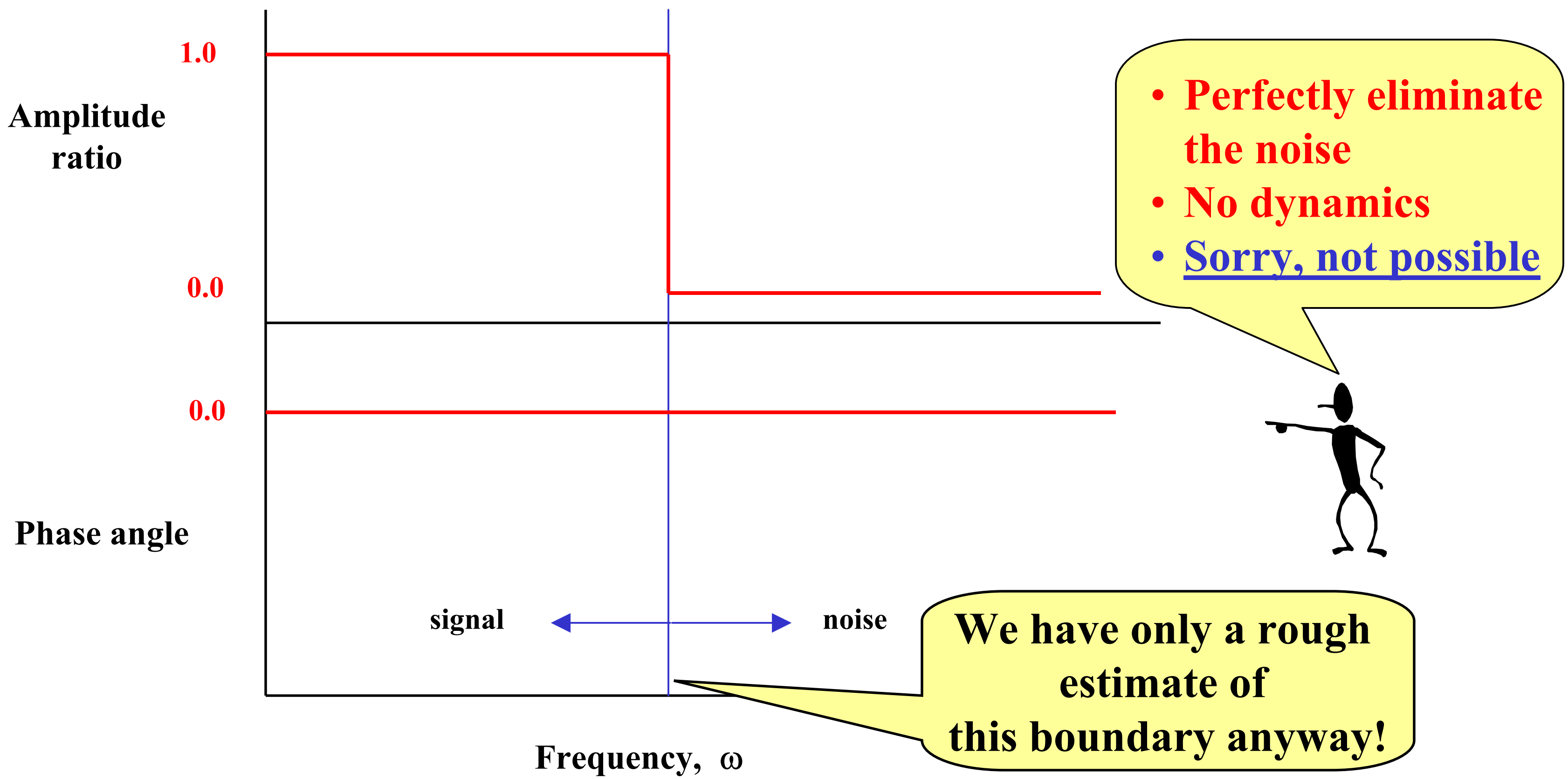




CHAPTER 12: PRACTICAL ISSUES

Input - Sensor and Pre-calculations

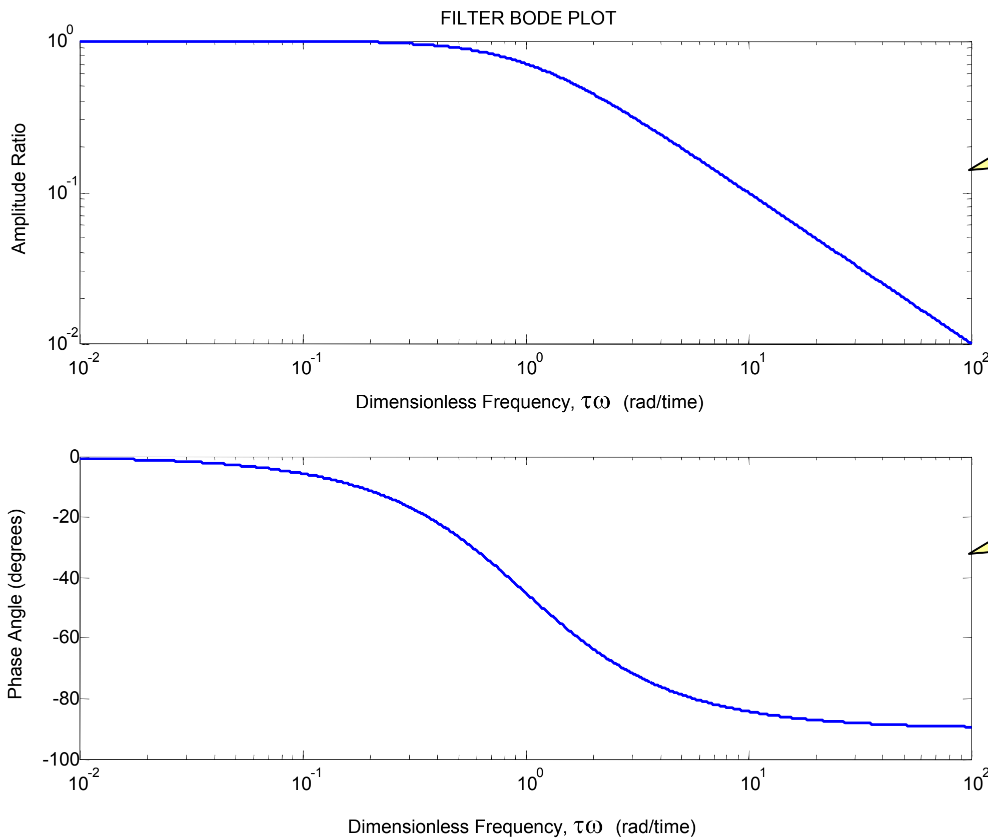




CHAPTER 12: PRACTICAL ISSUES

Input - Sensor and Pre-calculations

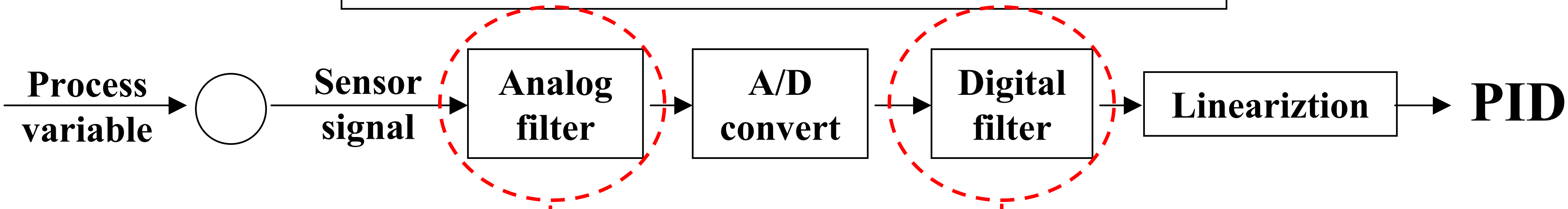
In the process industries, we typically use a first order system for the filter; $G_f(s) = 1.0/(\tau s+1) = CV_f(s)/CV_m(s)$.



Not a perfect step, but has the desired trend.

Contributes dynamics to the feedback loop, but only one (small?) time constant.

Input - Sensor and Pre-calculations



"Anti-Aliasing" filter

$$G_{f1}(s) = 1.0/(\tau_{f1}s+1)$$

- Time constant is small, e.g., few tenths of a second
- Usually part of commercial control equipment

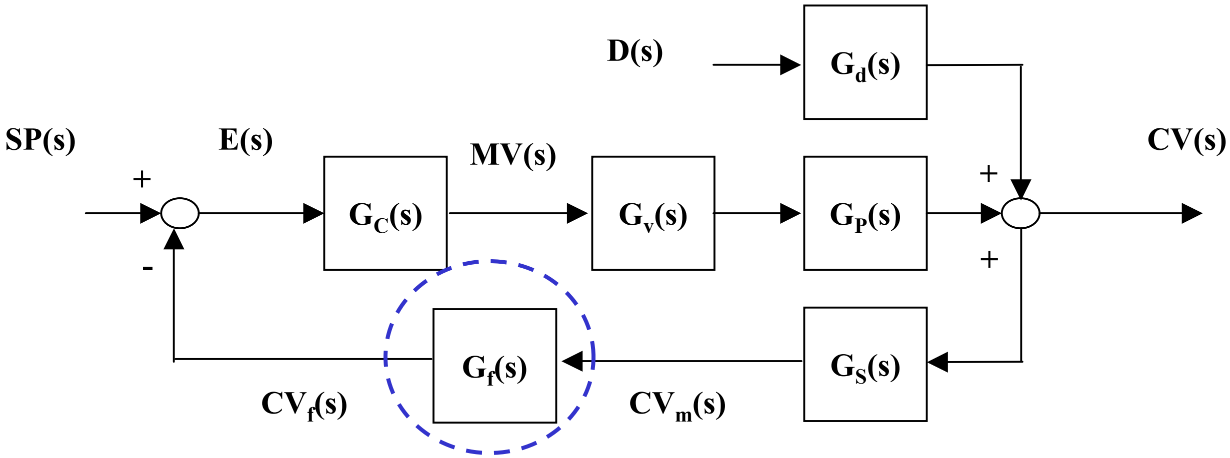
Digital Filter

$$G_{f2}(s) = 1.0/(\tau_{f2}s+1)$$

- Built by engineer for each application
- Time constant is small, e.g., few tenths of a second

CHAPTER 12: PRACTICAL ISSUES

Input - Sensor and Pre-calculations



Guidelines to reduce the effects of noise on feedback

1. Reduce the derivative time (often to 0.0)
2. Set filter time constant small compared to feedback dynamics, $\tau_{f2} < 0.05\ (\theta+\tau)$
3. Set filter time constant large compared to disturbance frequency, $\tau_{f2} < 5/\omega_n$ [but do not violate 2 above]

CHAPTER 12: PRACTICAL ISSUES

Feedback Controller - P, I and D

Continuous PID

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

Digital PID

Positional form

$$MV_N = K_c\left[E_N + \frac{\Delta t}{T_I}\sum_{i=1}^{N} E_i - \frac{T_d}{\Delta t}(CV_N - CV_{N-1})\right] + I$$

velocity form

$$\Delta MV_N = K_c\left[E_N - E_{N-1} + \frac{(\Delta t)}{T_I}E_N - \frac{T_d}{\Delta t}(CV_N - 2CV_{N-1} + CV_{N-2})\right]$$

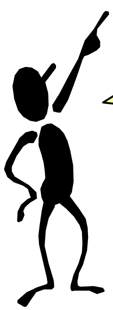
$$MV_N = MV_{N-1} + \Delta MV_N$$

CHAPTER 12: PRACTICAL ISSUES

Feedback Controller - P, I and D

Error - Let's remember that two conventions are common.

$$E = SP - CV \qquad\qquad E = CV - SP$$



This is just a simple convention that we must learn.
But, if we get it wrong, the controller will be unstable!

CHAPTER 12: PRACTICAL ISSUES

Feedback Controller - P, I and D

Controller sense - In most systems, the controller gain (K_c) is ALWAYS positive. Therefore, we need a way to determine the controller sign. This is the controller "sense".

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

K_{sense}	Convention A	Convention B
+1	Direct acting	Increase/increase
-1	Reverse acting	Increase/decrease

Feedback Controller - P, I and D

Proportional - The proportional mode can be formulated with various engineering units. Several common methods are used in commercial systems. They do not change the performance of the controller.

Scaled variables - Many digital (and all analog) systems represent variables in scaled (dimensionless) form.

$$CV_{scaled} = \frac{CV - CV_{\min}}{CV_{\max} - CV_{\min}} = \frac{CV - CV_{\min}}{CV_{range}}$$

$$MV_{scaled} = \frac{MV - MV_{\min}}{MV_{\max} - MV_{\min}} = \frac{MV - MV_{\min}}{MV_{range}}$$

$$E_{scaled} = \frac{(SP - SP_{\min}) - (CV - CV_{\min})}{CV_{\max} - CV_{\min}} = \frac{E}{CV_{range}}$$

Feedback Controller - P, I and D

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

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

$$(K_c)_s = K_c \left[\frac{CV_r}{MV_r} \right]$$

This is the scaled proportional gain. In some software, the engineer must input $(K_c)_s$.

CHAPTER 12: PRACTICAL ISSUES

Feedback Controller - P, I and D

$$\frac{MV(t)}{MV_r} = \left[\frac{100}{PB}\right]\left[\frac{E(t)}{CV_r} + \frac{1}{T_I}\int_0^t \frac{E(t')}{CV_r}dt' - T_d \frac{d\,{CV(t)}/{\mathrm{CV_r}}}{dt}\right] + I$$

$$(K_c)_s = \frac{100}{PB}$$

This is the Proportional Band. In some software, the engineer must input PB.

CHAPTER 12: PRACTICAL ISSUES

Feedback Controller - P, I and D

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

$$T_R = \frac{1}{T_I}$$

This is the Reset Time. In some software, the engineer must input T_R.

CHAPTER 12: PRACTICAL ISSUES

Feedback Controller - P, I and D

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

Reset Windup - The integral is persistent, it doesn’t stop until the error is zero. But, if the final element (valve) has reached its maximum or minimum, the integral should “stop”; if it doesn’t, the calculated value could increase in magnitude towards infinity.

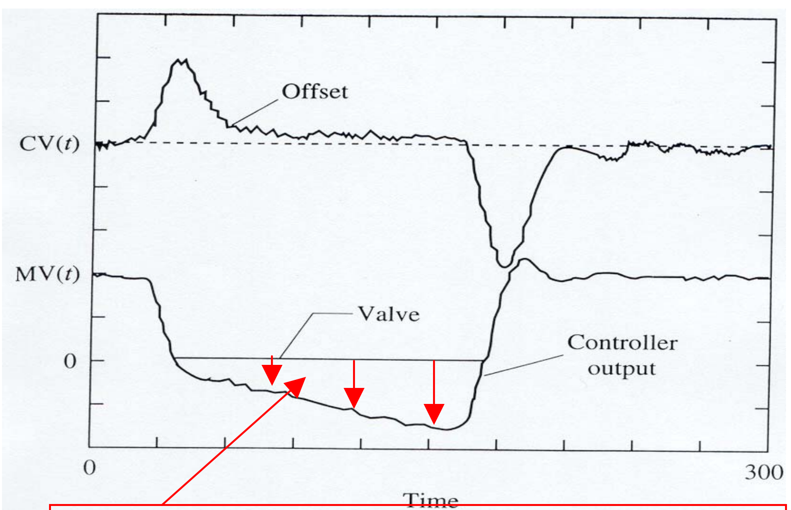
This is called reset windup and must be prevented.

CHAPTER 12: PRACTICAL ISSUES

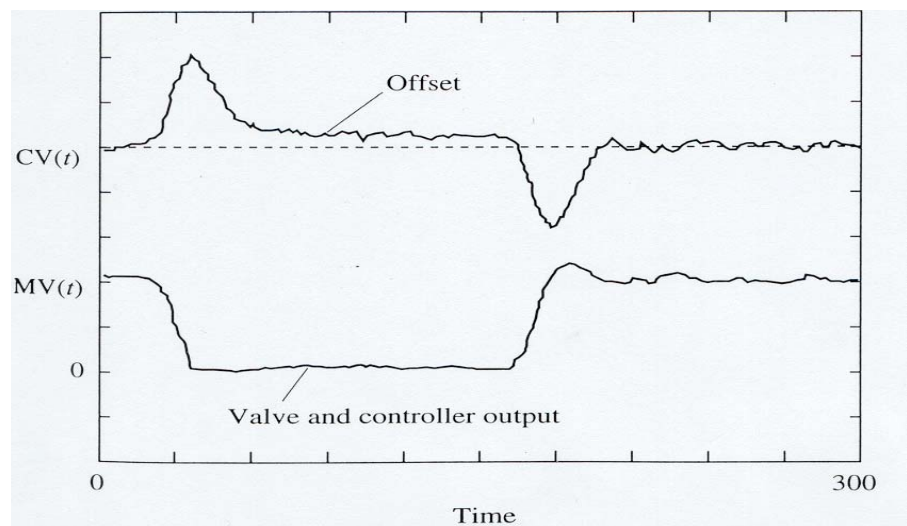
Feedback Controller - P, I and D

Behavior without anti-reset-windup: **The controller output continues to change (winds up). It takes some time to return to a value where the controller output affects the valve.**

Behavior with anti-reset-windup: **The controller output stops at the boundary (doesn't wind up). The increase in the controller output immediately affects the valve when needed**



Windup. The controller output exceeds the range of the valve movement.



No windup!

CHAPTER 12: PRACTICAL ISSUES

Feedback Controller - P, I and D

Anti-reset-windup - Several approaches are used. One simple approach is demonstrated here.

$$\Delta MV_N = K_c\left[E_N - E_{N-1} + \frac{(\Delta t)}{T_I}E_N - \frac{T_d}{\Delta t}(CV_N - 2CV_{N-1} + CV_{N-2})\right]$$

$$MV_N = MV_{N-1} + \Delta MV_N$$

$$\left.\begin{aligned} MV_N &\le MV_{\max} \\ MV_N &\ge MV_{\min} \end{aligned}\right\} \quad \textbf{Anti-reset-windup modification}$$

MV_N is implemented and stored for use as MV_{N-1} during the next iteration

CHAPTER 12: PRACTICAL ISSUES

Feedback Controller - P, I and D

Derivative Filter - If we filter the measurement, we "slow" all controller modes. An option exists to filter only the derivative mode.

$$\frac{T_d s}{\alpha T_d s + 1}$$

α usually is specified as 0.1, which gives a filter of 10% of the derivative time.

CHAPTER 12: PRACTICAL ISSUES

Output processing

Bumpless transfer - When the controller is switched from manual (off) to automatic (on), the final element (valve) should start from its initial value.

Special calculation for initialization

$$
\left\{
\begin{array}{l}
IF \quad N = 1 \\
MV_N = \textbf{Current output to final element} \\
\Delta \mathbf{MV_N} = 0 \\
E_N = SP_N - CV_N ; \quad CV_{N-1} = CV_N
\end{array}
\right.
$$

ELSE

$$E_{N-1} = E_N$$

$$E_N = SP_N - CV_N$$

$$\Delta MV_N = K_c \left[E_N - E_{N-1} + \frac{(\Delta t)}{T_I} E_N - \frac{T_d}{\Delta t} (CV_N - 2CV_{N-1} + CV_{N-2}) \right]$$

END

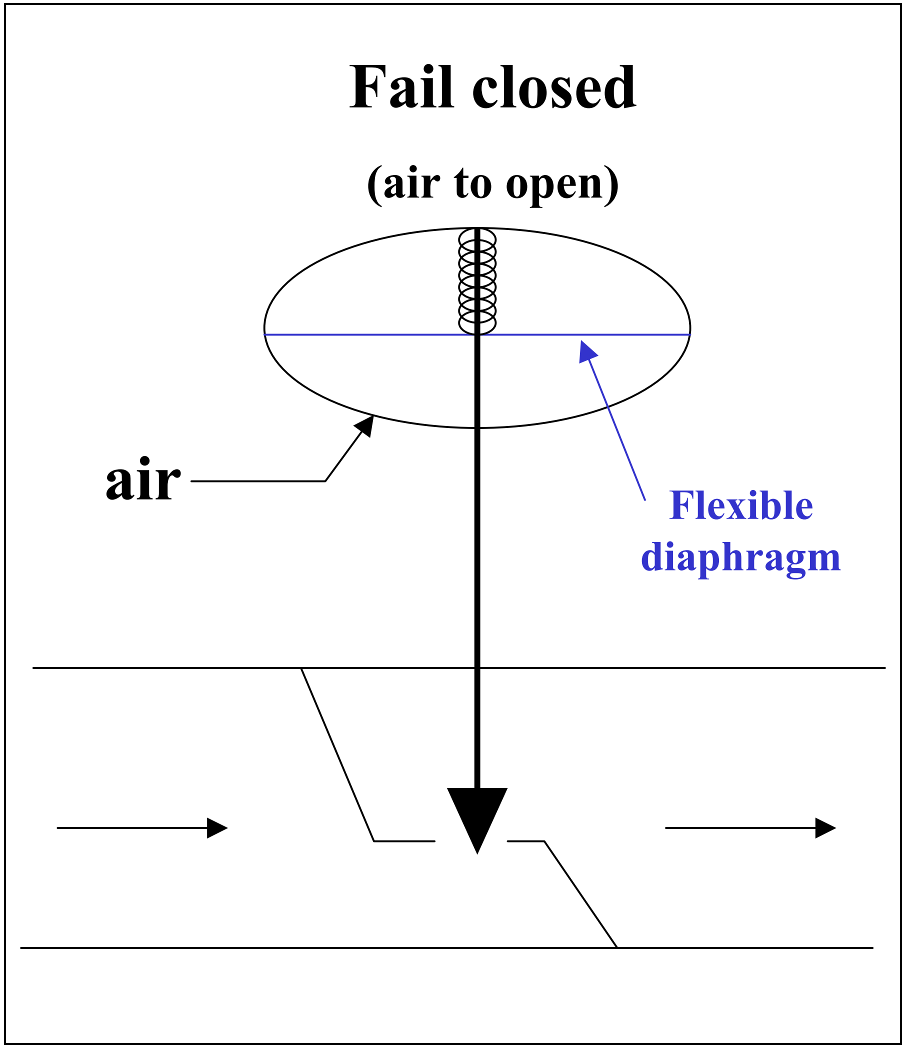
$$MV_N = MV_{N-1} + \Delta MV_N ; \quad CV_{N-2} = CV_{N-1} ; \quad CV_{N-1} = CV_N$$

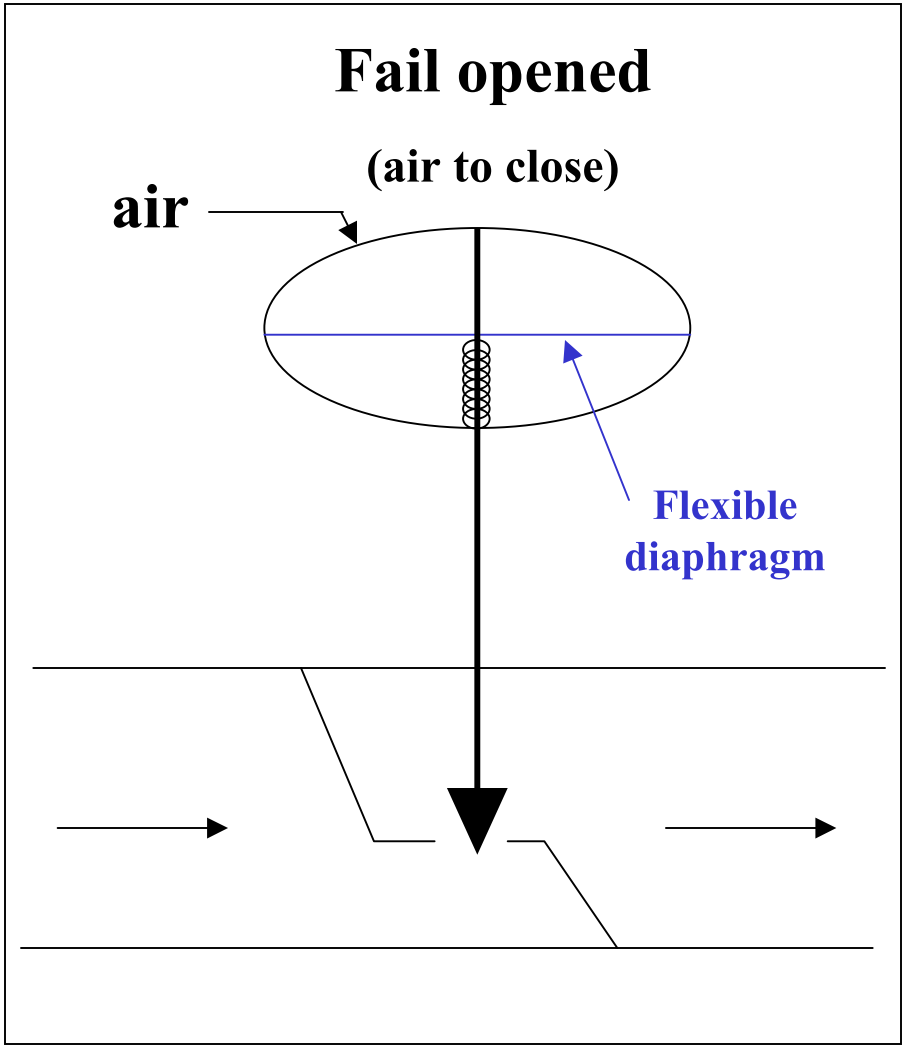
$$MV_N \leq MV_{max}$$

$$MV_N \geq MV_{min}$$

CHAPTER 12: PRACTICAL ISSUES

Output processing

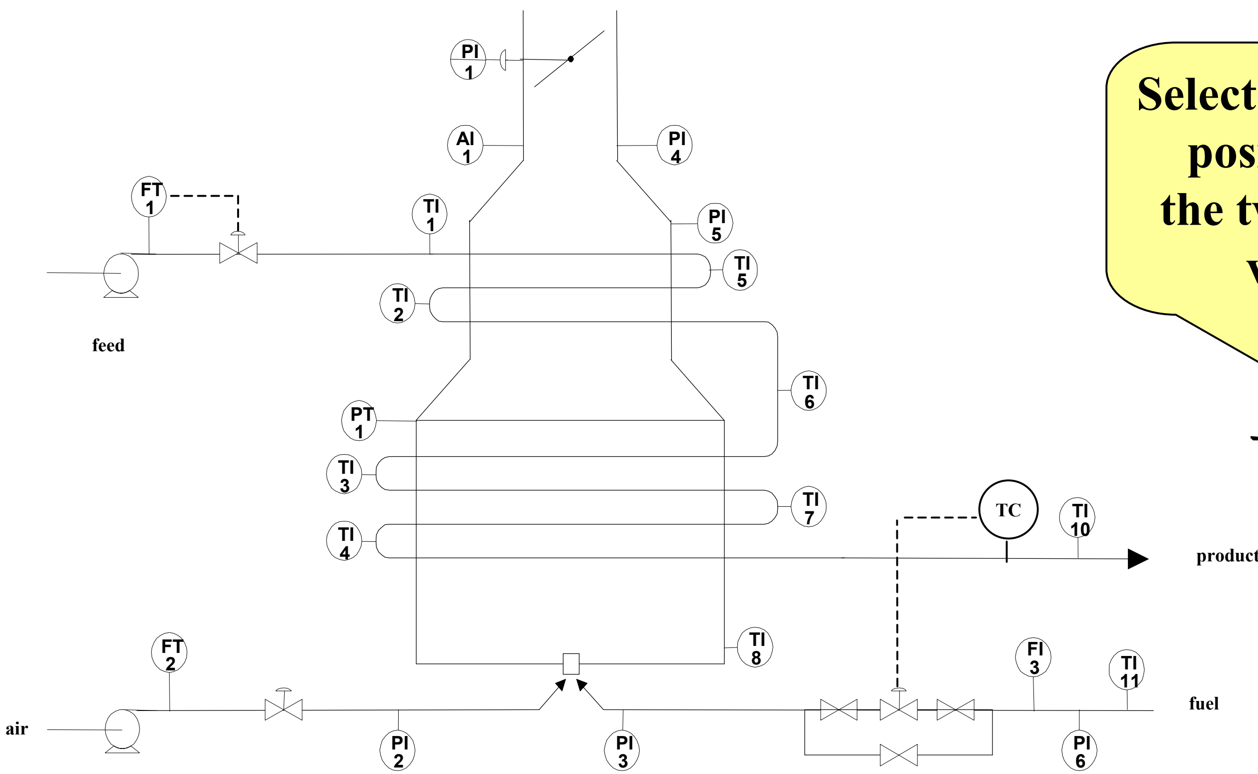




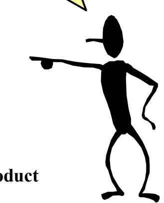
CHAPTER 12: PRACTICAL ISSUES

Output processing

Failure position - **This is selected based on safety. Remember that we must know the failure position to understand sign of the controller gain.**



Select the failure positions for the two control valves.

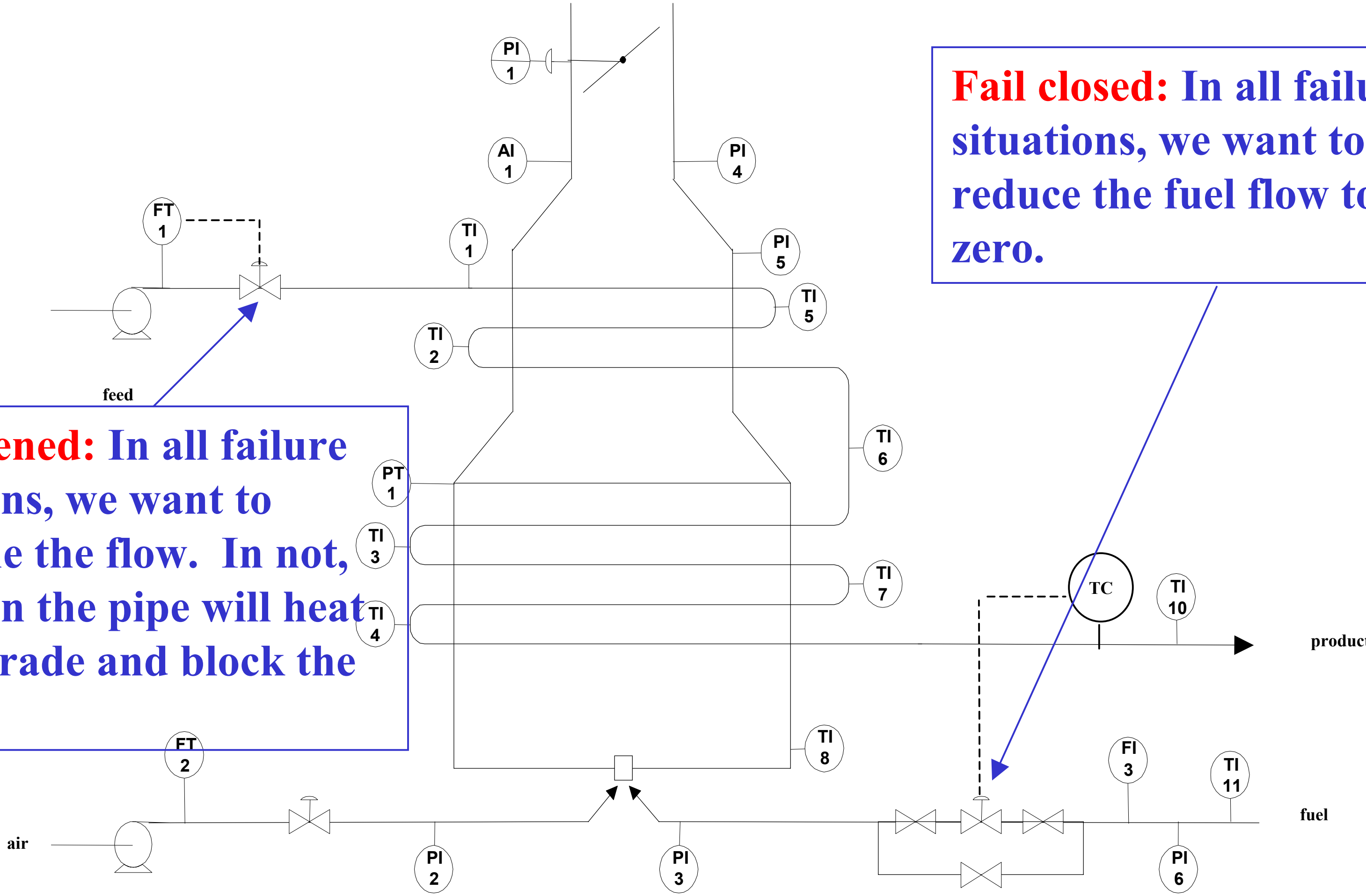


CHAPTER 12: PRACTICAL ISSUES

Output processing

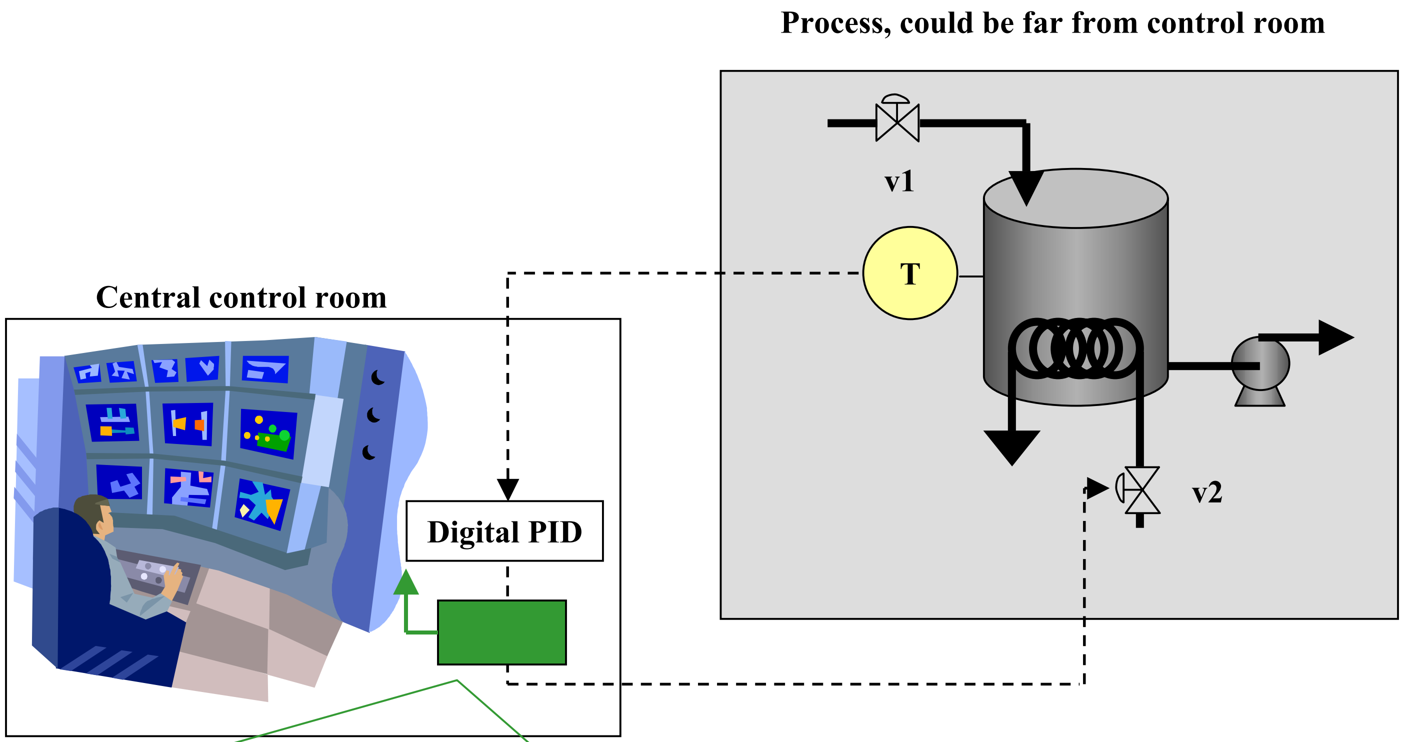
Failure position - This is selected based on safety.

Fail closed: In all failure situations, we want to reduce the fuel flow to zero.



Fail opened: In all failure situations, we want to continue the flow. In not, the oil in the pipe will heat up, degrade and block the pipe.

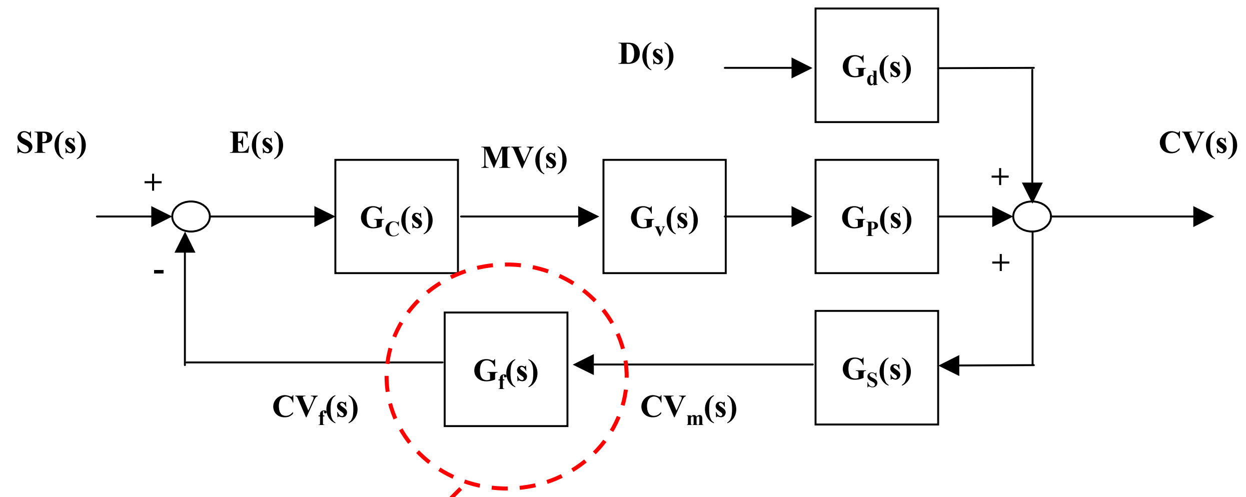
CHAPTER 12: PRACTICAL ISSUES WORKSHOP 1



You and a few friends started a company to design a new digital control system. The company has decided to provide anti-reset-windup using the "external feedback" method.

You have volunteered to provide "pseudo-code" for the PID and external feedback calculation.

CHAPTER 12: PRACTICAL ISSUES WORKSHOP 2



You wonder why the first order filter is used often in process control. So, you perform the following investigation.

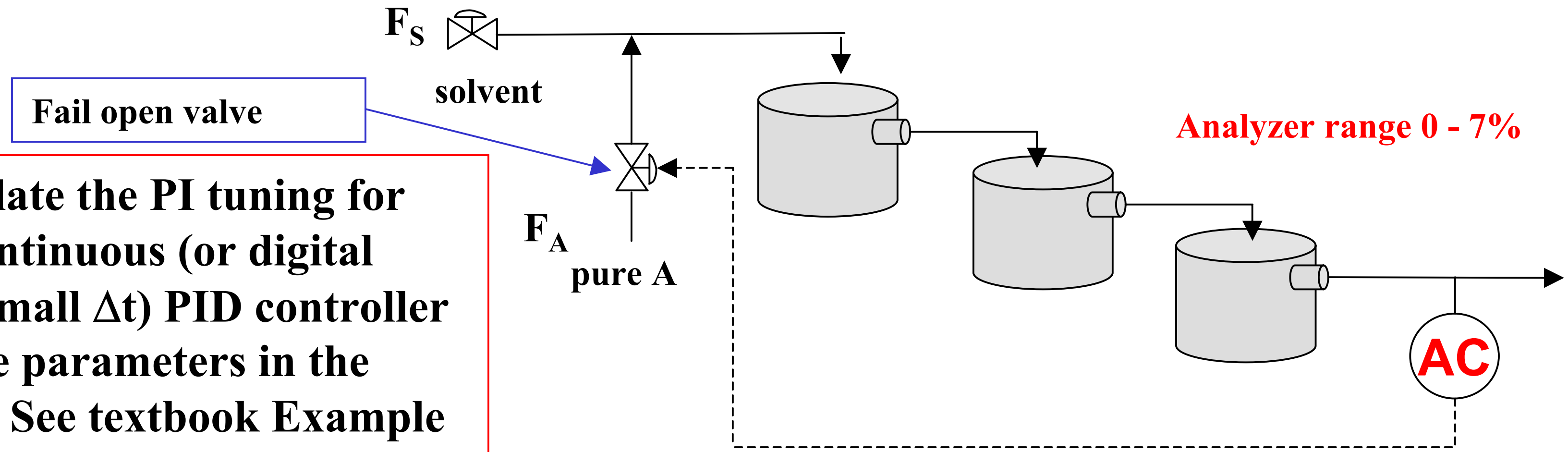
- Determine the transfer function for a 4th order filter, with four equal time constants.
- Calculate the frequency response for the fourth order filter.
- Identify advantages and disadvantages with respect to a 1st order filter.
- Decide which is generally best for feedback control.

CHAPTER 12: PRACTICAL ISSUES WORKSHOP 3

Sensors - Select one sensor for flow (F), temperature (T), Pressure (P) and level (L). For each

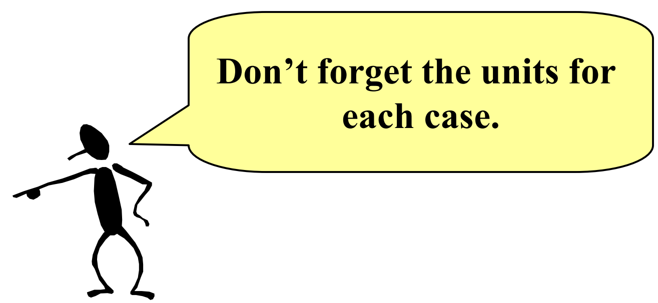
- **Estimate the accuracy and reproducibility**
- **Discuss several reasons for sensor errors**
- **For each reason for inaccuracy, suggest an method for reducing the inaccuracy, which could involve installation, calibration, other sensro principle, or other action.**

CHAPTER 12: PRACTICAL ISSUES WORKSHOP 4



Calculate the PI tuning for the continuous (or digital with small Δt) PID controller for the parameters in the table. See textbook Example 9.2 for initial tuning calculations.

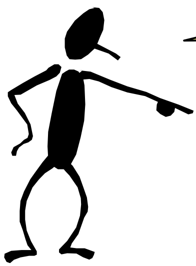
Before determining these, select correct controller sense.



Gain	Kc	(Kc)s	PB	PB
Integral	TI	TR	TI	TR

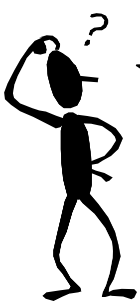
From Example 9.2

CHAPTER 12: PRACTICAL ISSUES



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

- Select appropriate sensors and valves
- Determine the controller parameters for commercial systems
- Tune methods for noise reduction
- Enhance the simple PID for shortcomings (windup, bumpless)



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 12: PRACTICAL ISSUES

- **<u>SITE PC-EDUCATION WEB</u>**
  - Instrumentation Notes - EVERYTHING!
  - Interactive Learning Module (Chapter 12)
  - Tutorials (Chapter 12)

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

CHAPTER 12: SUGGESTIONS FOR SELF-STUDY

1. Determine the accuracy for two common sensors measuring each of the following; flow, temperature pressure and level.
2. For two common control valve bodies, determine the admissible fluid characteristics and summarize the +/- in selection criteria.
3. Search the WWW to locate suppliers of flow sensors. Find a specification sheet for an orifice meter and discuss how you would determine the information when designing a plant.

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4. **Search the WWW to locate suppliers of control valves. Find a specification sheet for a globe valve with diaphragm actuator and discuss how you would determine the information when designing a plant.**

5. **Locate the book "What Went Wrong" by Trevor Kletz. Skim the cases in the book to find one in which a sensor error lead to a hazardous condition. What was recommended to prevent this situation from reoccurring?**

6. **Search the WWW for digital instrumentation and communication (check "fieldbus"). Determine the enhanced features provided when the following have digital calculations; sensor and valve (positioner).**