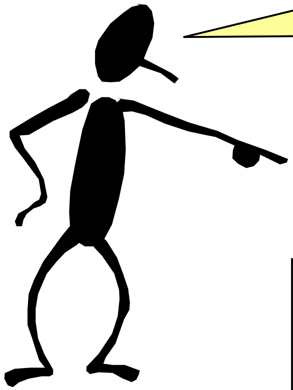
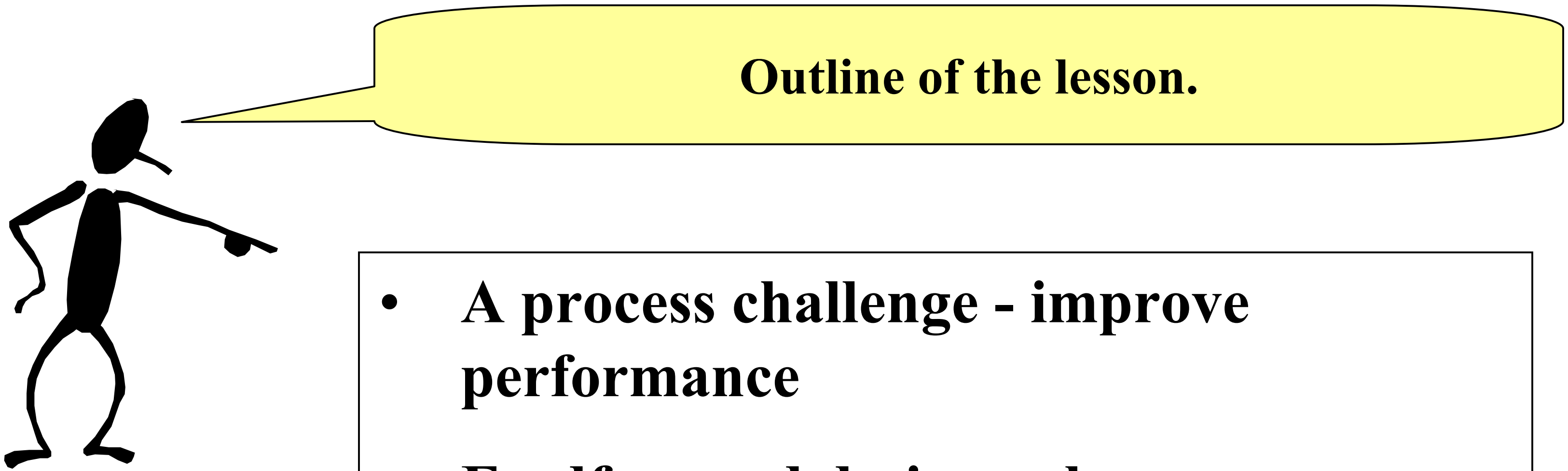
CHAPTER 15: FEEDFORWARD CONTROL



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

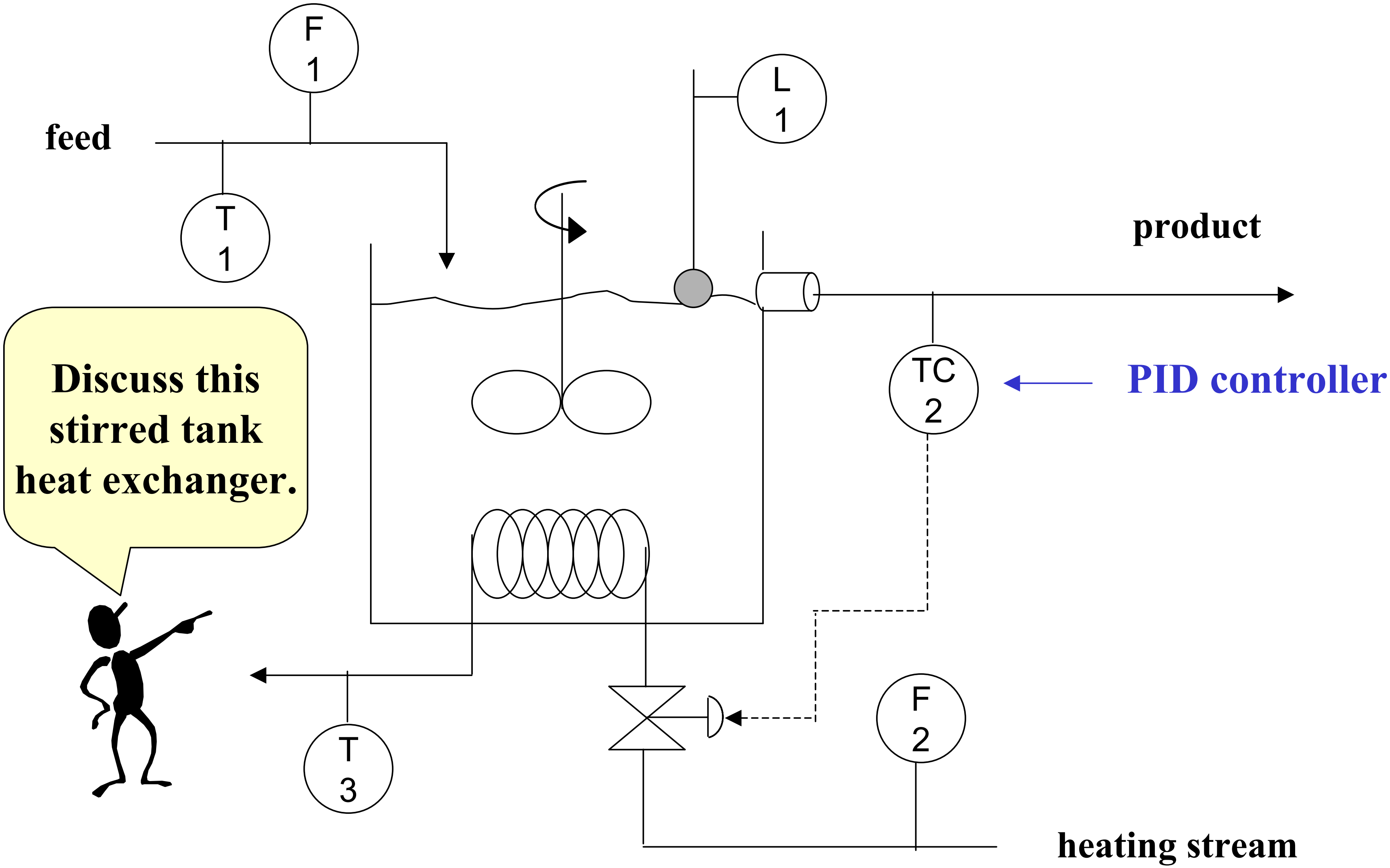
- **Identify situations for which feedforward is a good control enhancement**
- **Design feedforward control using the five design rules**
- **Apply the feedforward principle to other challenges in life**

CHAPTER 15: FEEDFORWARD CONTROL



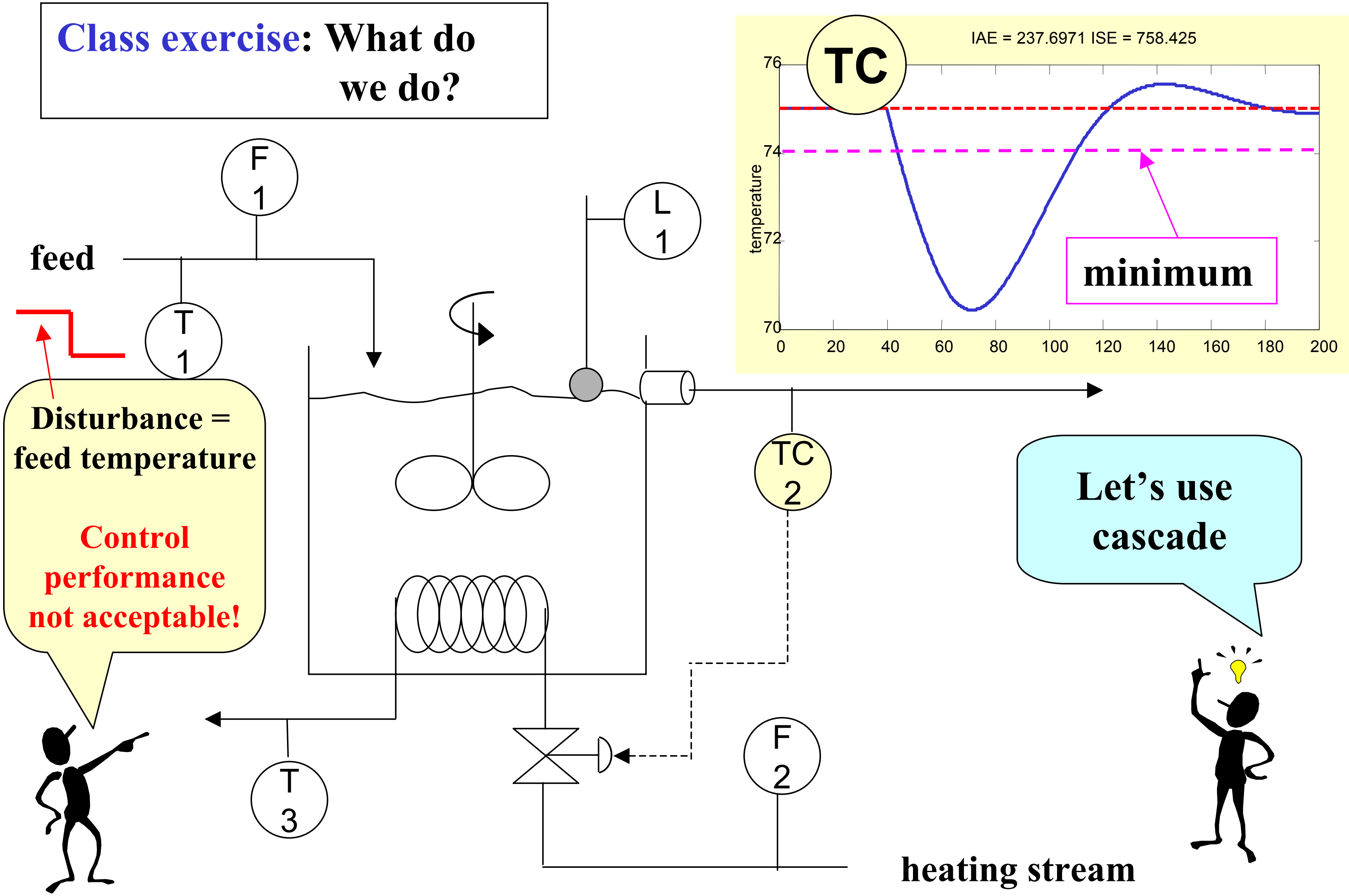
- A process challenge - improve performance
- Feedforward design rules
- Good features and application guidelines
- Several process examples
- Analogy to management principle

CHAPTER 15: FEEDFORWARD CONTROL



CHAPTER 15: FEEDFORWARD CONTROL

Class exercise: What do we do?



CASCADE DESIGN CRITERIA FOR T1

Cascade is desired when

1. Single-loop performance unacceptable
2. A measured variable is available

A secondary variable must

3. Indicate the occurrence of an important disturbance
4. Have a causal relationship from valve to secondary
5. Have a faster response than the primary

CHAPTER 15: FEEDFORWARD CONTROL

CASCADE DESIGN CRITERIA FOR T1

Cascade is desired when

OK

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CASCADE DESIGN CRITERIA FOR T1

Cascade is desired when

OK
1. Single-loop performance **unacceptable**

OK
2. A **measured** variable is available

A secondary variable must

OK
3. Indicate the occurrence of an **important** disturbance
4. Have a **causal** relationship from valve to secondary
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CASCADE DESIGN CRITERIA FOR T1

Cascade is desired when

OK

1. Single-loop performance unacceptable

OK

2. A measured variable is available

A secondary variable must

OK

3. Indicate the occurrence of an important disturbance
4. Have a causal relationship from valve to secondary
5. Have a faster response than the primary

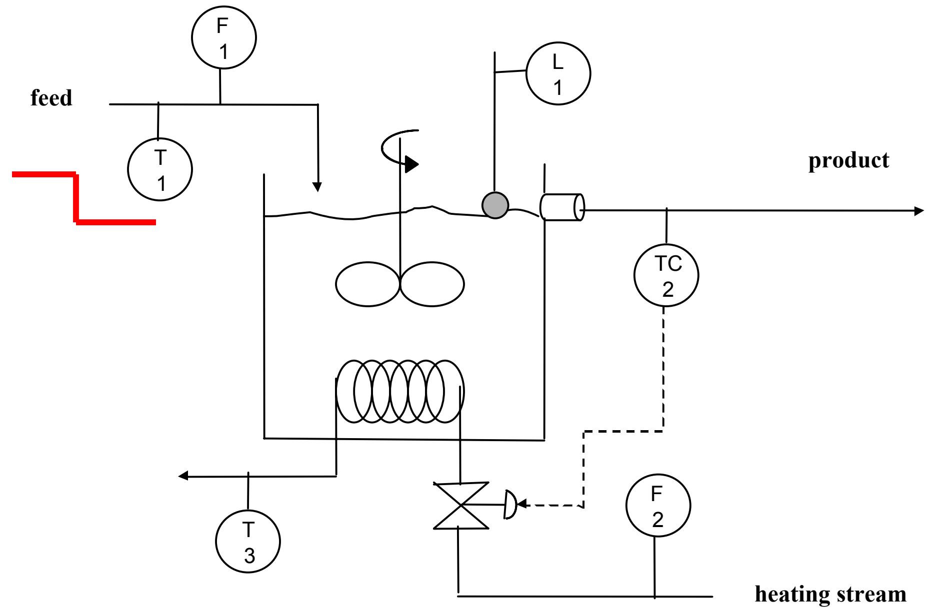
NO!

Cascade not possible. We need another enhancement!

CHAPTER 15: FEEDFORWARD CONTROL

Let's think about the process behavior.

- **Causal relationship from T_1 disturbance to T_2 (without control)**
- **How can we manipulate valve to compensate?**

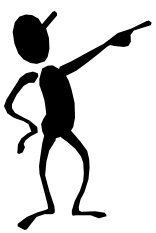


$$v\ (\text{valve}) \rightarrow Q \rightarrow TC$$

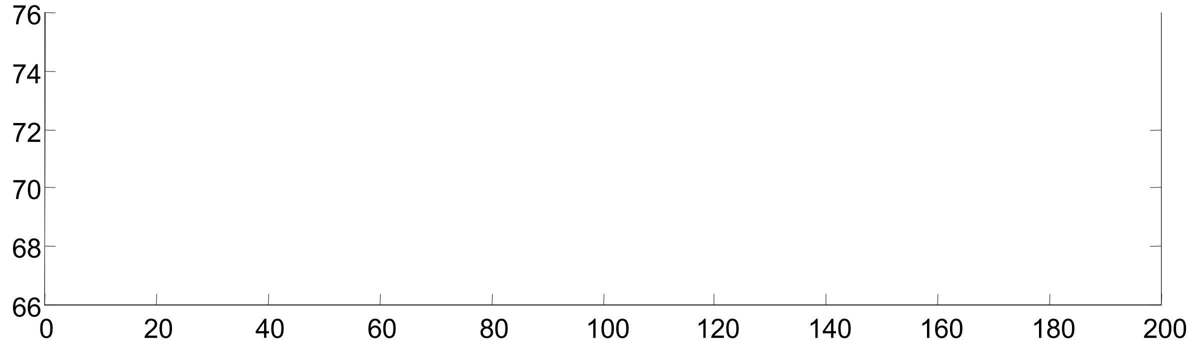
T_0 (Feed temperature) $\rightarrow$ TC

CHAPTER 15: FEEDFORWARD CONTROL

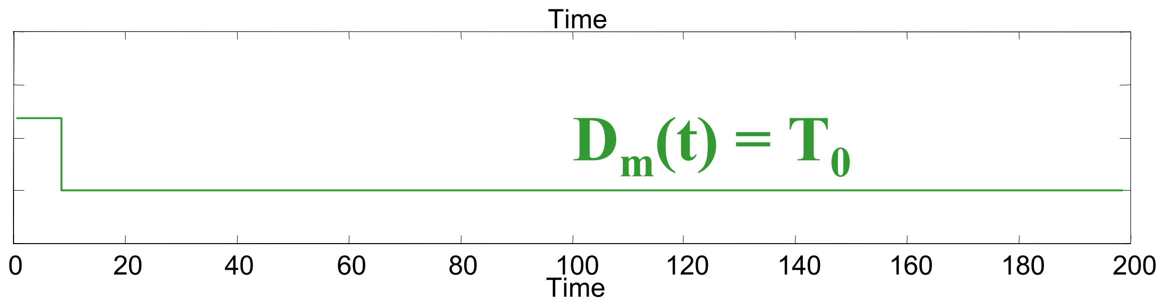
We want to adjust the valve to cancel the effect of the disturbance.



T

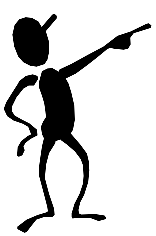


T_0



CHAPTER 15: FEEDFORWARD CONTROL

We want to adjust the valve to **cancel** the effect of the disturbance.



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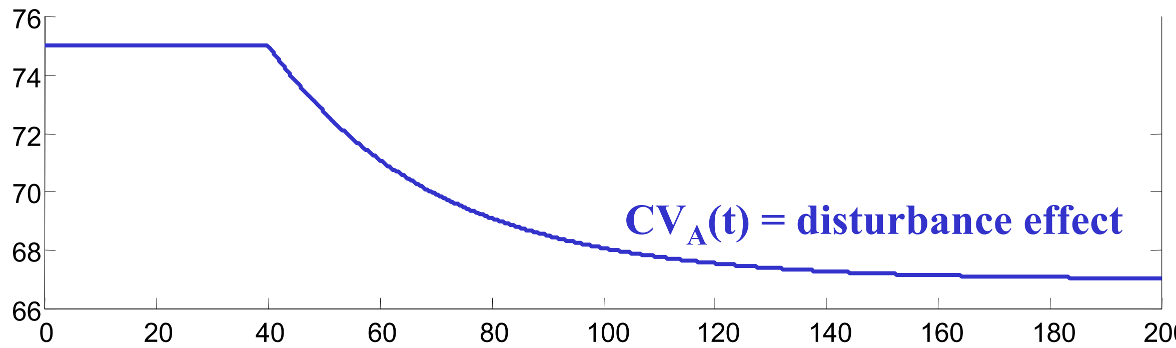
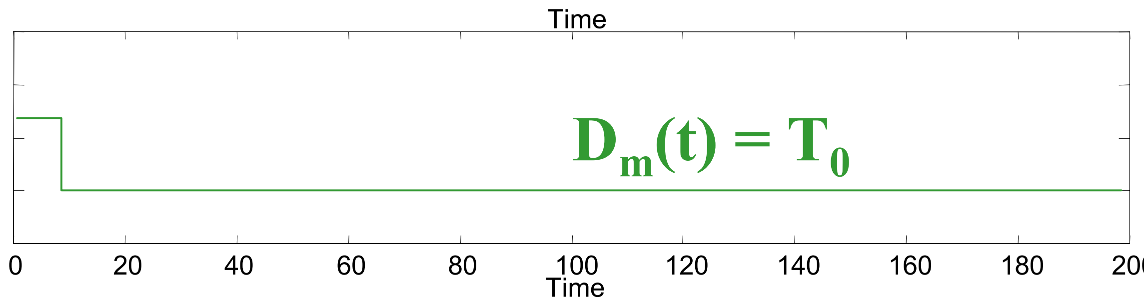
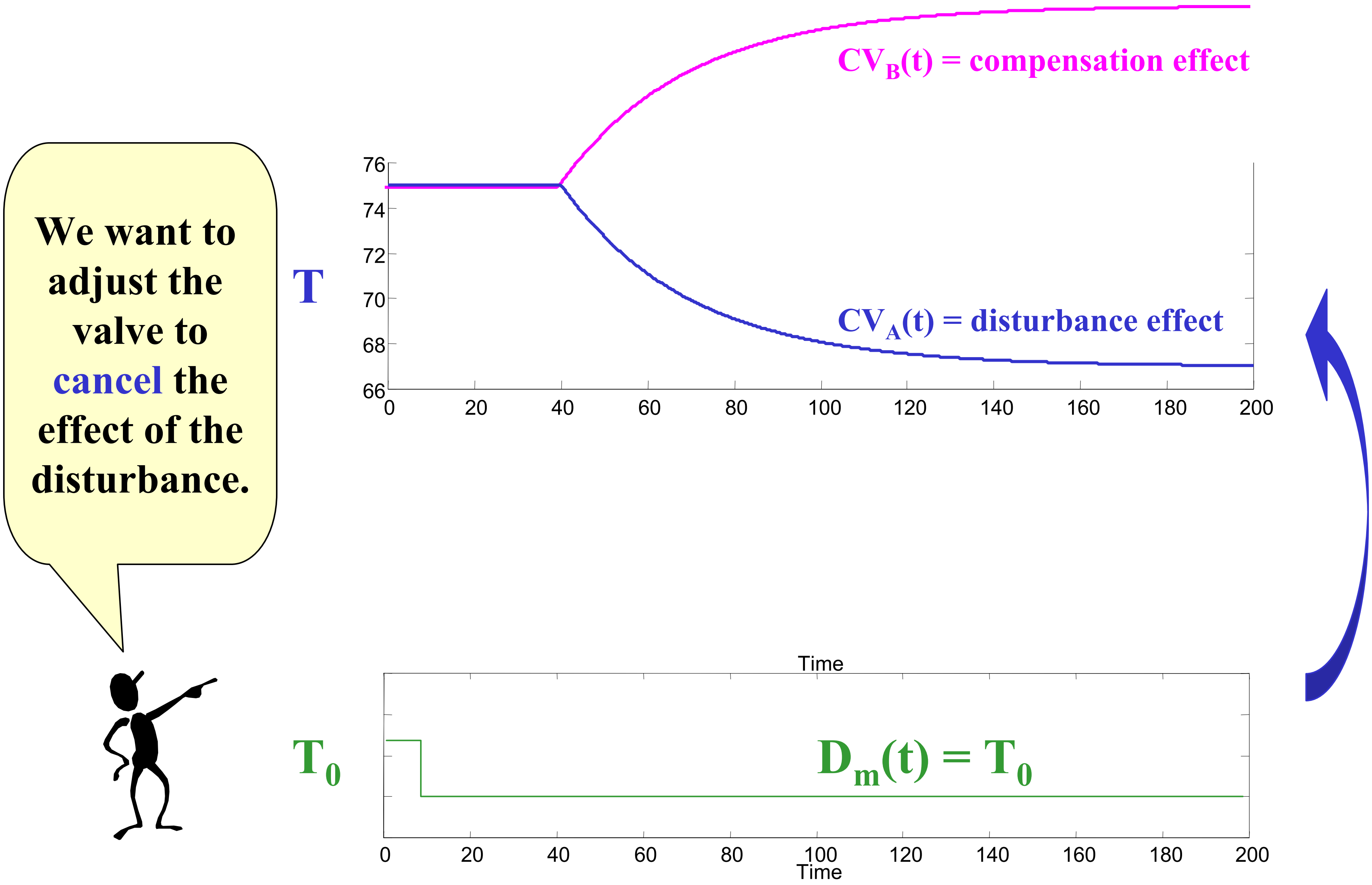


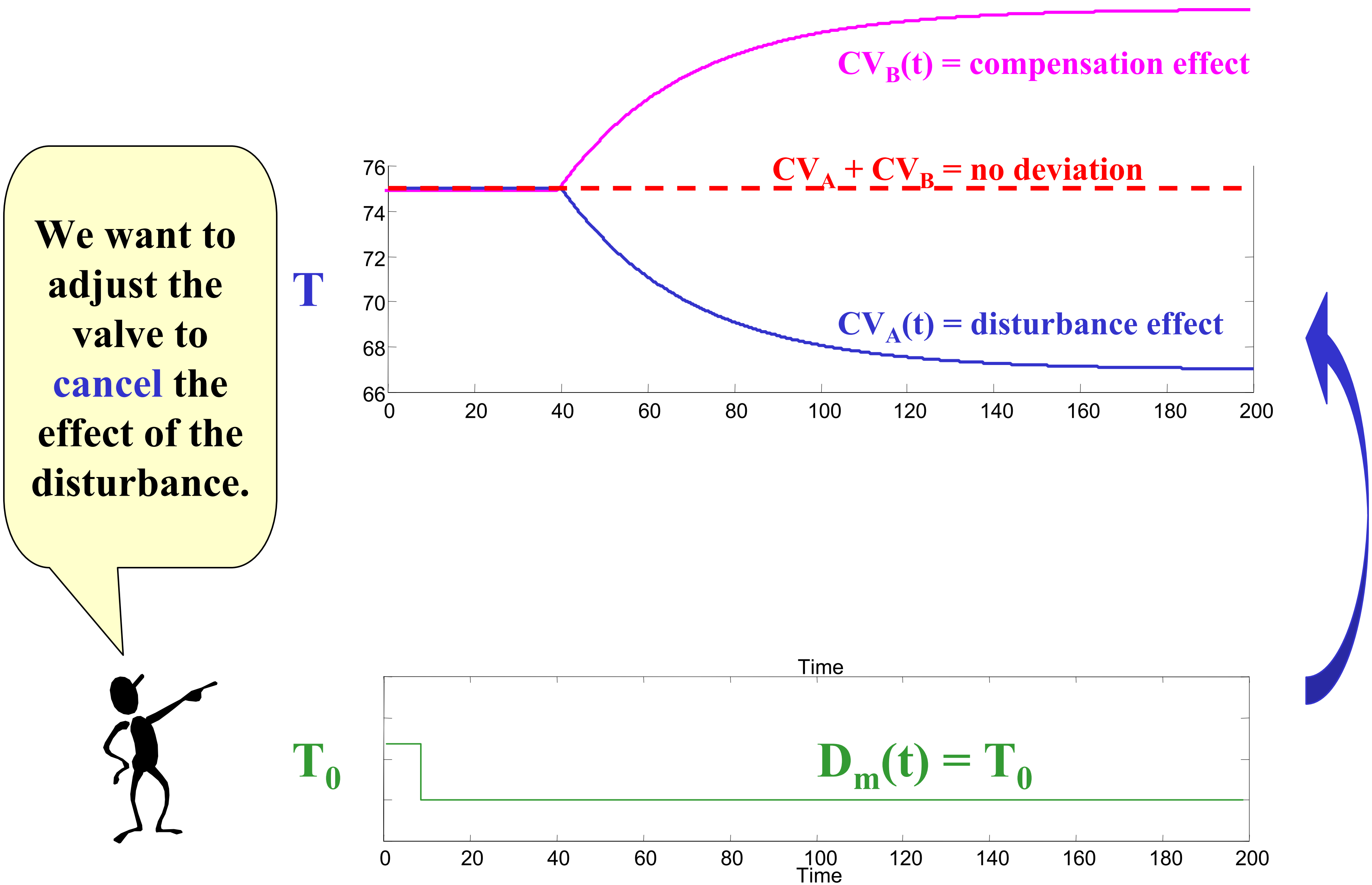
T_0



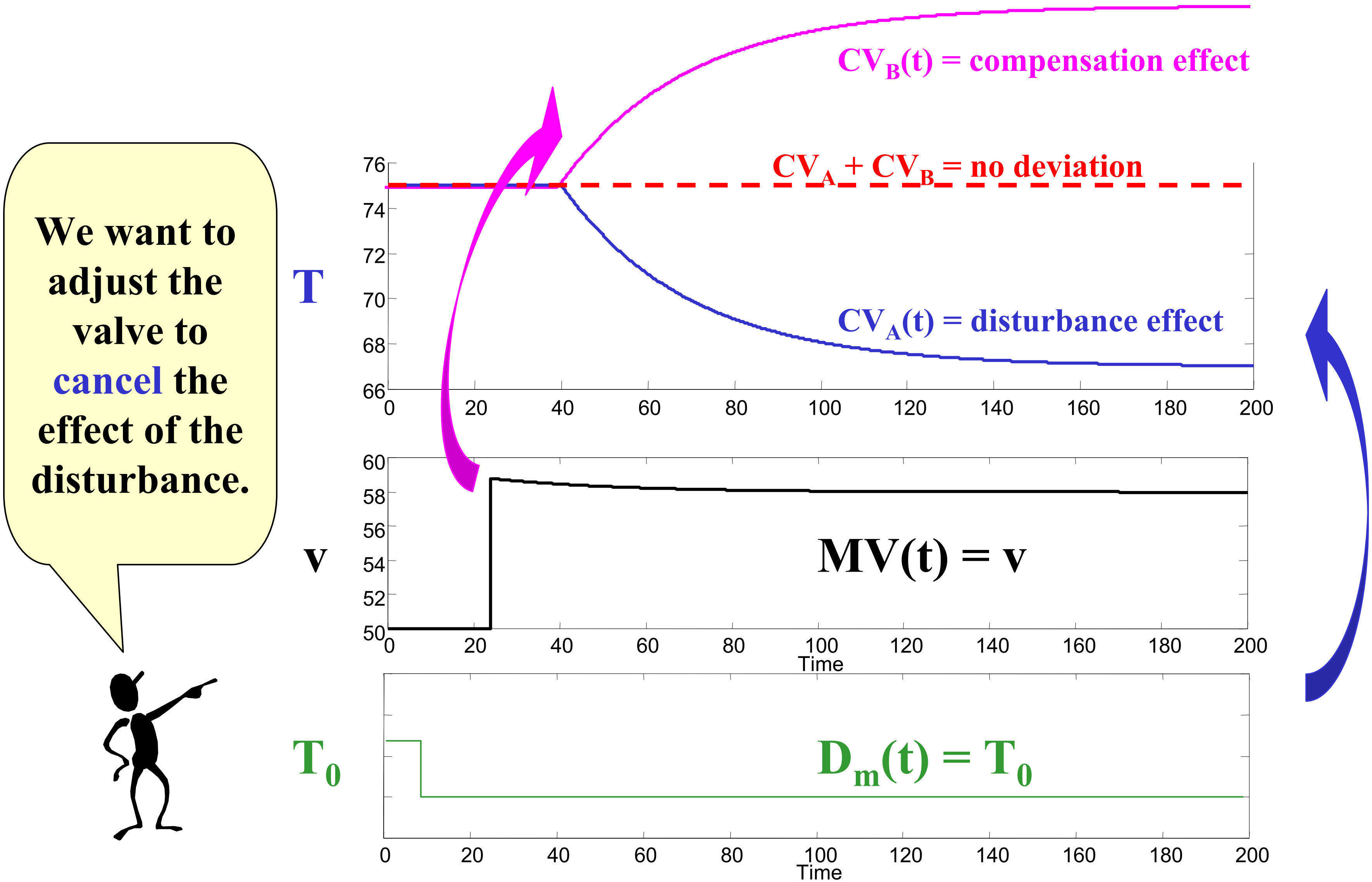
CHAPTER 15: FEEDFORWARD CONTROL



CHAPTER 15: FEEDFORWARD CONTROL

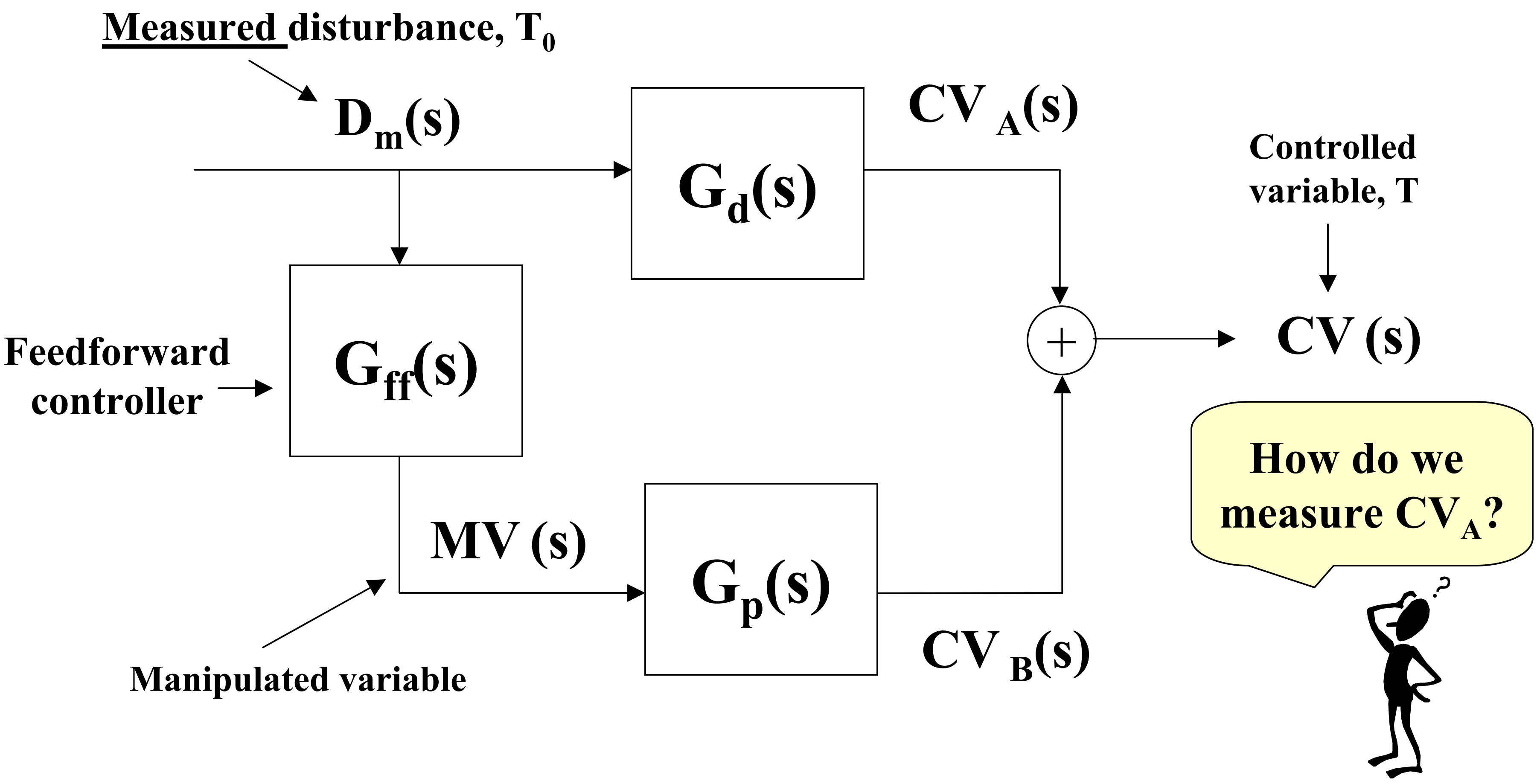


CHAPTER 15: FEEDFORWARD CONTROL



CHAPTER 15: FEEDFORWARD CONTROL

We use block diagram algebra to determine the form of the calculation [$G_{ff}(s)$] to achieve the desired performance.

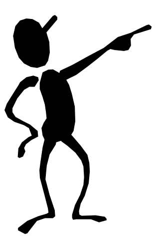


CHAPTER 15: FEEDFORWARD CONTROL

$$CV(s) = CV_A(s) + CV_B(s) = 0 \longleftarrow \text{??}$$

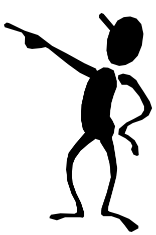
$$= \left[G_d(s) + G_{ff}(s)G_p(s)\right]D_m(s) = 0$$

Not a PID algorithm! Why?



$$\boxed{G_{ff}(s) = \frac{MV(s)}{D_m(s)} = -\frac{G_d(s)}{G_p(s)}}$$

This is general!



CHAPTER 15: FEEDFORWARD CONTROL

$$G_{ff}(s) = \frac{MV(s)}{D_m(s)} = -\frac{G_d(s)}{G_p(s)}$$

Special case of $G_p(s)$ and $G_d(s)$ being first order with dead time

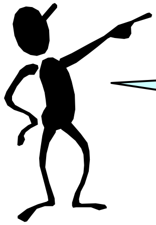
$$G_{ff}(s) = \frac{MV(s)}{D_m(s)} = K_{ff} \; \frac{T_{ld}s+1}{T_{lg}s+1} \; e^{-\theta_{ff}s}$$

Gain **Lead-lag** **Dead time**

CHAPTER 15: FEEDFORWARD CONTROL

$$G_{ff}(s) = K_{ff} \; \frac{T_{ld}s + 1}{T_{\mathbf{lg}}s + 1} \; e^{-\theta_{ff}s}$$

Lead-lag	$= (T_{ld}s+1)/T_{lg}s+1)$
FF controller gain	$= K_{ff} = - K_d/K_p$
controller dead time	$= \theta_{ff} = \theta_d - \theta_p \;\; \geq 0$
Lead time	$= T_{ld} = \tau_p$
Lag time	$= T_{lg} = \tau_d$



How do we get values for these parameters?

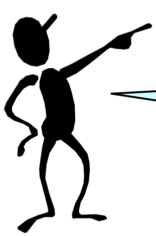
CHAPTER 15: FEEDFORWARD CONTROL

$$G_{ff}(s) = K_{ff} \frac{T_{ld}s+1}{T_{\mathbf{lg}}s+1} e^{-\theta_{ff}s}$$

$$(MV_{ff})_N = \frac{T_{\mathbf{lg}}/\Delta t}{T_{\mathbf{lg}}/\Delta t+1}(MV_{ff})_{N-1} + K_{ff}\left(\frac{T_{ld}/\Delta t+1}{T_{\mathbf{lg}}/\Delta t+1}\right)(D_m)_{N-\Gamma}$$

$$-K_{ff}\left(\frac{T_{ld}/\Delta t}{T_{\mathbf{lg}}/\Delta t+1}\right)(D_m)_{N-\Gamma-1}$$

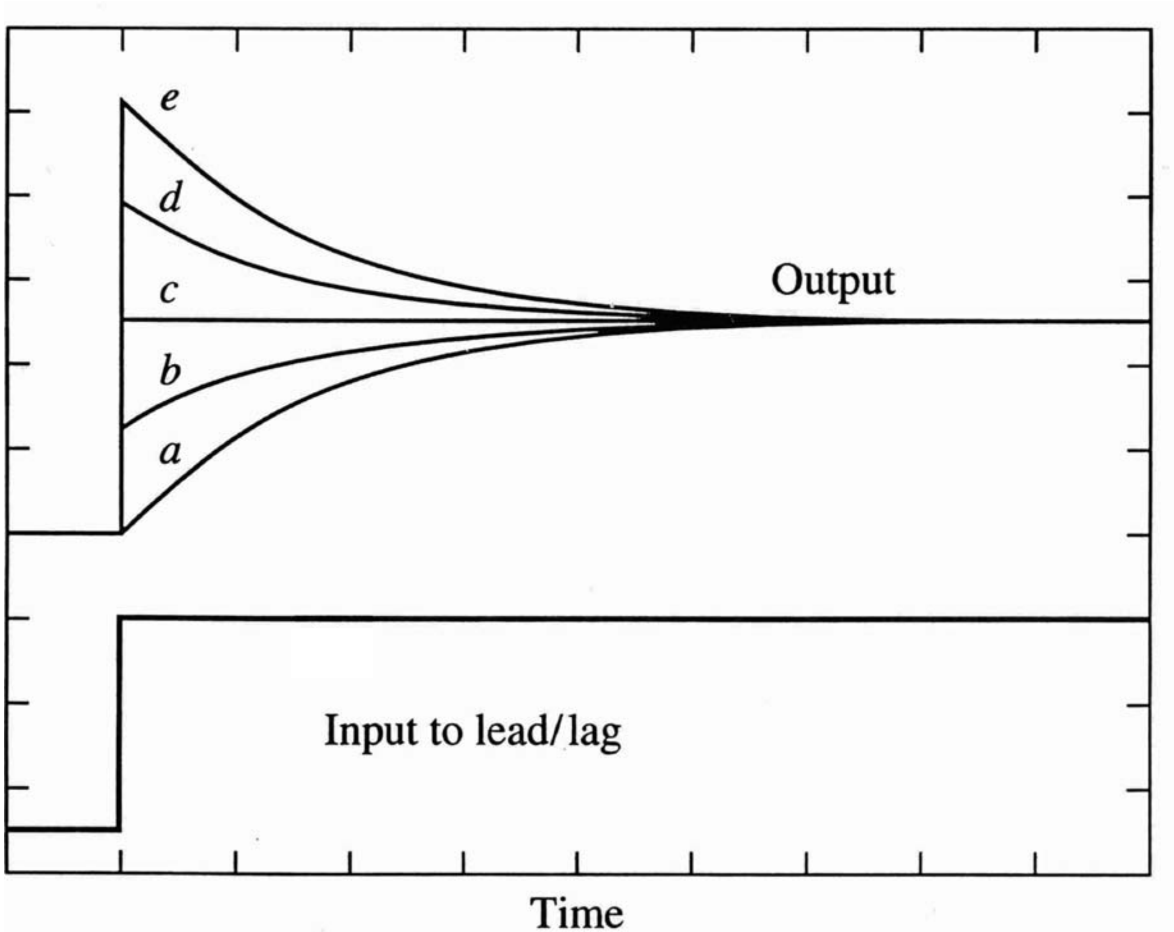
$$(MV_{ff})_N = a(MV_{ff})_{N-1} + b(D_m)_{N-\Gamma} + c(D_m)_{N-\Gamma-1}$$



Digital implementation is straightforward.
Its derived in textbook.

CHAPTER 15: FEEDFORWARD CONTROL

Typical dynamic responses from the lead-lag element in the feedforward controller. It synchronizes the compensation and disturbance effects.



Results for several cases of Tlead/Tlag :

a. 0.0

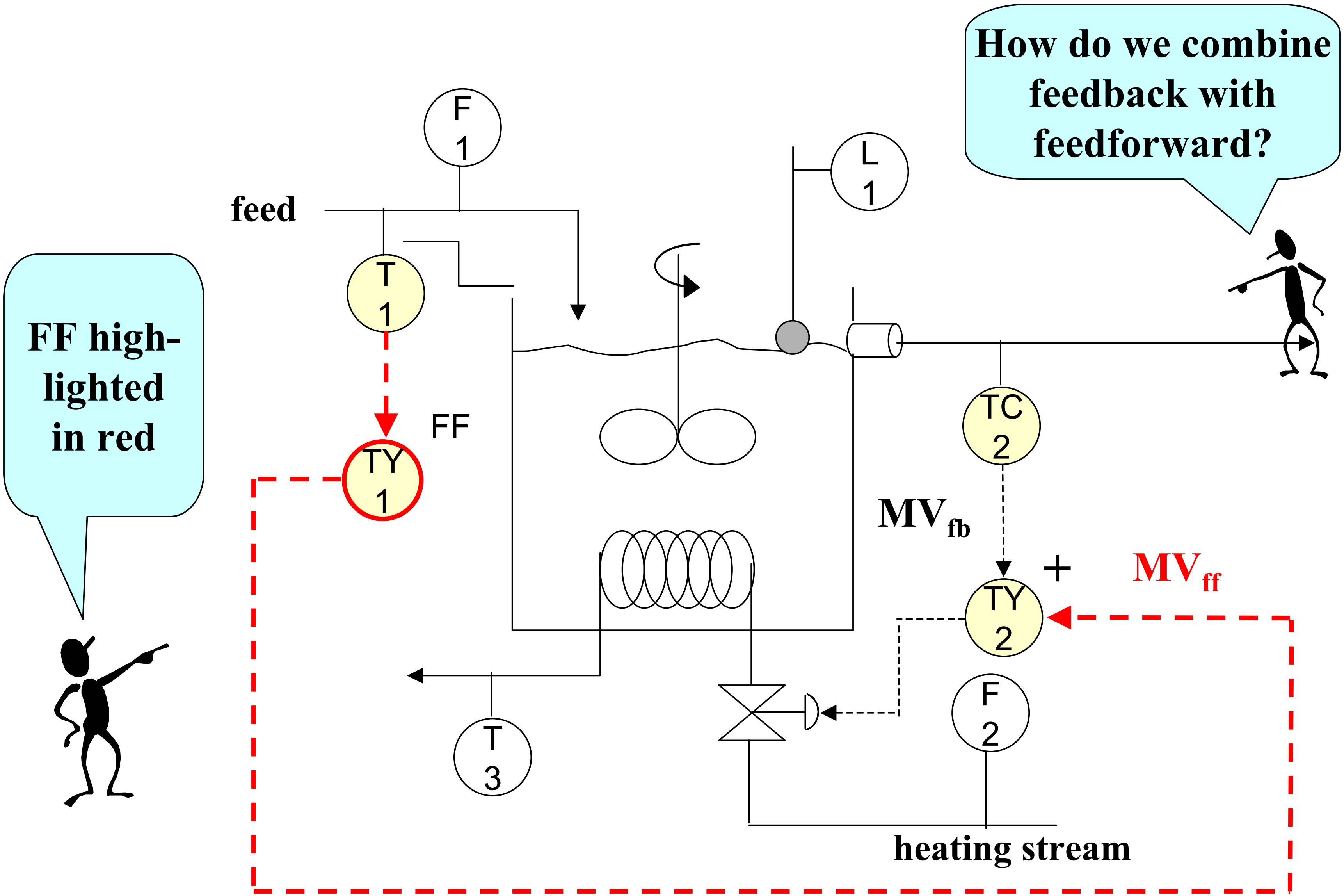
b. 0.5

c. 1.0

d. 1.5

e. 2.0

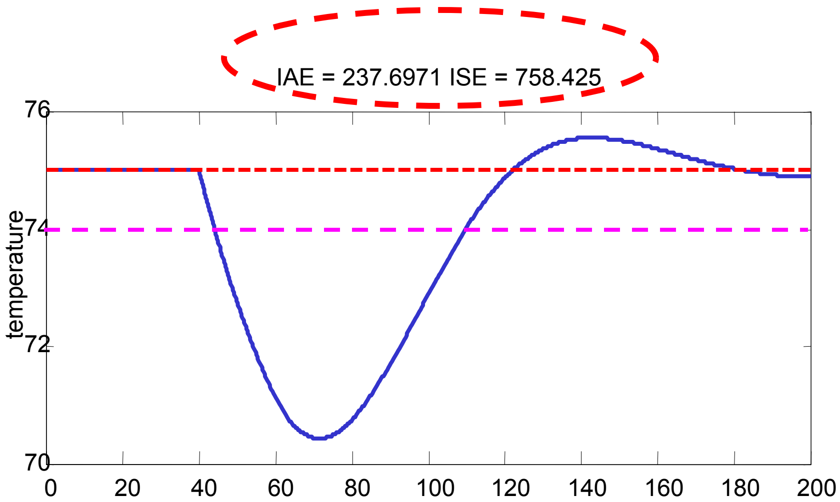
CHAPTER 15: FEEDFORWARD CONTROL

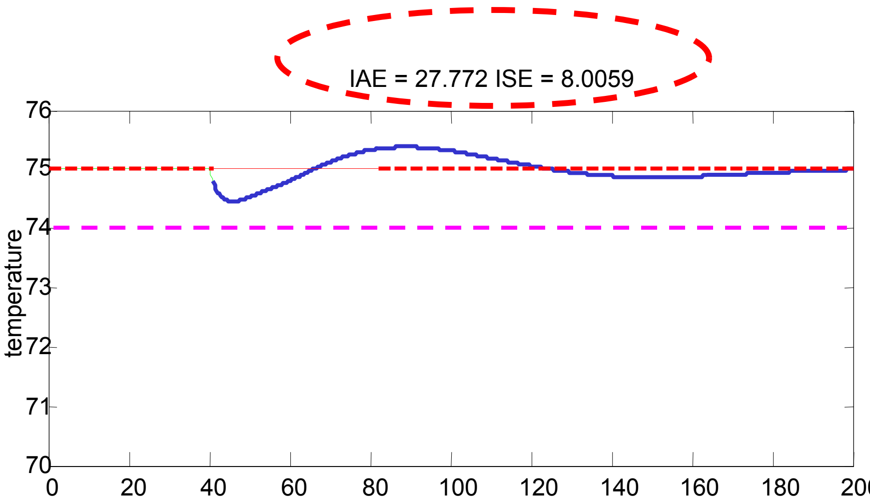


CHAPTER 15: FEEDFORWARD CONTROL

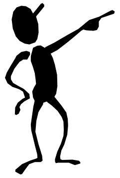
Control Performance Comparison for CST Heater

Single-Loop | **Feedforward with feedback**

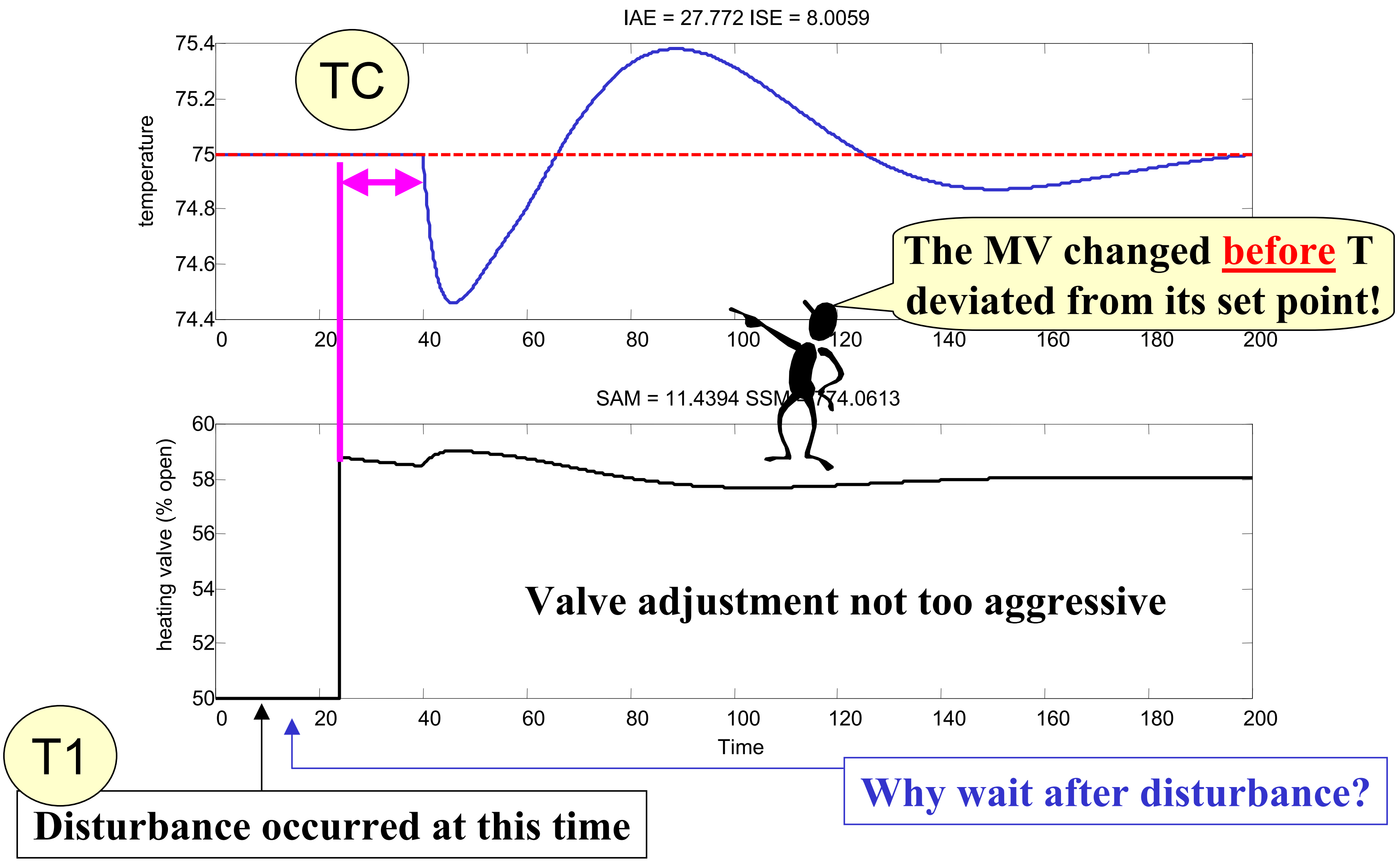




Much better performance! WHY?



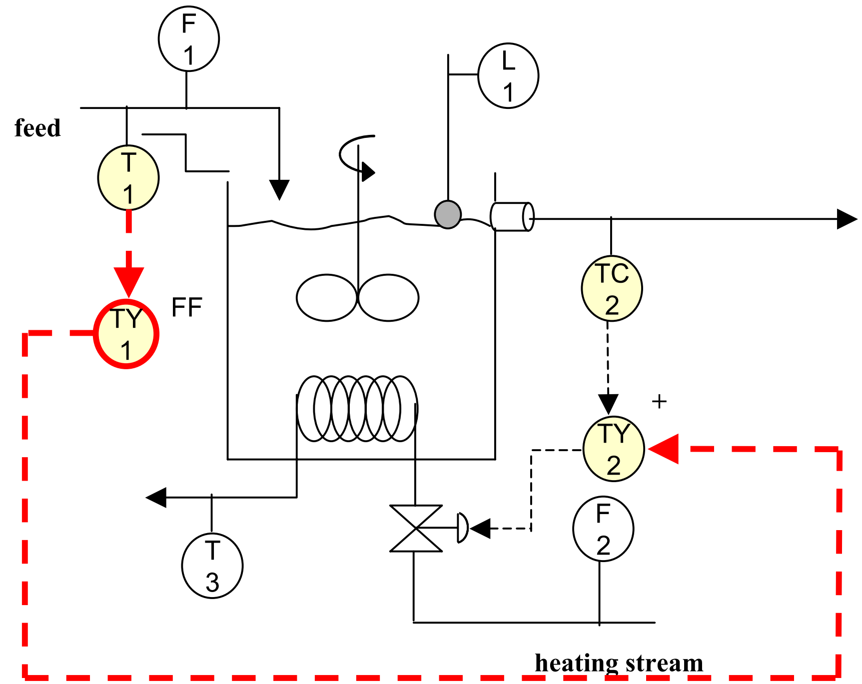
CHAPTER 15: FEEDFORWARD CONTROL



CHAPTER 15: FEEDFORWARD CONTROL

What have we **gained and lost** using feedforward and feedback?

For each case, is FF with FB better, same, worse than single-loop feedback (TC2 $\rightarrow$ v)??

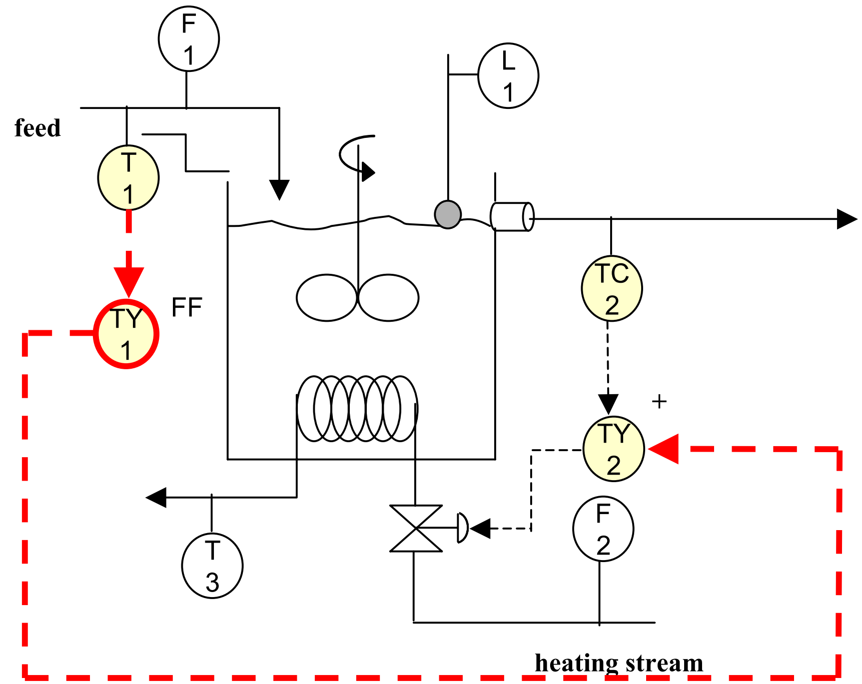


- A disturbance in feed inlet temperature
- A disturbance in heating medium inlet pressure
- A disturbance in feed flow rate
- A change to the TC set point

CHAPTER 15: FEEDFORWARD CONTROL

What have we gained and lost using feedforward and feedback?

For each case, is FF and FB better, same, worse than single-loop feedback (TC2 → v)??



- **A disturbance in feed inlet temperature** — FF/FB better
- **A disturbance in heating medium inlet pressure** — Both the same
- **A disturbance in feed flow rate** — Both the same
- **A change to the TC set point** — Both the same

CHAPTER 15: FEEDFORWARD CONTROL

FEEDFORWARD DESIGN CRITERIA

Feedforward is desired when

1. **Single-loop performance unacceptable**
2. **A measured variable is available**

A measured disturbance variable must

3. **Indicate the occurrence of an important disturbance**
4. **NOT have a causal relationship from valve to measured disturbance sensor**
5. **Not have a much faster affect on the CV than the MV (when combined with feedback)**

CHAPTER 15: FEEDFORWARD CONTROL

Feedforward and Feedback are complementary

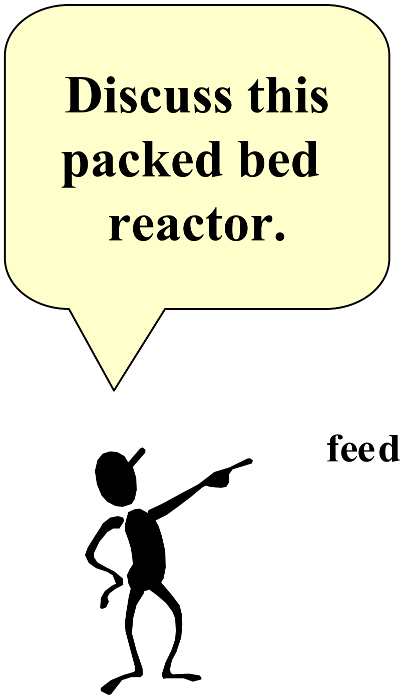
	Feedforward	**Feedback**
Advantages	• Compensates for disturbance before CV is affected • Does not affect the stability of the control sysytem (if $G_{ff}(s)$ stable)	• Provides zero steady-state offset • Effective for all disturbances
Disadvantages	• Cannot eliminate steady-state offset • Requires a sensor and model for each disturbance	• Does not take control action until the CV deviates from its set point • Affects the stability of the control system

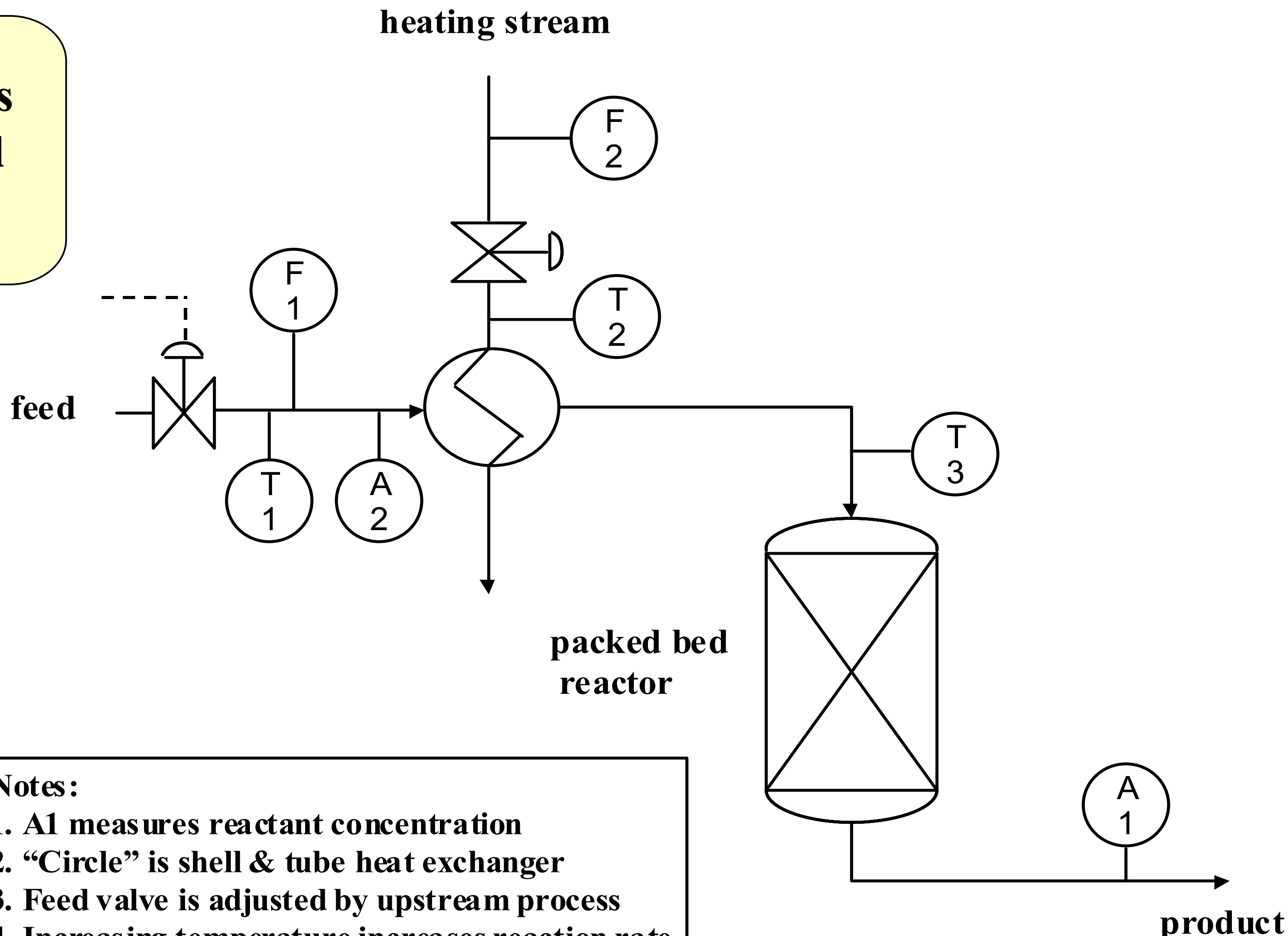
CHAPTER 15: FEEDFORWARD CONTROL

CLASS EXERCISE: SOME QUESTIONS ABOUT FEEDFORWARD CONTROL

- Why do we retain the feedback controller?
- When would feedforward give zero steady-state offset?
- Why does the feedforward controller sometimes delay its compensation? Don't we always want fast control?
- What is the additional cost for feedforward control?
- How can we design a strategy that has two controllers both adjusting the same valve?
- What procedure is used for tuning feedforward control?

CHAPTER 15: FEEDFORWARD CONTROL

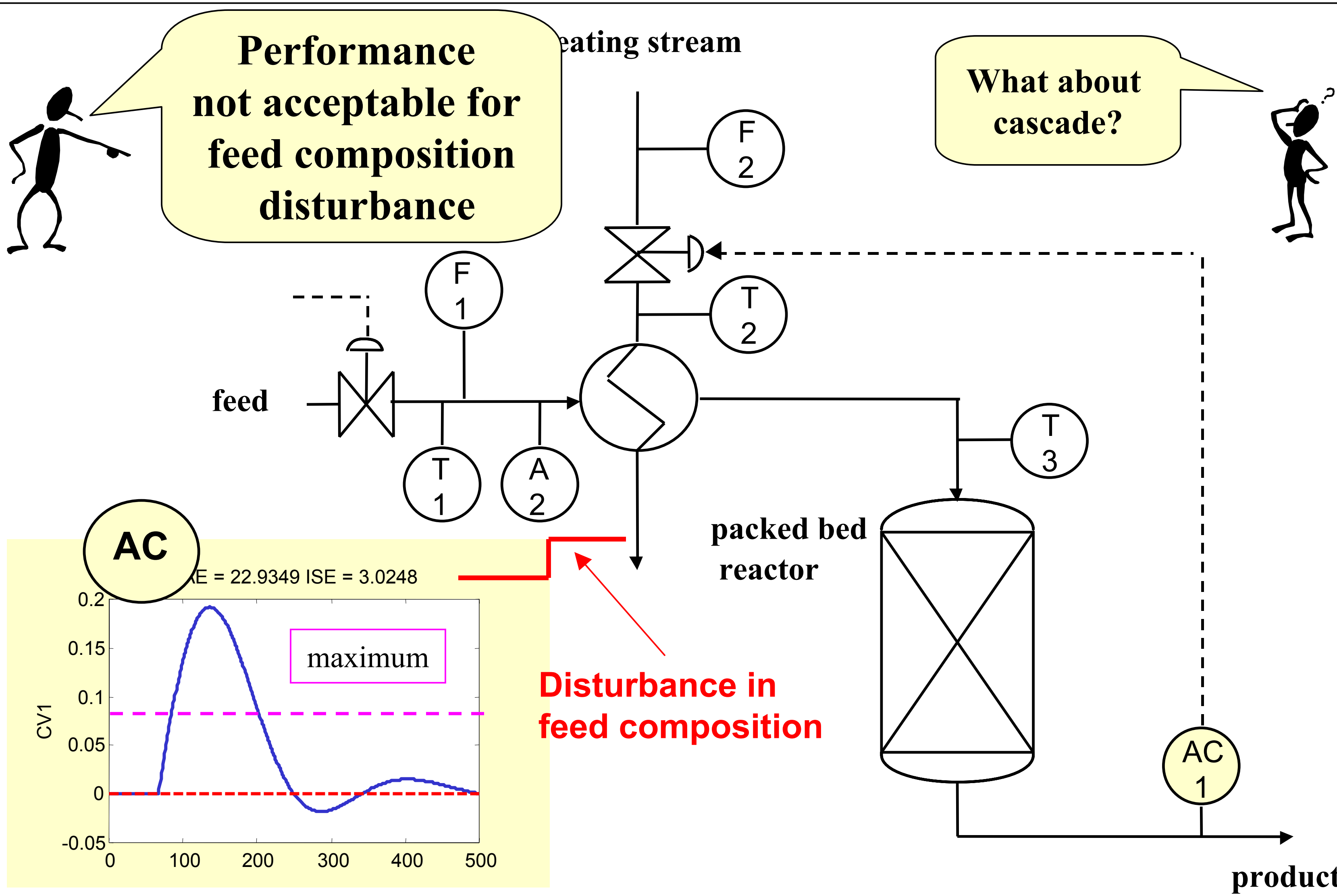




Notes:
1. A1 measures reactant concentration
2. “Circle” is shell & tube heat exchanger
3. Feed valve is adjusted by upstream process
4. Increasing temperature increases reaction rate

CHAPTER 15: FEEDFORWARD CONTROL

Class exercise: Design feedforward control to improve the performance.

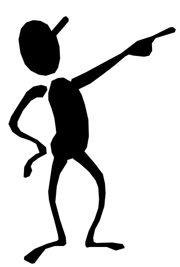


CHAPTER 15: FEEDFORWARD CONTROL

Class exercise: **Design feedforward control to improve the performance.**

Feedforward design criteria	A2	F1	F2	T1	T2	T3
1. Single-loop not acceptable						
2. Disturbance variable is measured						
3. Indicates a key disturbance						
4. No Causal relationship, valve $\rightarrow D_m$						
5. Disturbance dynamics not much faster than compensation						

Let's use the feedforward design rules!



Remember: **The disturbance is the feed composition.**

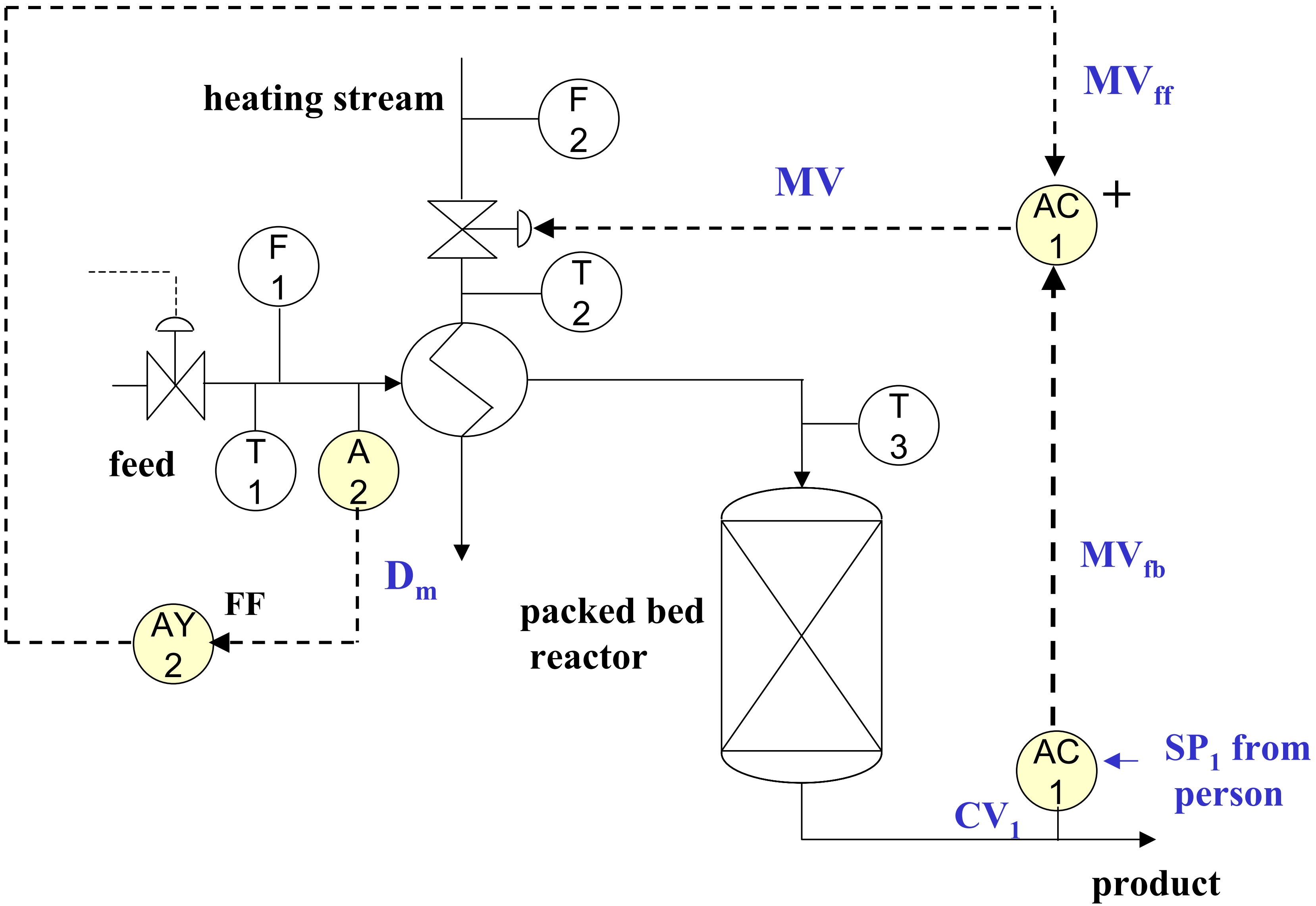
CHAPTER 15: FEEDFORWARD CONTROL

Class exercise: Design feedforward control to improve the performance.

Feedforward design criteria	A2	F1	F2	T1	T2	T3
1. Single-loop not acceptable	Y	Y	Y	Y	Y	Y
2. Disturbance variable is measured	Y	Y	Y	Y	Y	Y
3. Indicates a key disturbance	Y	N	N	N	N	N
4. No Causal relationship, valve $\rightarrow D_m$	Y	Y	N	Y	Y	N
5. Disturbance dynamics not much faster than compensation	Y	N/A	N/A	N/A	N/A	N/A

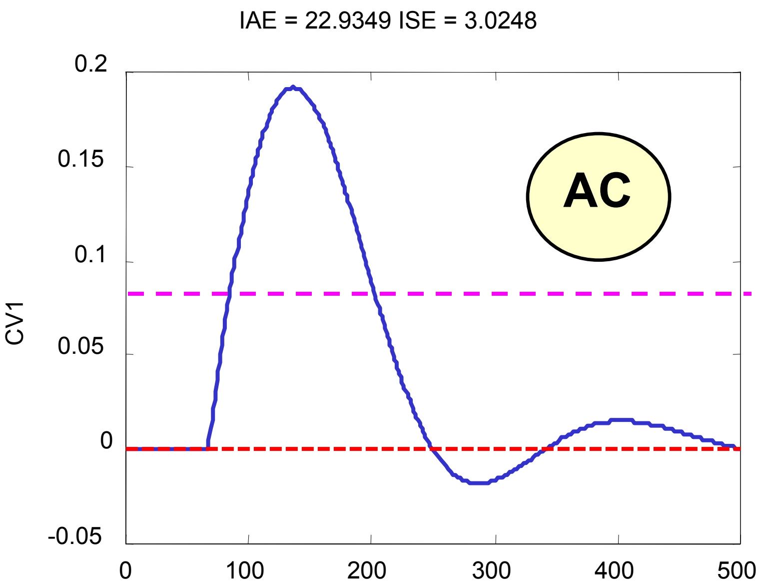
A2 satisfies all of the rules and can be used as a feedforward variable.

CHAPTER 15: FEEDFORWARD CONTROL

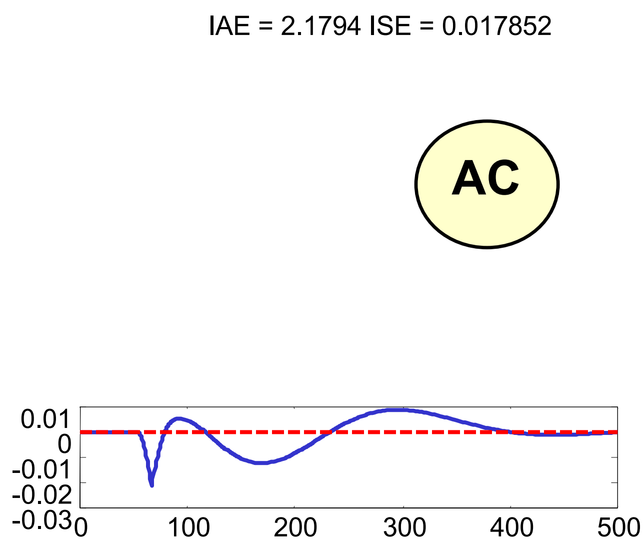


Control Performance Comparison for Packed Bed Reactor

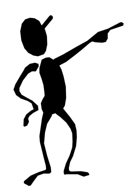
Single-Loop



Feedforward and feedback



Much better performance!
WHY?

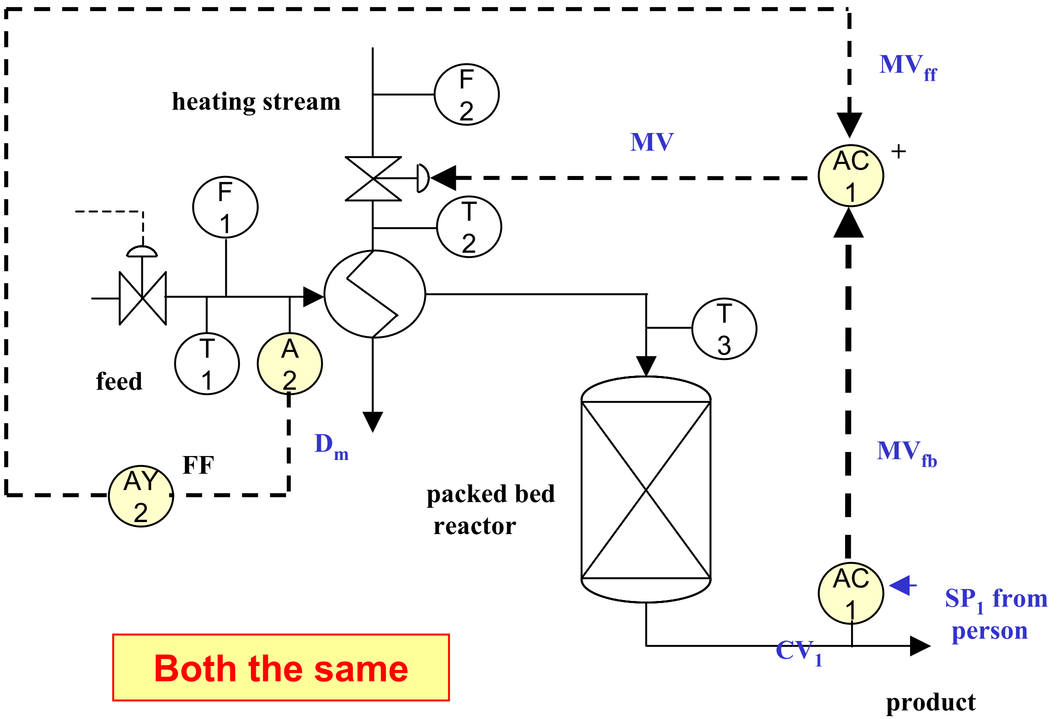


Little model error, most experimental feedforward not this good!

CHAPTER 15: FEEDFORWARD CONTROL

What have we gained and lost using feedforward and feedback?

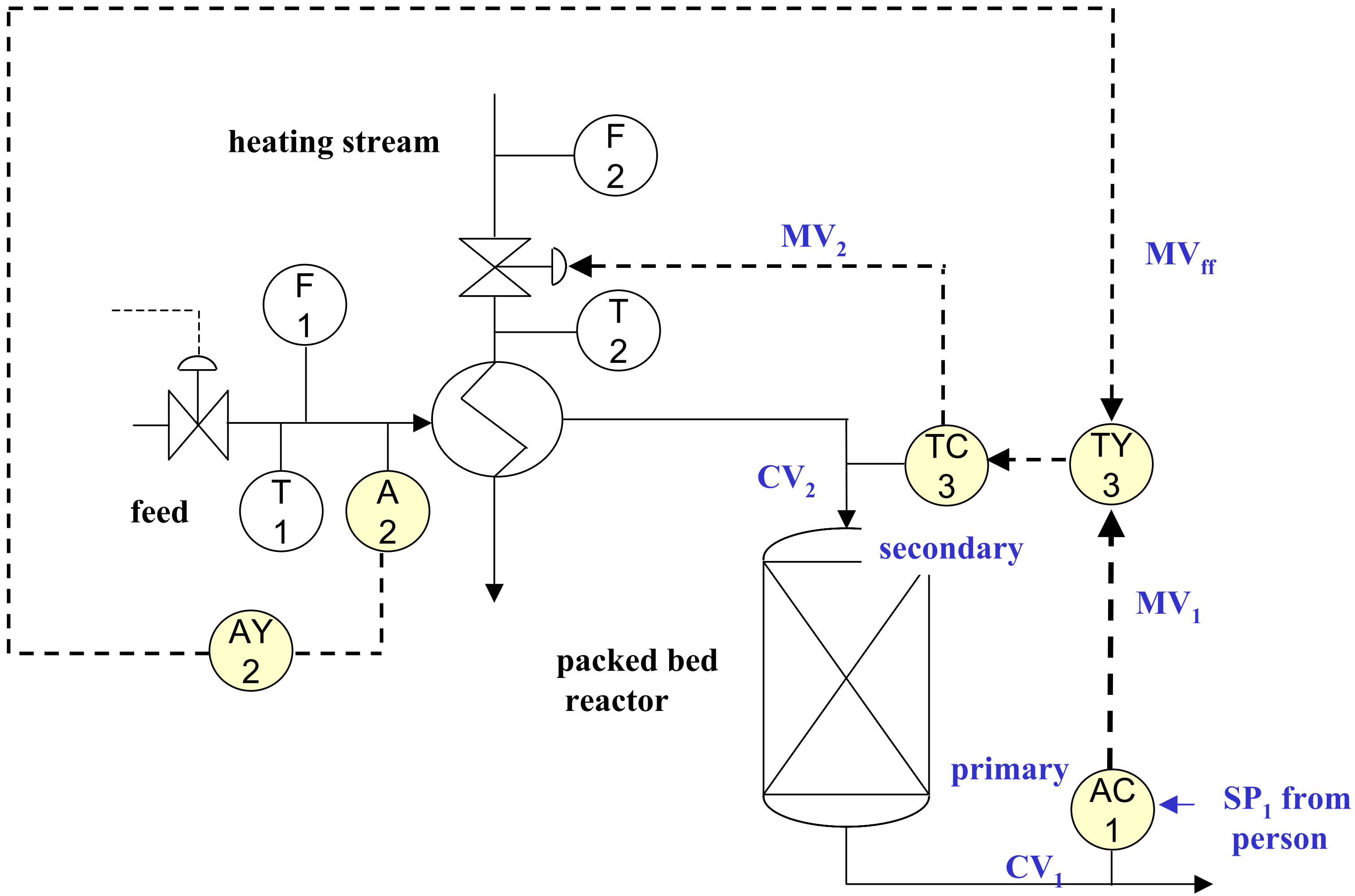
How does the system respond to the following?



- **A disturbance in T2** — Both the same
- **A disturbance in heating medium inlet pressure** — Both the same
- **A disturbance inT1** — Both the same
- **A disturbance to feed composition, A2** — FF/FB better
- **A change to the AC-1 set point** — Both the same

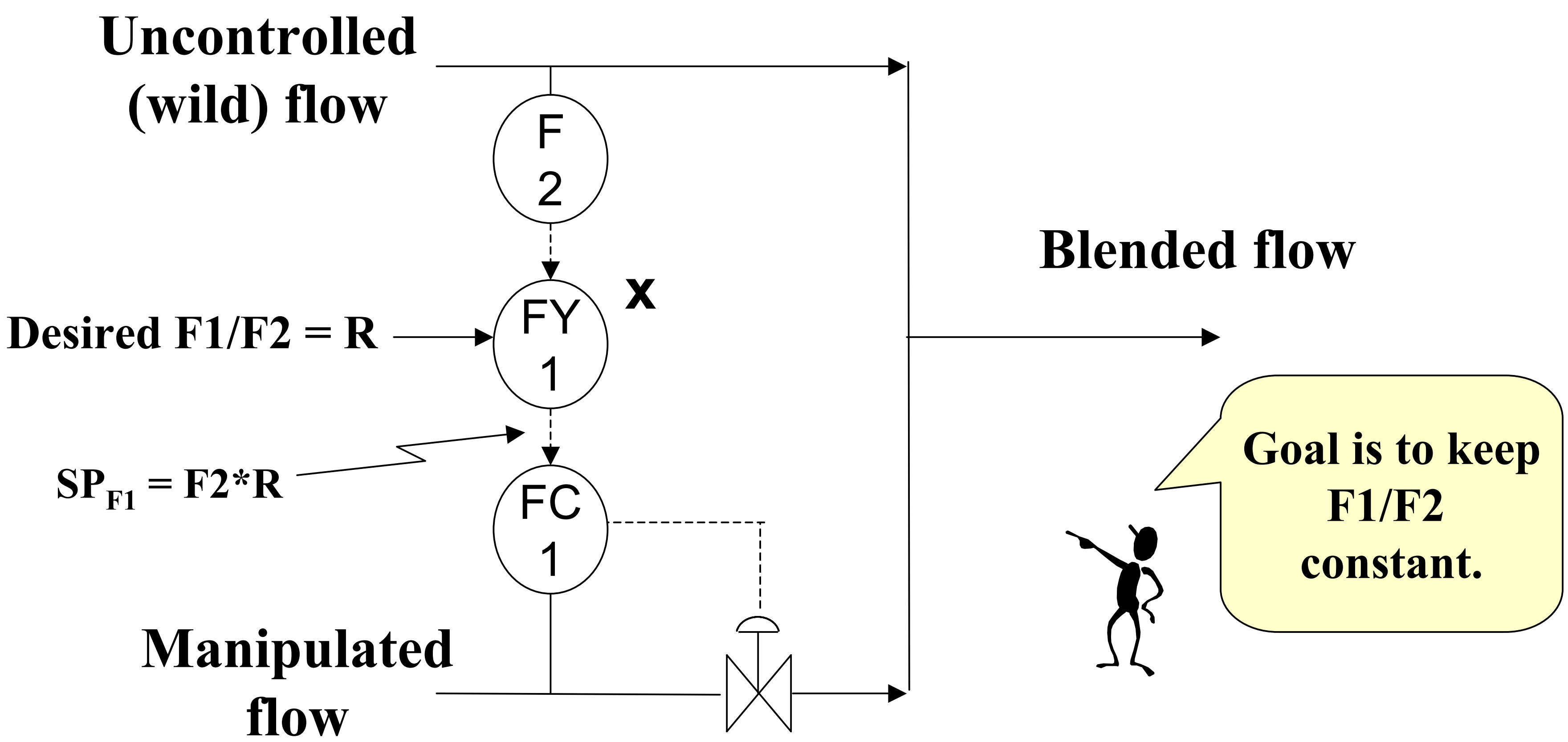
CHAPTER 15: FEEDFORWARD CONTROL

We can combine cascade and feedforward to gain the advantages of both.



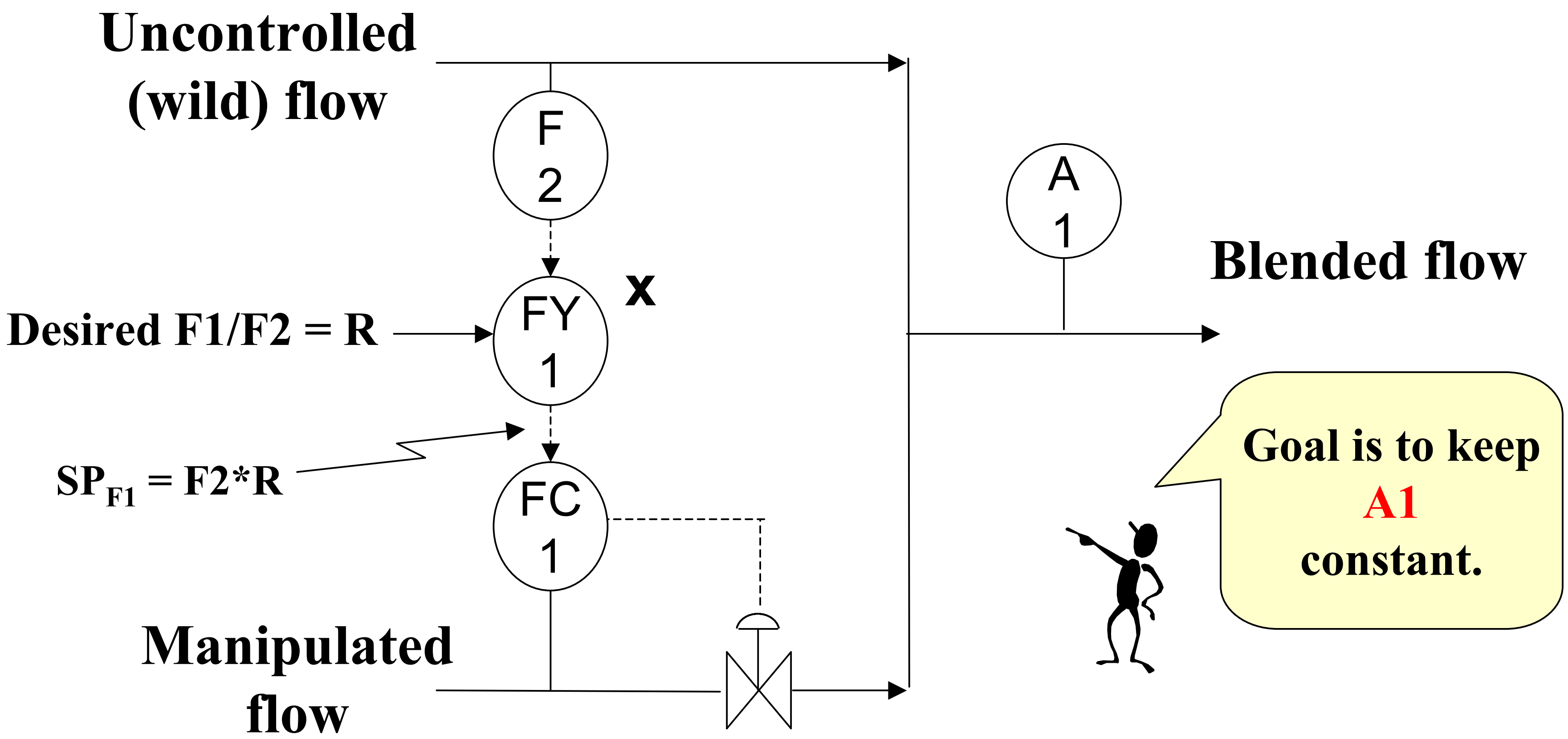
CHAPTER 15: FEEDFORWARD CONTROL

Ratio control is a simple and frequently used feedforward application. In ratio control, the dynamics are negligible.



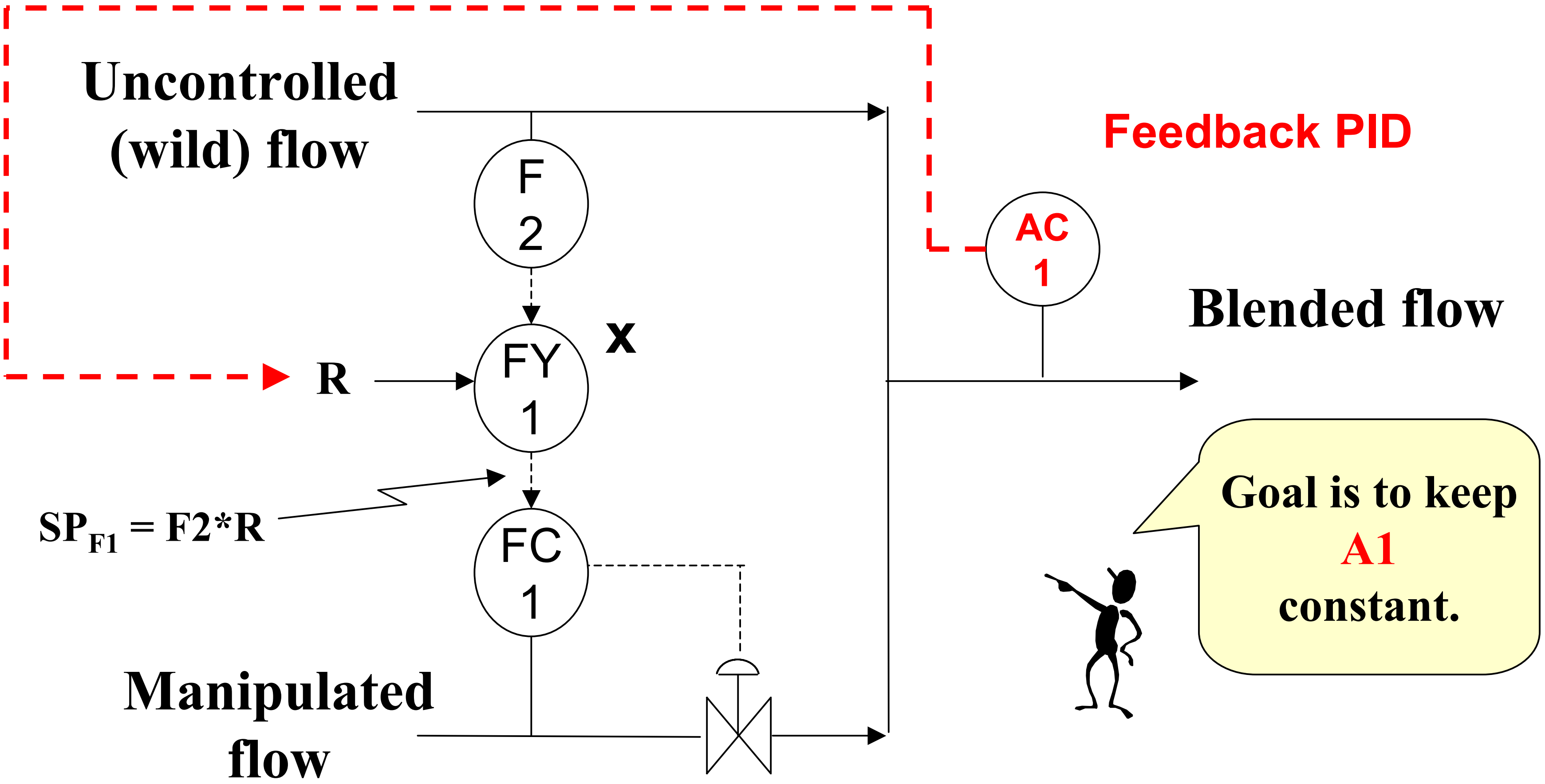
CHAPTER 15: FEEDFORWARD CONTROL

CLASS EXERCISE: Use analyzer in automatic control while retaining the good aspects of ratio control.



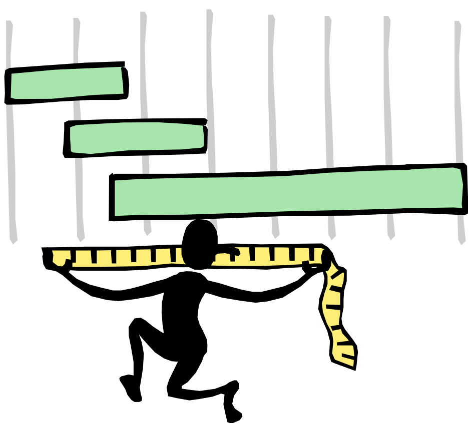
CHAPTER 15: FEEDFORWARD CONTROL

CLASS EXERCISE: Use analyzer in automatic control while retaining the good aspects of ratio control.



CHAPTER 15: FEEDFORWARD CONTROL

In many organizations, we take actions on inputs to prevent large disturbances to outputs. Sometimes, these are called "pre-actions".



After you have measured the change, you have some time to react before it hits you

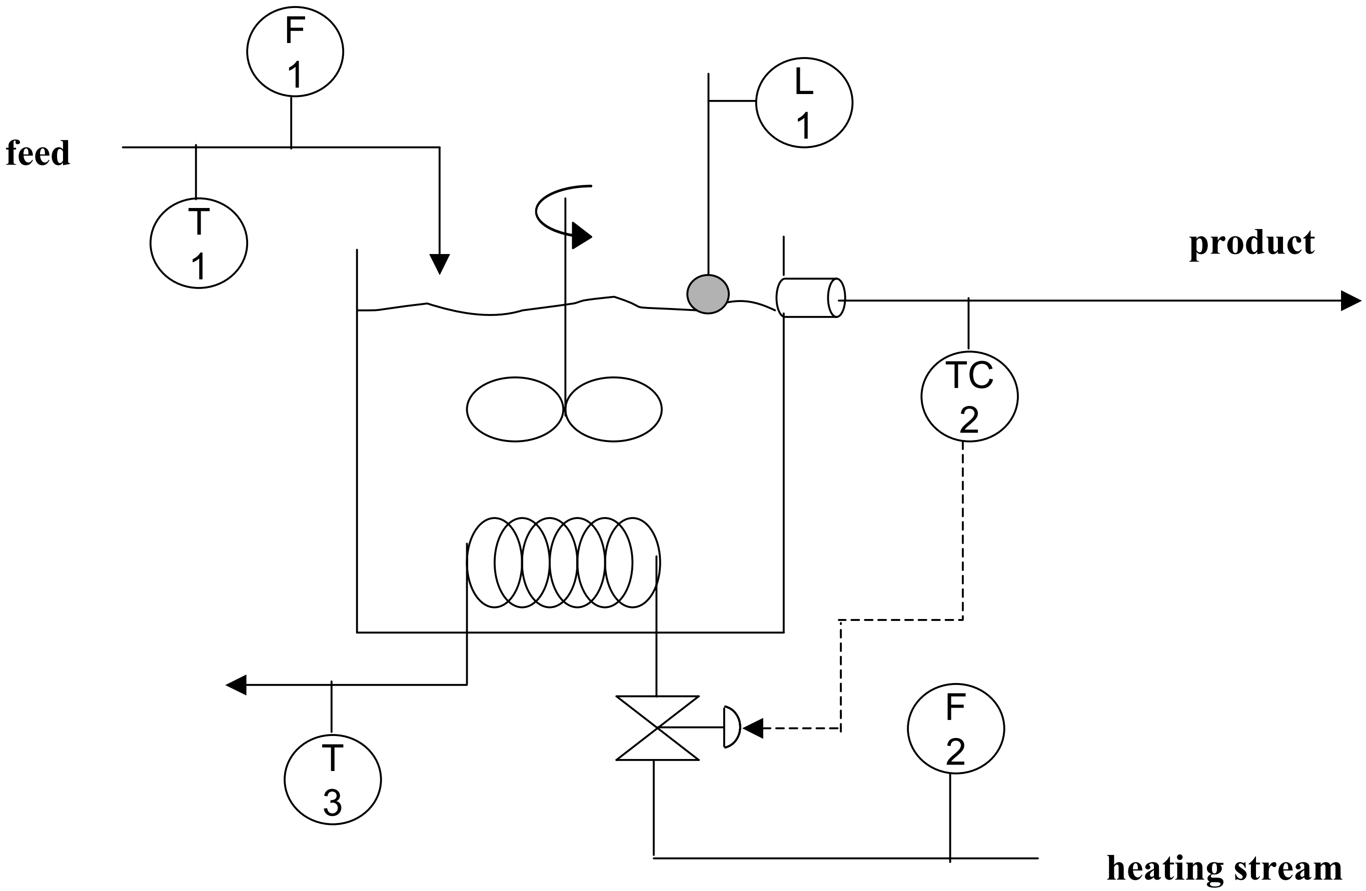
What would you do if?

- **Number of births per year increases by 10% in your country**
- **A drought occurs in in the most fertile area of your country**
- **New legislation will impose stricter emissions regulations in three years**

Do we need feedback? What is your algorithm? What would you do if the measurement were noisy?

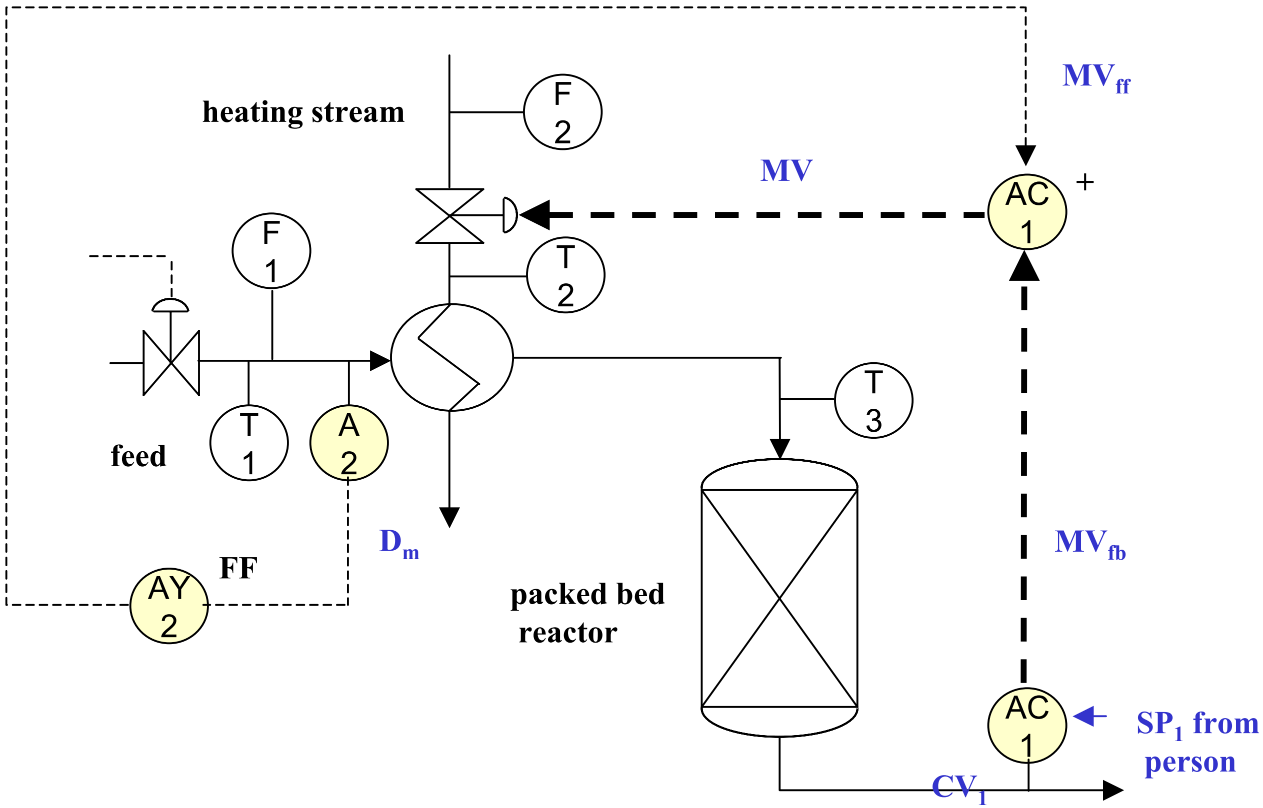
CHAPTER 15: FEEDFORWARD WORKSHOP 1

Evaluate feedforward control for a disturbance in the heating medium inlet temperature. You may add a sensor but make no other changes to the equipment.



CHAPTER 15: FEEDFORWARD WORKSHOP 2

Prepare a flowchart for the calculations performed by the packed bed feedforward controller. Show every calculation and use process variable symbols (e.g., A1), not generic symbols (CV_1). Report the equations for digital control.



CHAPTER 15: FEEDFORWARD WORKSHOP 3

Answer each of the following questions true or false

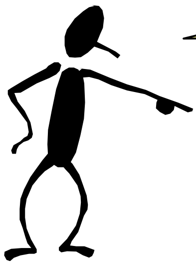
1. The feedback controller tuning does not change when combined with feedforward compensation.
2. The feedforward controller has no tuning parameter.
3. The feedforward controller should react immediately when the measured disturbance is measured.
4. Feedforward could be applied for a set point change.

CHAPTER 15: FEEDFORWARD WORKSHOP 4

Identify a process that would benefit from ratio control. You may select from examples in your summer/co-op jobs, engineering laboratories, and course projects.

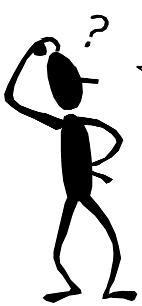
Draw a sketch of the process with ratio control. Explain the advantages and any disadvantages of the design.

CHAPTER 15: FEEDFORWARD



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

- **Identify situations for which feedforward is a good control enhancement**
- **Design feedforward control using the five design rules**
- **Apply the feedforward principle to other challenges in life**



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 15: LEARNING RESOURCES

- **<u>SITE PC-EDUCATION WEB</u>**
  - Instrumentation Notes
  - Interactive Learning Module (Chapter 15)
  - Tutorials (Chapter 15)

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

CHAPTER 15: SUGGESTIONS FOR SELF-STUDY

1. **Suggest some methods for fine-tuning a feedforward controller.**
2. **Program a feedforward controller for one of the processes modelled in Chapters 3-5.**
3. **Explain why the feedforward compensation should not be much slower than the disturbance. Why doesn’t this guideline apply when no feedback is implemented?**
4. **Discuss whether you would recommend more than one feedforward controller on the same process.**
5. **Write a memorandum explaining feedforward compensation for a company with non-technical employees**

CHAPTER 15: SUGGESTIONS FOR SELF-STUDY

6. **A friend asks whether the general sketch for feedback, textbook Figure 1.4, applies to feedforward. Answer completely, including any changes to the sketch.**

7. **Discuss why the feedforward controller dead time must be positive.**