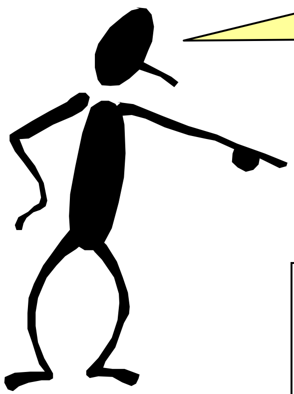
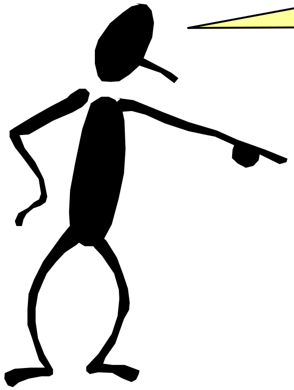
CHAPTER 11: DIGITAL CONTROL



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

- Identify examples of analog and digital computation and signal transmission.
- Program a digital PID calculation
- Select a proper execution rate for a feedback controller.
- Tune a digital PID

CHAPTER 11: DIGITAL CONTROL



Outline of the lesson.

- Brief history of control equipment
- Sampling the measurement
- Digital PID calculation
- Effect of digital execution period on tuning and performance

CHAPTER 11: DIGITAL CONTROL

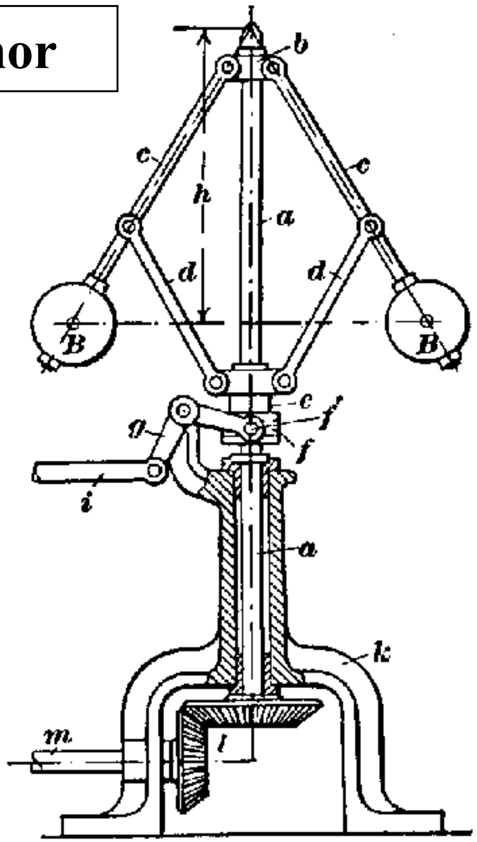
A BRIEF HISTORY OF PROCESS CONTROL

- **A little history helps us to understand the common approaches to process control. The realities of available equipment have shaped the theory and practice of process control.**
- **While digital technology has revolutionized what is possible today, equipment has a life of many decades. Therefore, we see older approaches in most plants, and will for a long time.**
- **Let's start from about the 19th century to today. What happened in the 19th century that "got things going"?**

CHAPTER 11: DIGITAL CONTROL

Making the steam engine work all the time

governor



http://oldenginehouse.users.btopenworld.com/watt.htm

Inventors wanted to control the pressure of the boiler and the speed of the device driven by the steam (using a governor).

People experienced

- Explosions!

- Unstable behavior

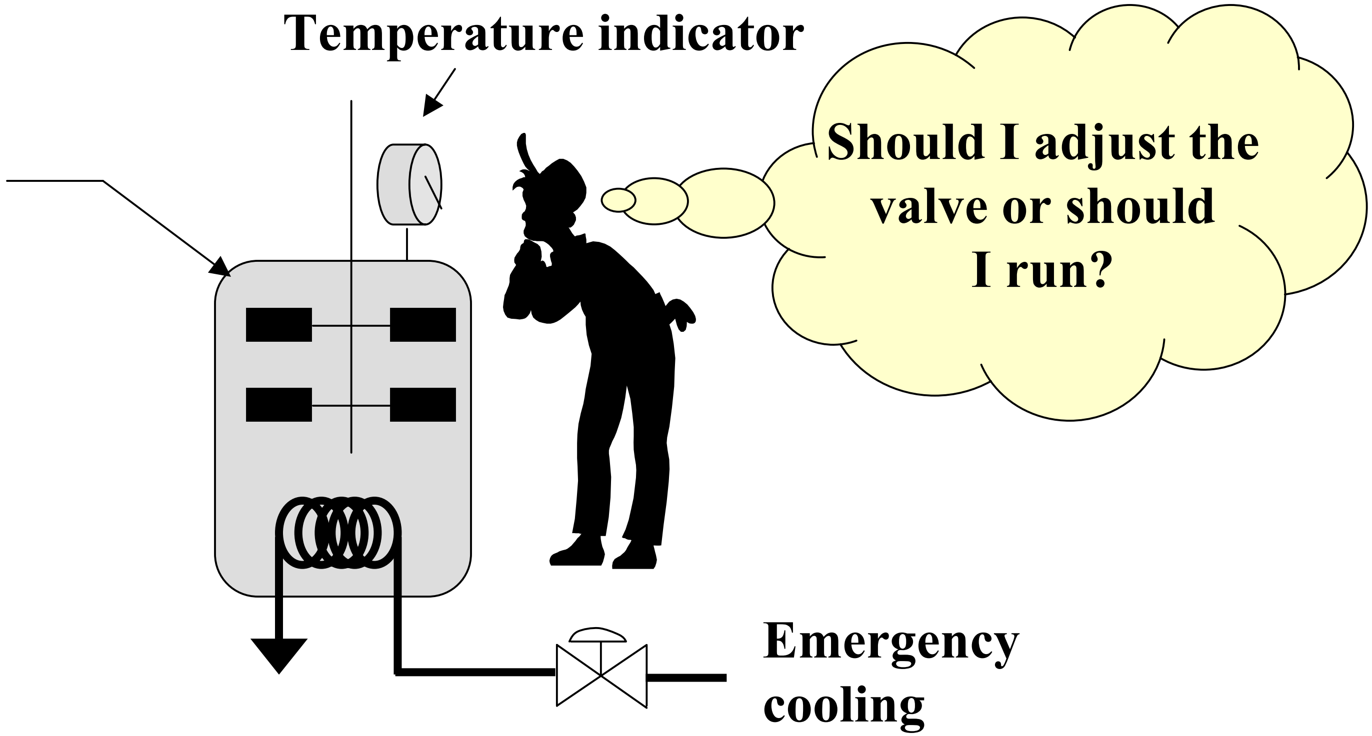
And control engineering was born!

CHAPTER 11: DIGITAL CONTROL

- Manual operation
- Mechanical devices
- Pneumatic devices
- Electronic devices
- Digital calculations
- Digital calc. & communication

Manual Operation

People know more than machines, so leave decisions to them.



CHAPTER 11: DIGITAL CONTROL

- Manual operation
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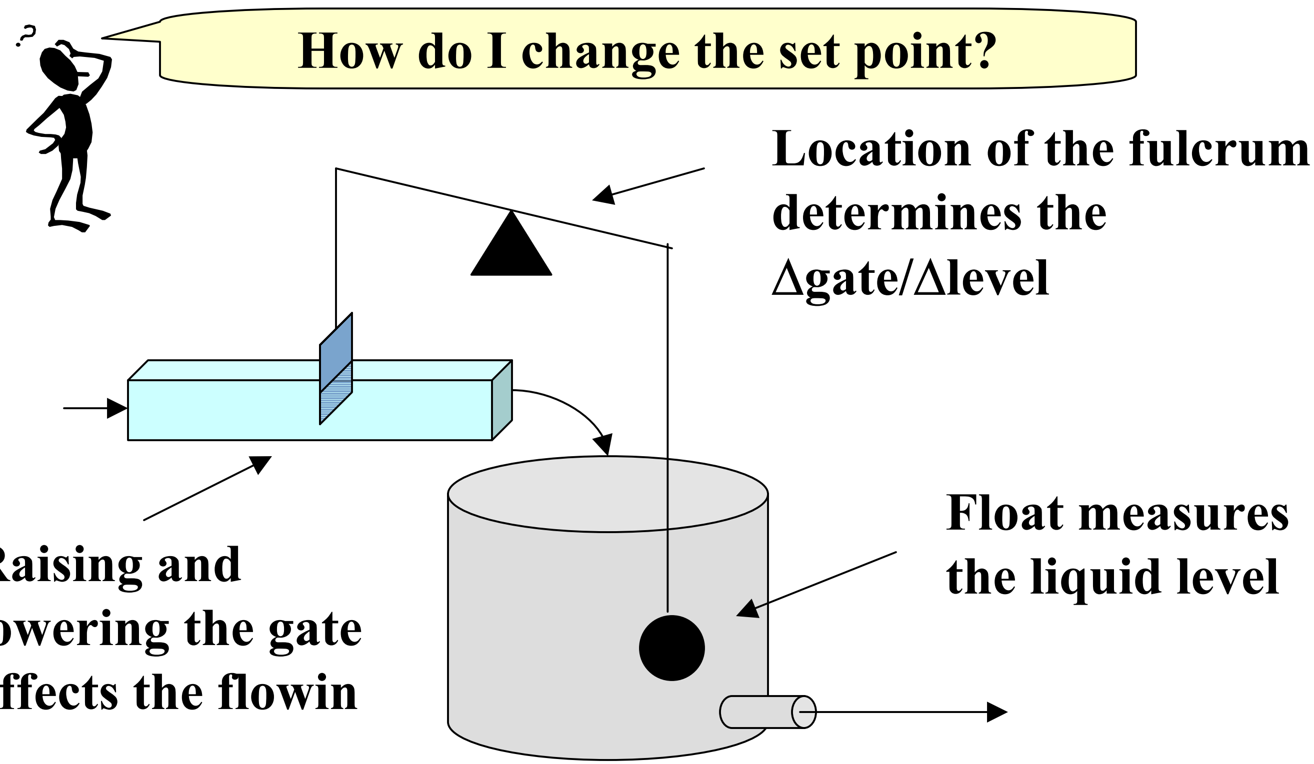
Mechanical Device

The value of the variable is represented by position of equipment.



CHAPTER 11: DIGITAL CONTROL

- **Manual operation**
- **Mechanical devices**
- **Pneumatic devices**
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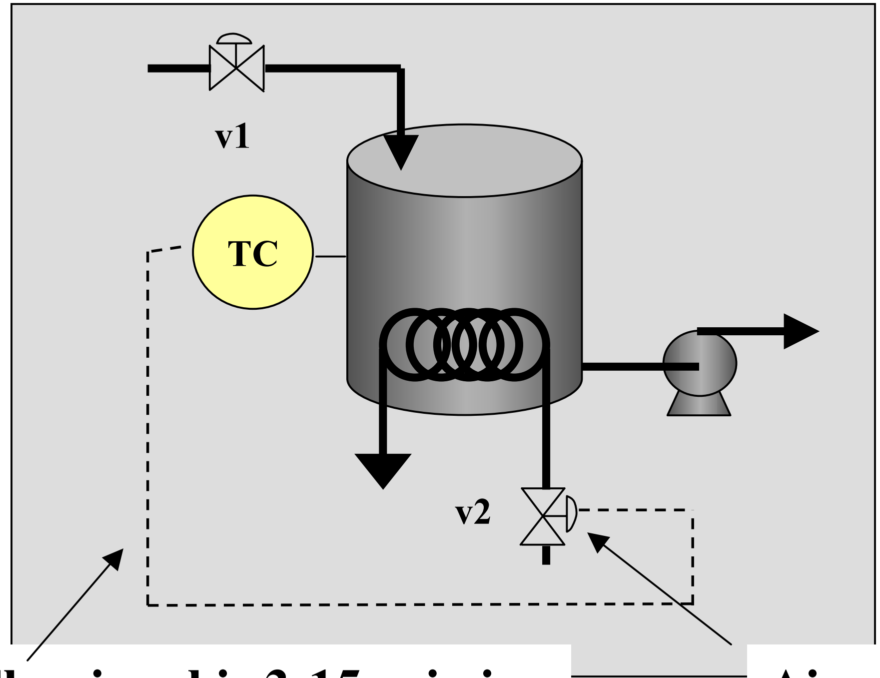
Pneumatic Device

The value of the variable is proportional to air pressure (50 - 150 C = 3 -15 psi).



How do I perform the PID calculation?

The signal is 3-15 psi air pressure in a pipe.

Air pressure moves flexible diaphragm

CHAPTER 11: DIGITAL CONTROL

- **Manual operation**
- **Mechanical devices**
- **Pneumatic devices**
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- **Digital calc. & communication**

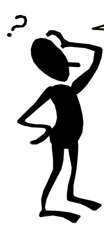
Pneumatic & Electronic Devices

Principle of analog computation!

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

Build a physical system that (approximately) obeys the same model.

- **Pneumatic - force balance (Newton's laws)**
- **Electronic - current balance (Kirkoff's laws)**



I wonder what these devices look like.

CHAPTER 11: DIGITAL CONTROL

Analog computation!

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

Pneumatic

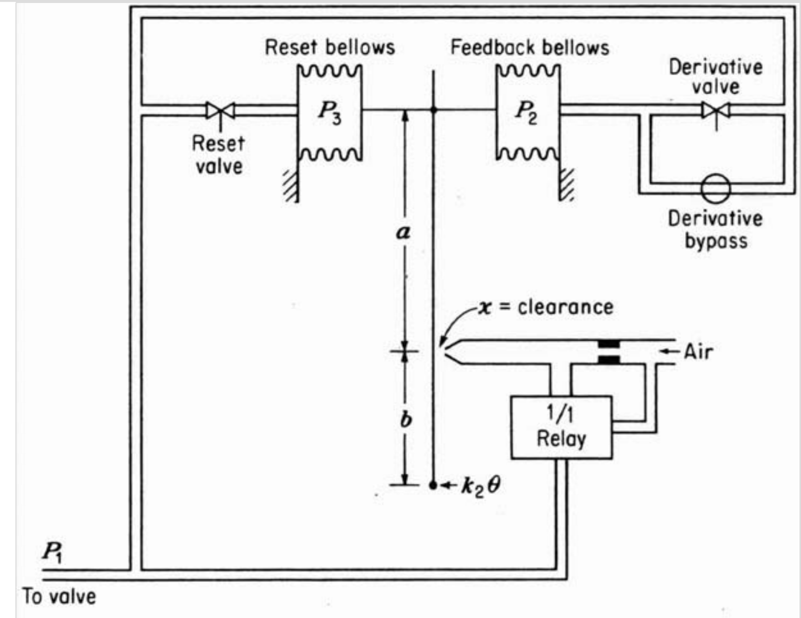


FIGURE 6-9 Three-mode controller with parallel feedback.

Electronic

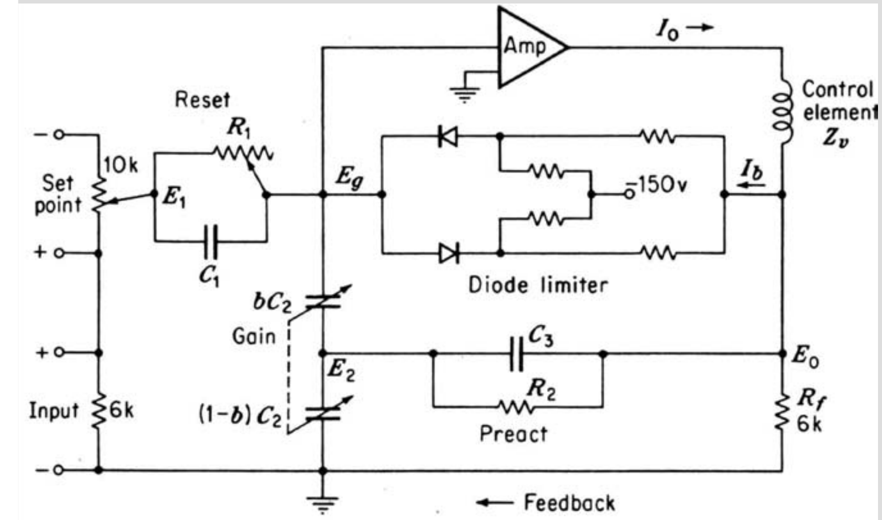


FIGURE 6-15 Simplified diagram of Taylor Transcope electronic controller, model 70RF.

From Harriott, P., Process Control, McGraw-Hill, New York, 1964

CHAPTER 11: DIGITAL CONTROL

- Manual operation
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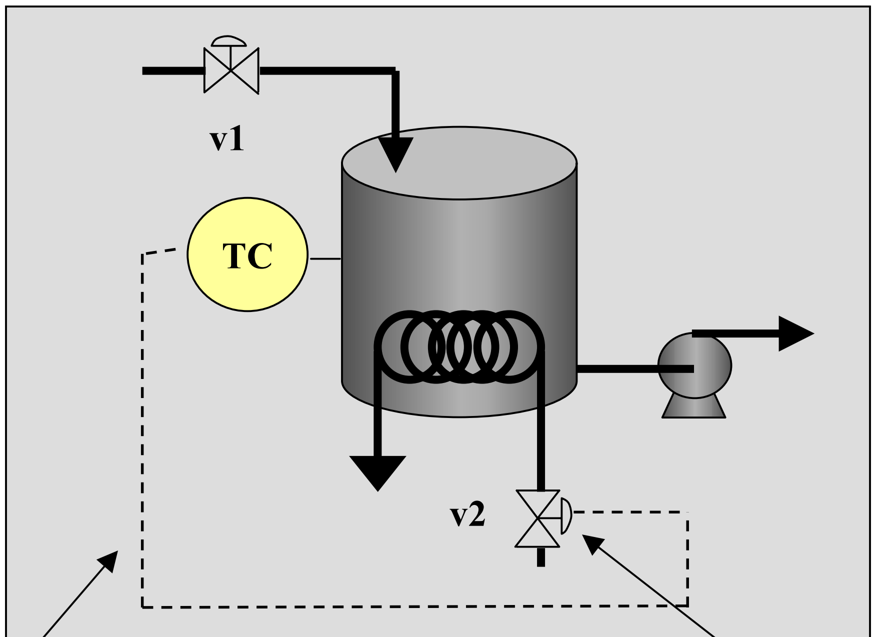
Electronic Device

The variable is proportional to current or voltage (50 - 150 C = 4 - 20 mA).



The signal is 4-20 mA transmitted by wire.

Current converted to air pressure to affect valve

CHAPTER 11: DIGITAL CONTROL

- Manual operation
- Mechanical devices
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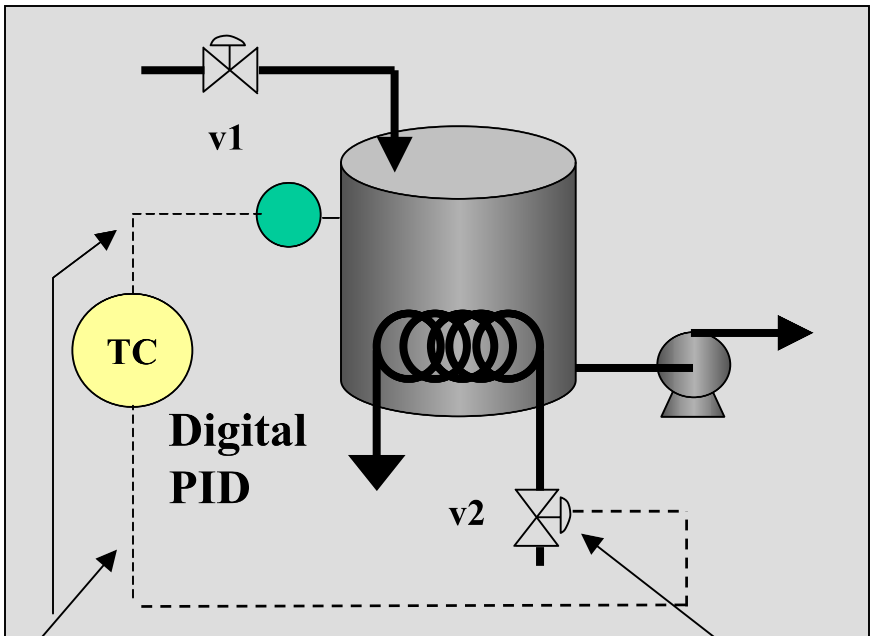
Digital Calculation

Digital calculations with electronic transmission.



We'll soon see how to calculate PID digitally.

The signal is 4-20 mA transmitted by wire.

Current converted to air pressure to affect valve

CHAPTER 11: DIGITAL CONTROL

- Manual operation
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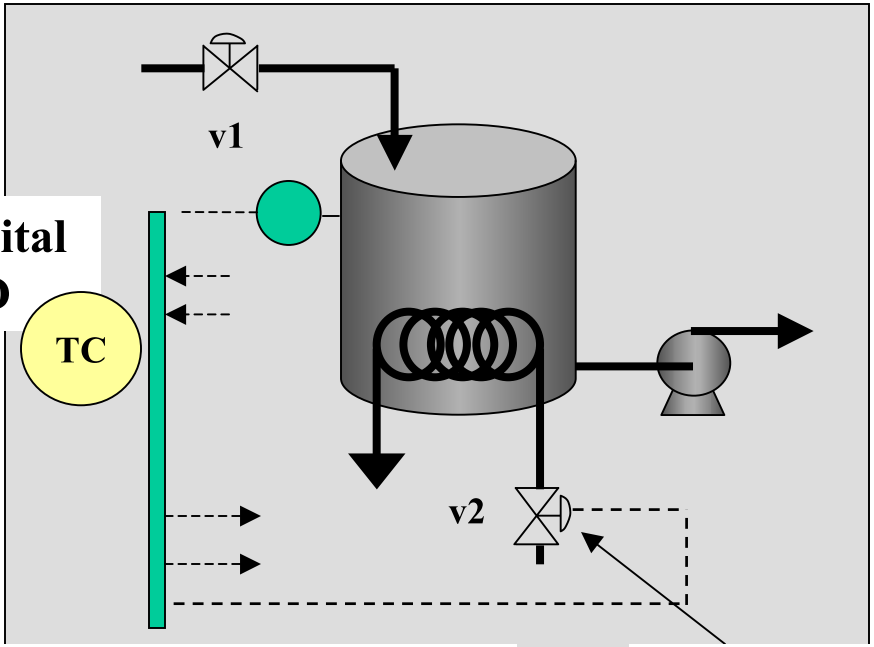
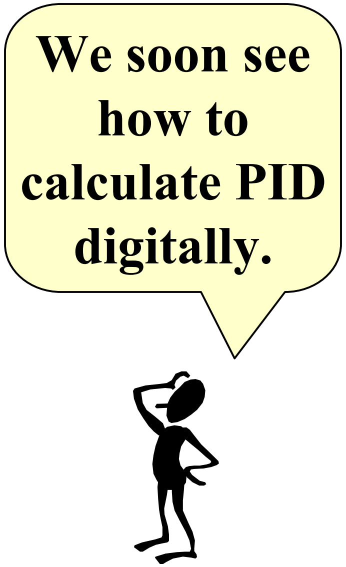
- Digital calc. & communication

Digital Calculation & Communication

Digital calculations with transmission by local area network. Sensor and valve can have microprocessors too!

Digital PID



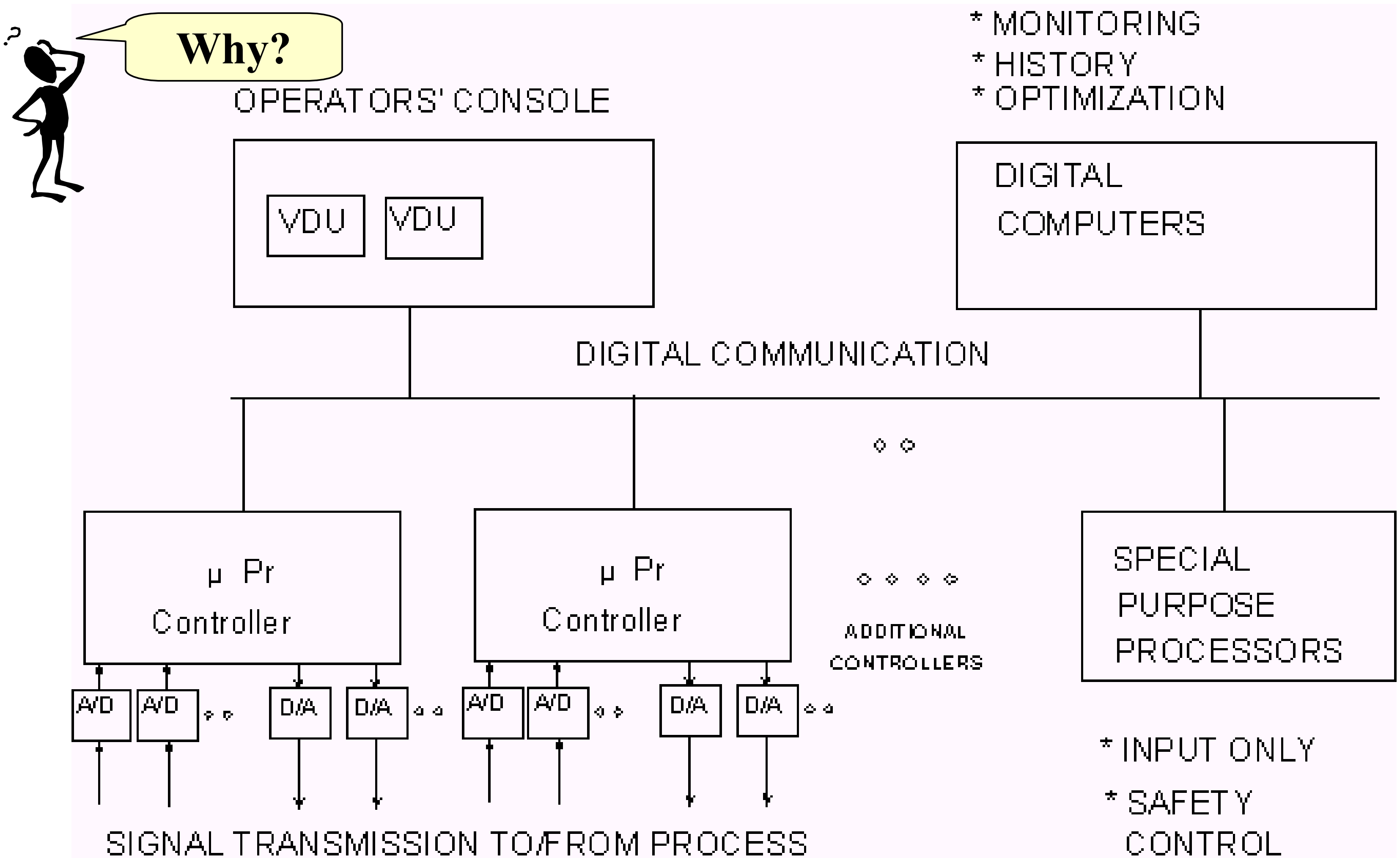


The signal transmitted digitally.

converted to air pressure to affect valve

CHAPTER 11: DIGITAL CONTROL

Digital control employs a <u>distributed</u> computing network



CHAPTER 11: DIGITAL CONTROL

Digital control employs a distributed computing network

Feature	Effect on process control
Calculations performed in parallel by numerous processors	Control calculations are performed faster than if by one processor
Limited number of controller calculations performed by a single processor	Control system is more reliable since a processor failure affects only few control loops
Control calculations and interfacing to process independent of other devices connected to the LAN	Control is more reliable since failure of other devices does not immediately affect a control processor
Small amount of equipment required for the minimum system	Only the equipment required must be purchased, and the system is easily expanded at low cost
Each type of processor can have different hardware and software	Hardware and software can be tailored to specific applications like control, monitoring, operator console, and general data processing

CHAPTER 11: DIGITAL CONTROL

Let's remember that control is performed many places; locally and remotely by people and equipment.

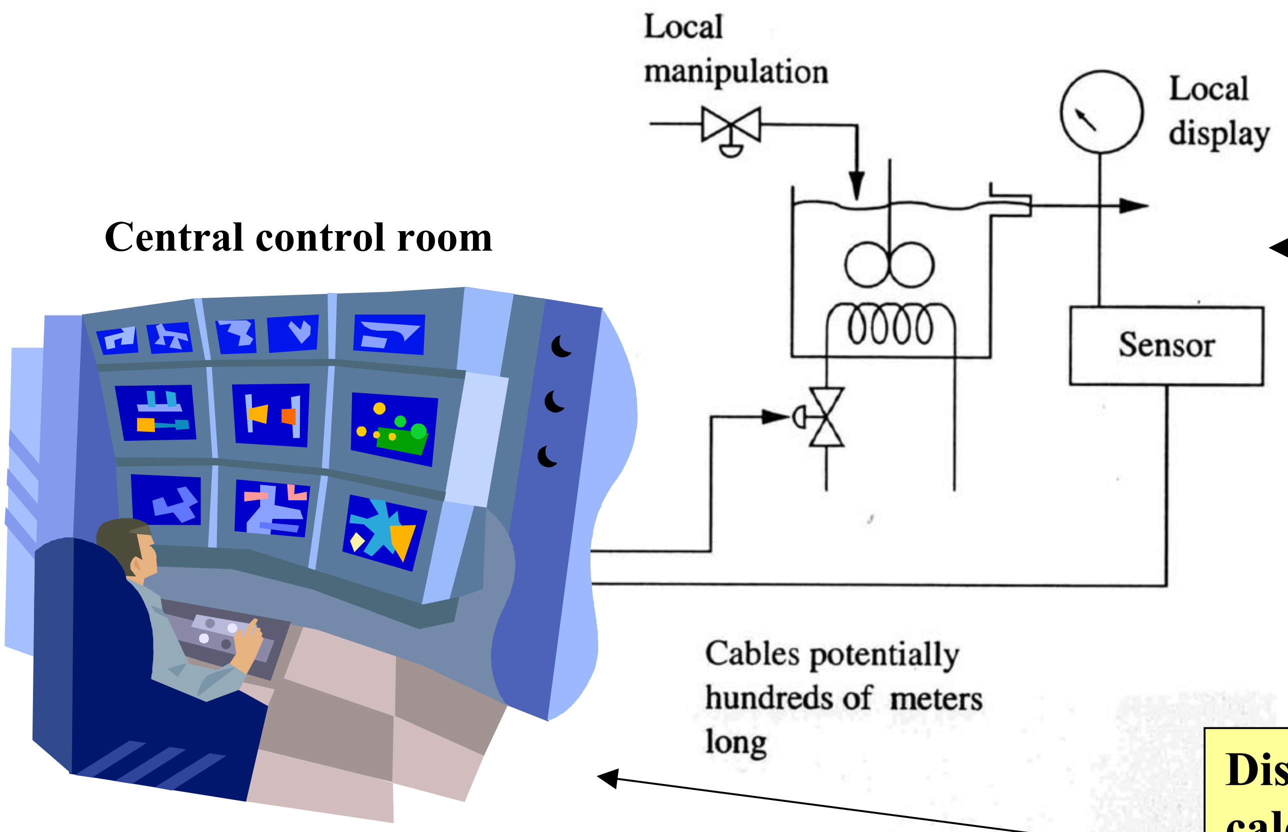


FIGURE 1.6

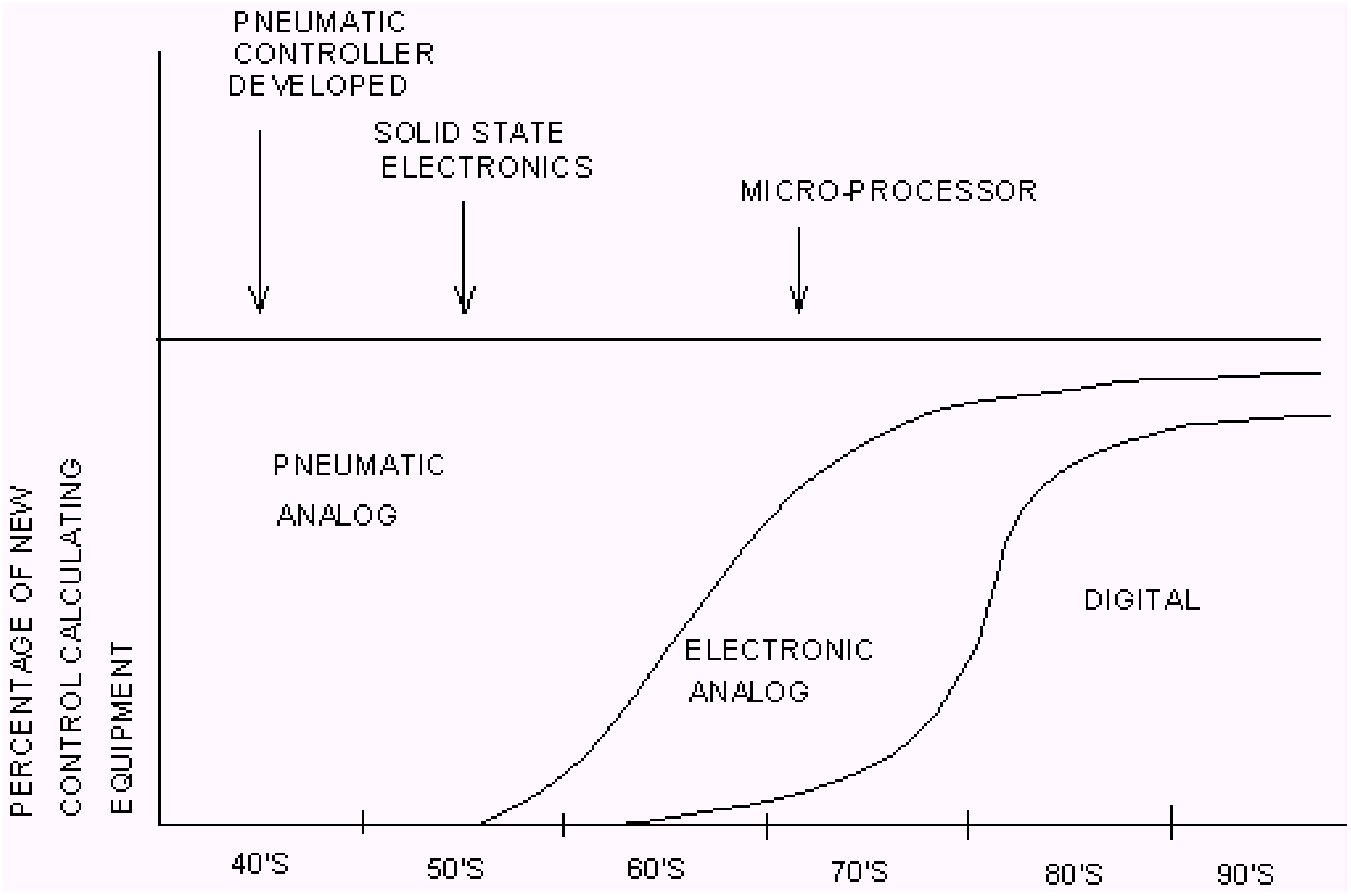
Sensors, local indicators, and valves in the process.

Some actions and automation done here.

Displays of variables, calculations, and commands to valves are in the centralized control center.

CHAPTER 11: DIGITAL CONTROL

A rough indication of the use of various devices for control calculations for <u>new</u> industrial process control systems.



CHAPTER 11: DIGITAL CONTROL

- Manual operation
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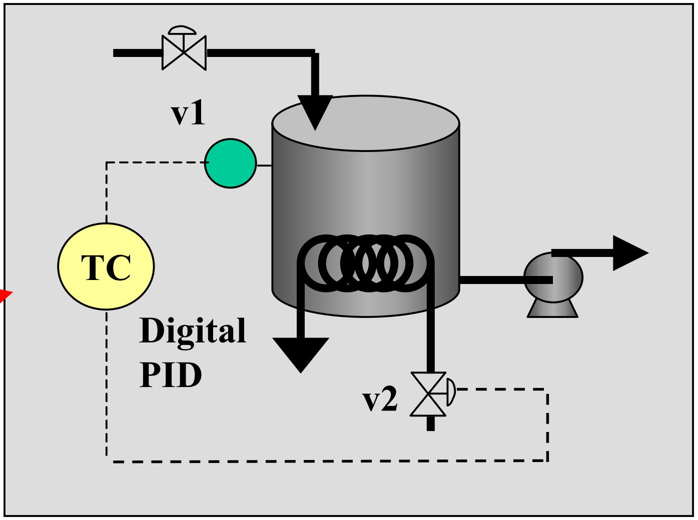
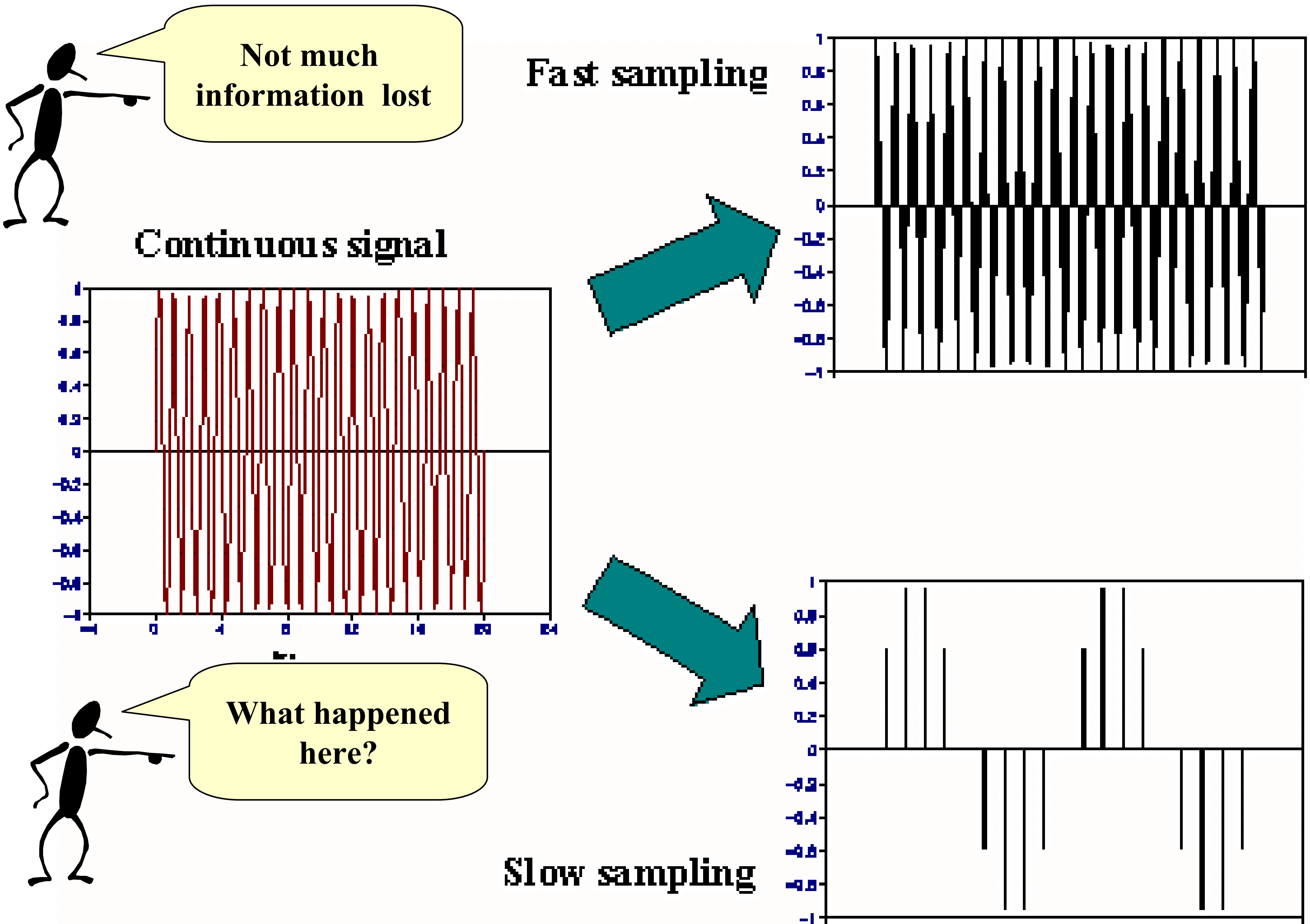
The techniques presented will be applicable for digital sampling and calculation. Transmission can be electronic or digital.

Periodically, the measurement is sampled and a calculation is performed.



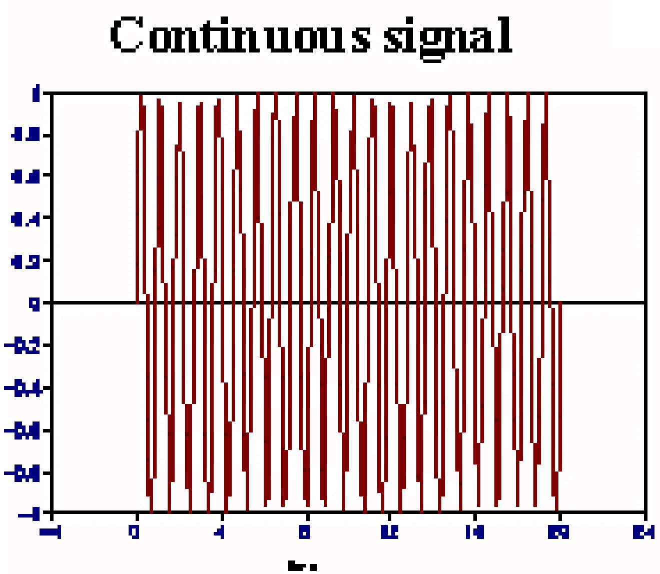
CHAPTER 11: DIGITAL CONTROL

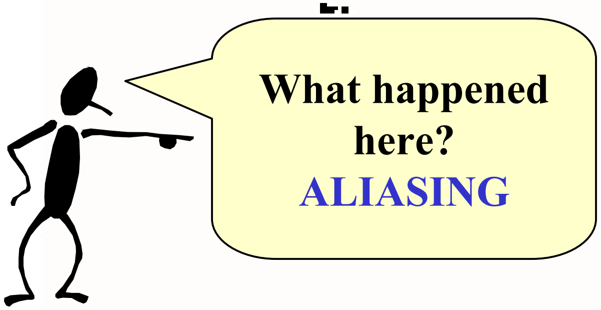


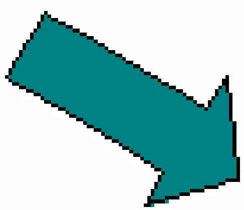
CHAPTER 11: DIGITAL CONTROL

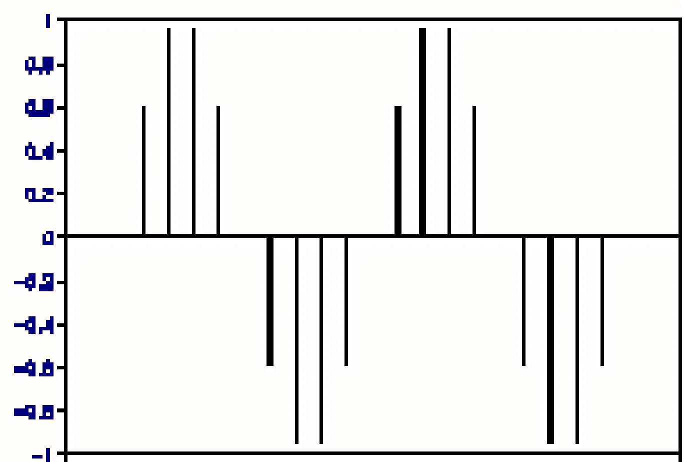
Aliasing: Sampling much slower than the measurement changes causes significant loss of information.

Engineer should design for sampling "fast enough".



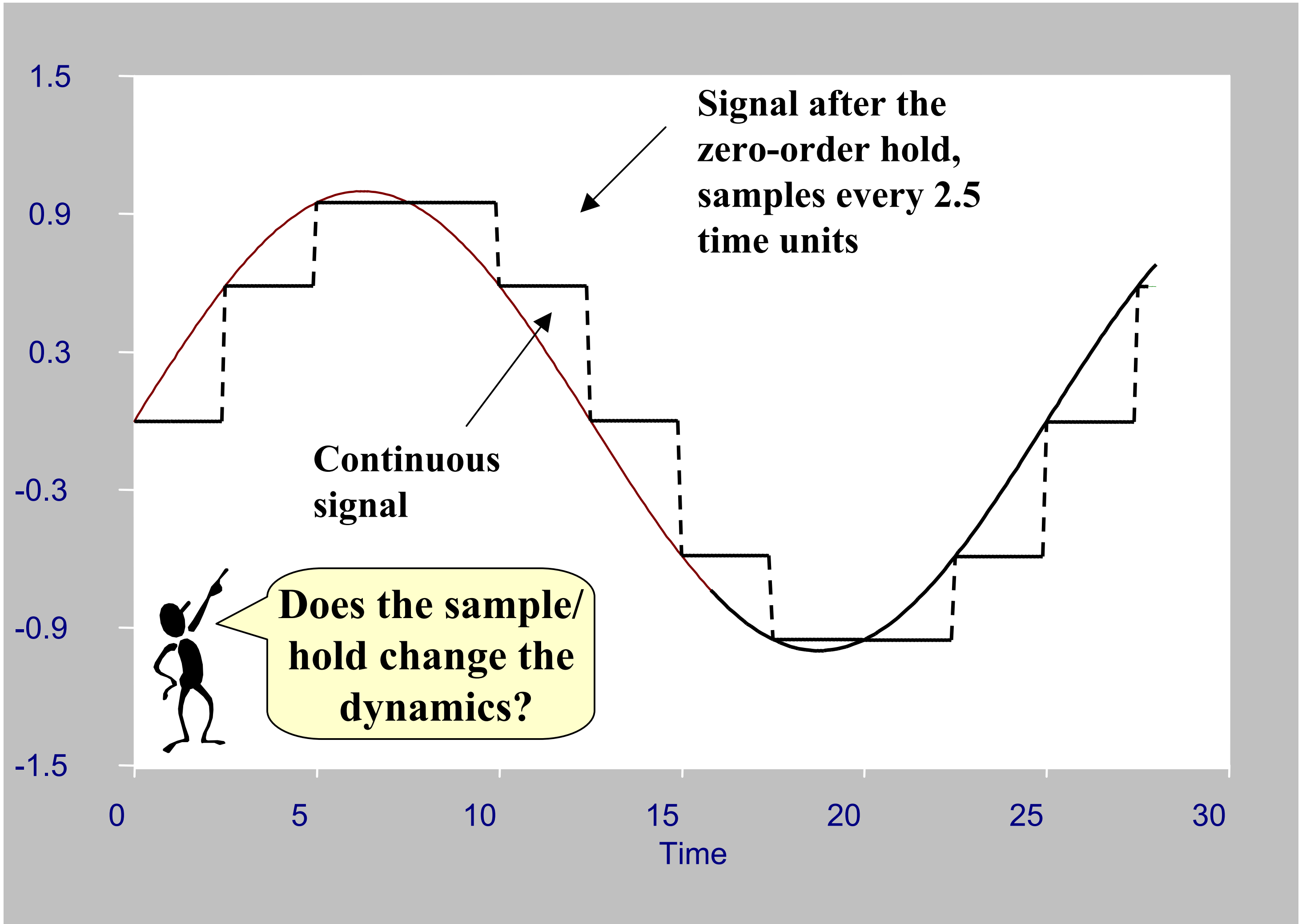






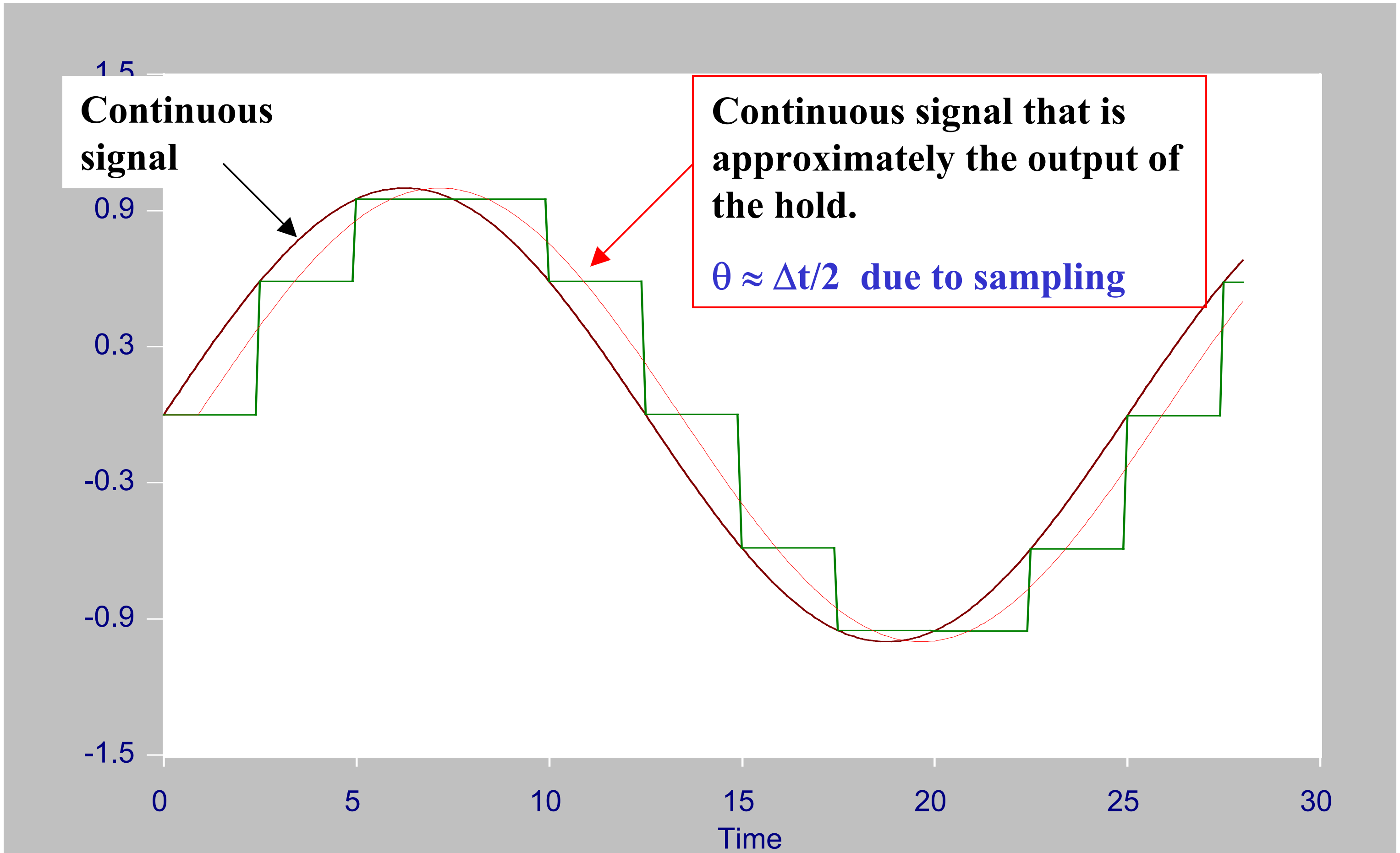
CHAPTER 11: DIGITAL CONTROL

We "hold" the last sampled value between control executions.



CHAPTER 11: DIGITAL CONTROL

The red line is the continuous approximation of the signal after the sample & hold. This shows that the effect is to introduce a "dead time" of about $\Delta t/2$.



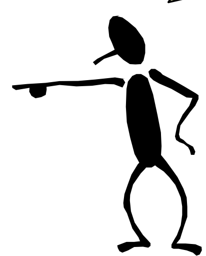
CHAPTER 11: DIGITAL CONTROL

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

We have a sample of values; CV_1, CV_2, …., CV_N

Proportional:

Integral:



Hint: How would you estimate each mode using numerical methods?

Derivative:

CHAPTER 11: DIGITAL CONTROL

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

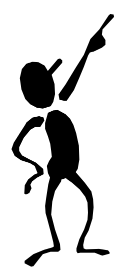
We have a sample of values; CV_1, CV_2, …., CV_N

Proportional:

$$E_N = SP_N - CV_N$$

$$(MV_N)_{proportional} = K_C E_N$$

Integral:



Calculated every time the controller is executed.

Derivative:

CHAPTER 11: DIGITAL CONTROL

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

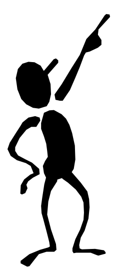
We have a sample of values; CV_1, CV_2, …., CV_N

Proportional:

$$E_N = SP_N - CV_N$$

Integral:

$$(MV_N)_{\textbf{integral}} = \frac{K_C(\Delta t)}{T_I} \sum_{i=1}^{N} E_i$$



Calculated every time the controller is executed.

- **Δt = constant**
- **How many elements in sum?**

Derivative:

CHAPTER 11: DIGITAL CONTROL

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

We have a sample of values; CV_1, CV_2, …., CV_N

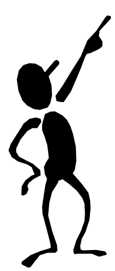
Proportional:

$$E_N = SP_N - CV_N$$

$$SUM_N = SUM_{N-1} + E_N$$

Integral:

$$(MV_N)_{\textbf{integral}} = \frac{K_C(\Delta t)}{T_I}(SUM_N)$$



Efficient calculation in realtime!

Derivative:

CHAPTER 11: DIGITAL CONTROL

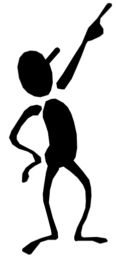
$$MV(t) = K_c \left[E(t) + \frac{1}{T_I} \int_0^t E(t')dt' - T_d \frac{d\,CV(t)}{dt} \right] + I$$

We have a sample of values; CV$_1$, CV$_2$, …., CV$_N$

Proportional:

Integral:

$$(MV_N)_{derivative} = -K_C T_d \frac{(CV_N - CV_{N-1})}{\Delta t}$$



Calculated every time the controller is executed.

Derivative:

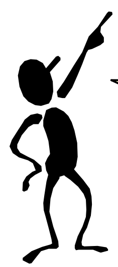
CHAPTER 11: DIGITAL CONTROL

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

We have a sample of values; CV_1, CV_2, …., CV_N

$$I = MV_1 - K_c \left[E_1 - T_d \frac{(CV_1 - CV_0)}{\Delta t} \right]$$

"I" is sometimes called the bias.



Calculated only when the controller is turned on, N=1.
Thereafter, I is constant

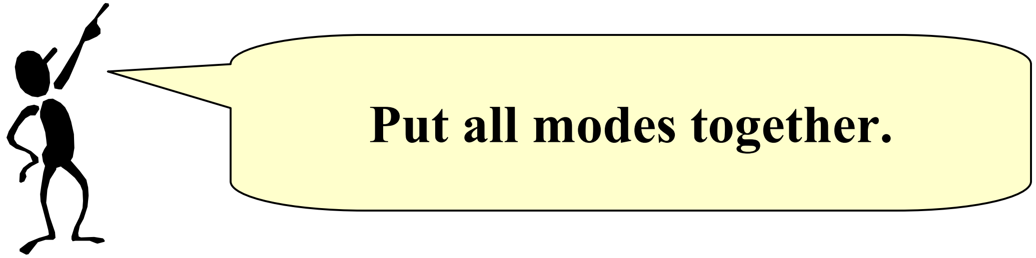
Bumpless transfer: No change to the MV when controller is first executed

CHAPTER 11: DIGITAL CONTROL

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

Digital PID, positional form **calculates the output to the final element**

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



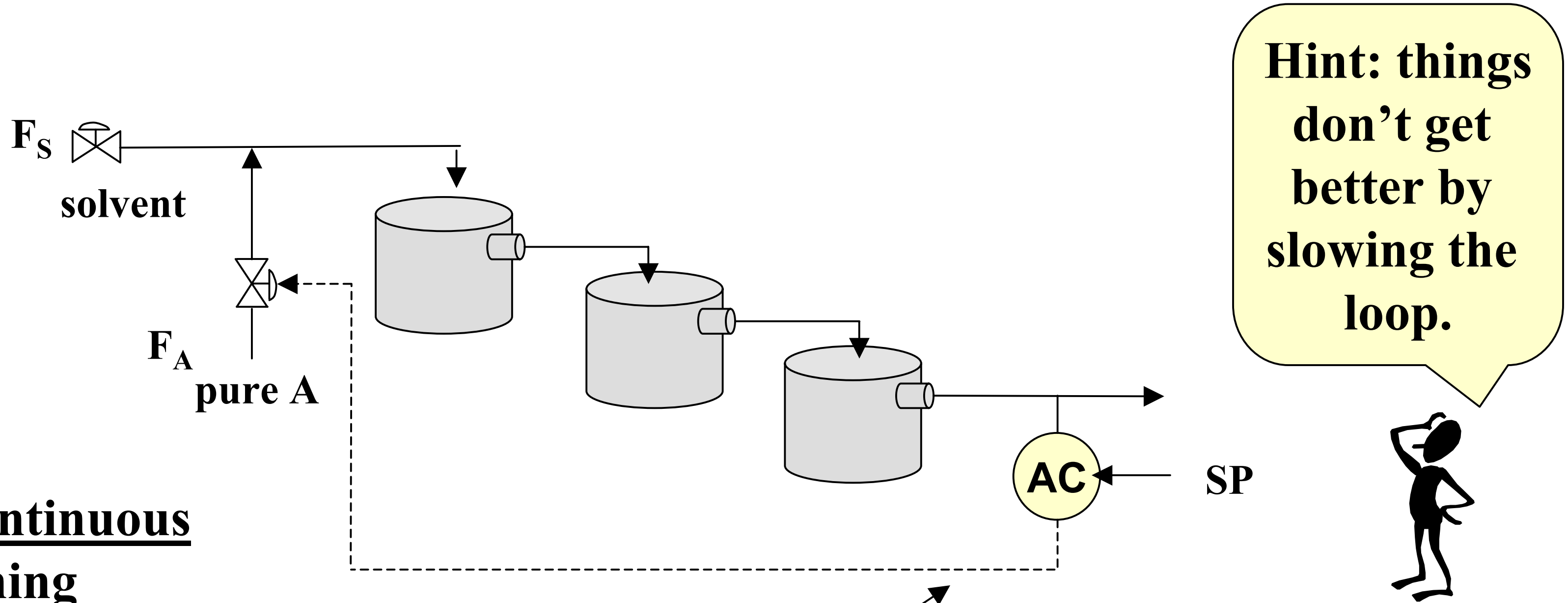
$$MV_N = K_c\left[E_N + \frac{\Delta t}{T_I}\sum_{i=1}^{N} E_i - \frac{T_d}{\Delta t}(CV_N - CV_{N-1})\right] + I$$

Digital PID, Velocity form - Alternatively, we can calculate the change in the signal at every execution.

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

CHAPTER 11: DIGITAL CONTROL

What is the effect of digital execution of the PID controller on tuning and performance?



Continuous tuning

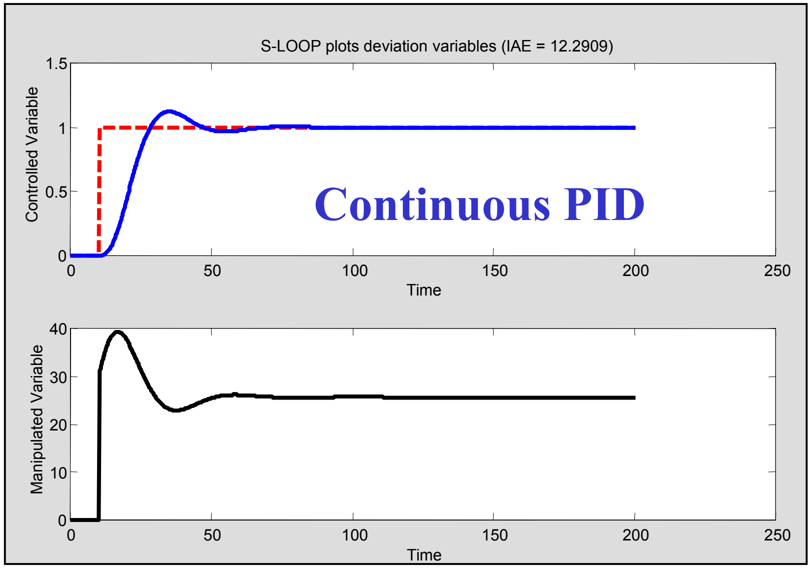
Kc = 30

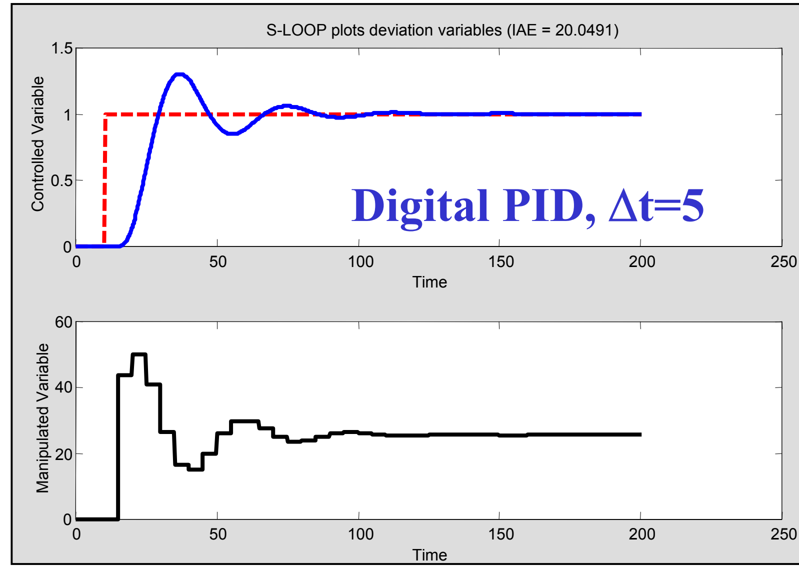
TI = 11

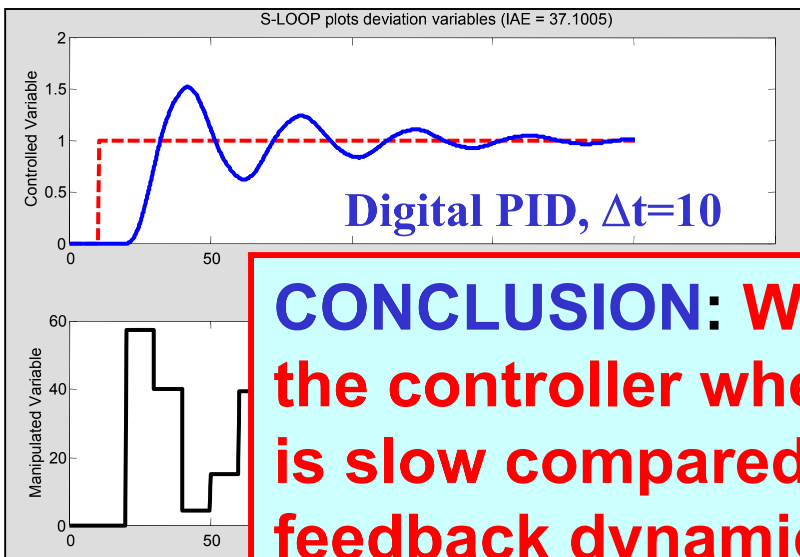
Td = 0.80

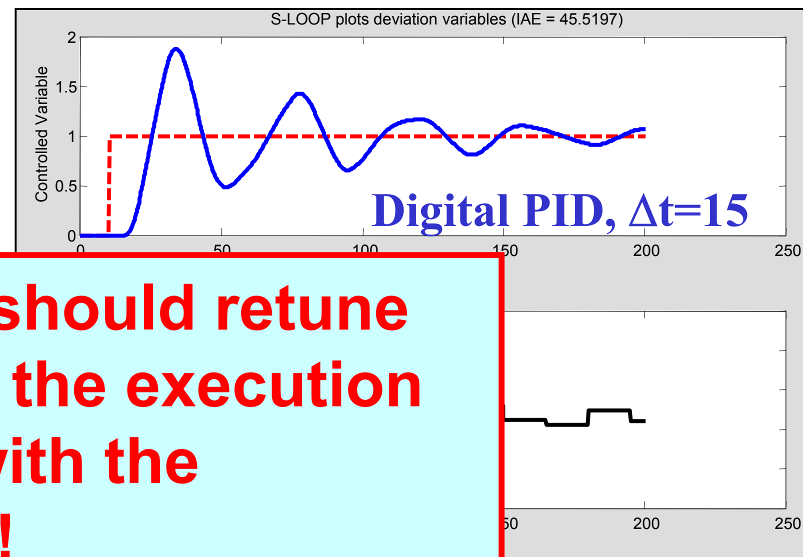
$$MV_N = K_c\left[E_N + \frac{\Delta t}{T_I}\sum_{i=1}^{N} E_i - \frac{T_d}{\Delta t}(CV_N - CV_{N-1})\right] + I$$

CHAPTER 11: DIGITAL CONTROL



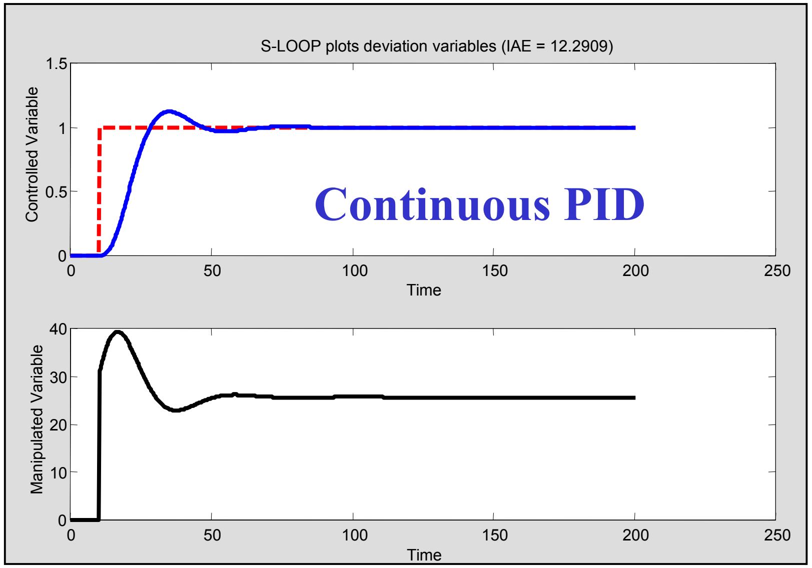


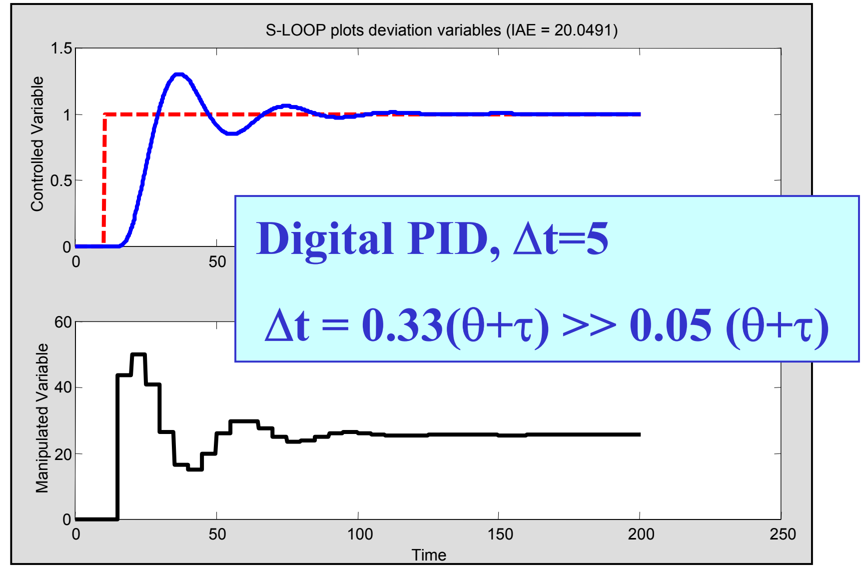




CONCLUSION: We should retune the controller when the execution is slow compared with the feedback dynamics!

CHAPTER 11: DIGITAL CONTROL





Guideline for selecting the execution time:

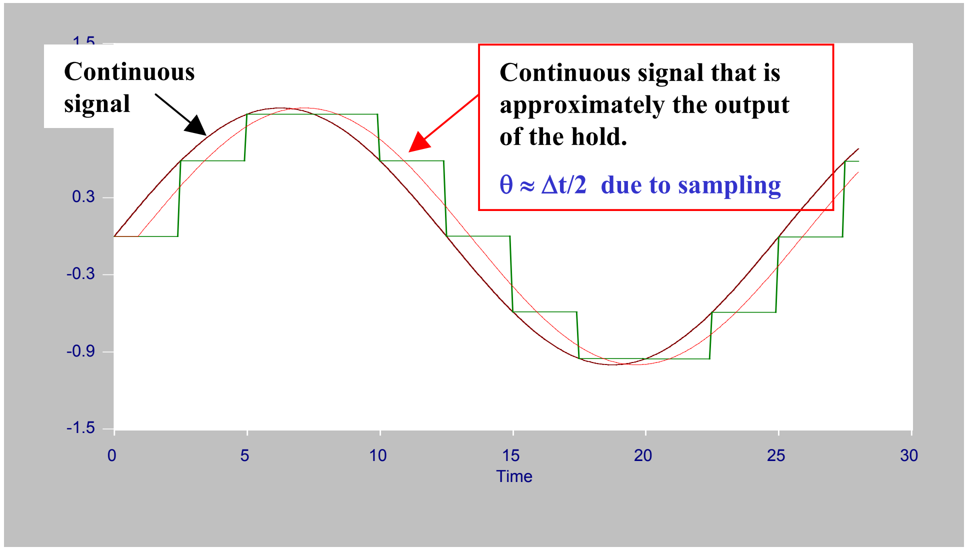
To prevent degradation of control loop performance, select a controller execution time of $\boxed{\Delta t \leq 0.05(\theta+\tau)}$.

Note: Typical sample period for chemical process control is 1/3-1/2 second. Much faster is possible, if needed.

CHAPTER 11: DIGITAL CONTROL

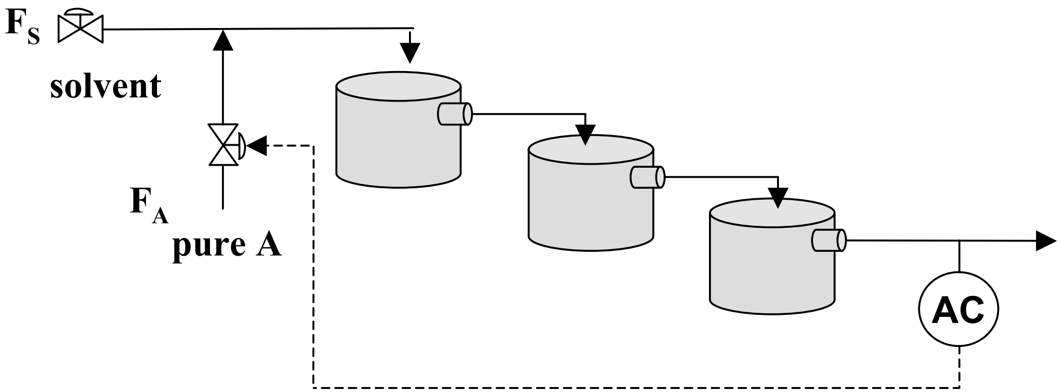
Modified PID tuning for digital controllers - this is a guideline that usually works adequately.

We learned that sampling introduces an additional dead time of about $\Delta t/2$.



1. **Obtain model, usually using empirical method**
2. **Determine the sample period, $\Delta t \leq 0.05(\theta+\tau)$, if possible**
3. **Recalculate the dead time as $\boxed{\theta' = \theta + \Delta t/2}$**
4. **Calculate tuning using continuous method**
5. **Implement and fine tune as needed**

Let's apply this guideline for the three-tank mixer with a long sample time = 15 minutes.



Process reaction curve
Kp = 0.039 %A/%open
θ = 5.5 + ?? = ?? min
τ = 10.5 min

Tuning from chart
Kc = ??
TI = ??
Td = ??

The performance is about as good as possible with this very long sampling time! Would you fine tune further?

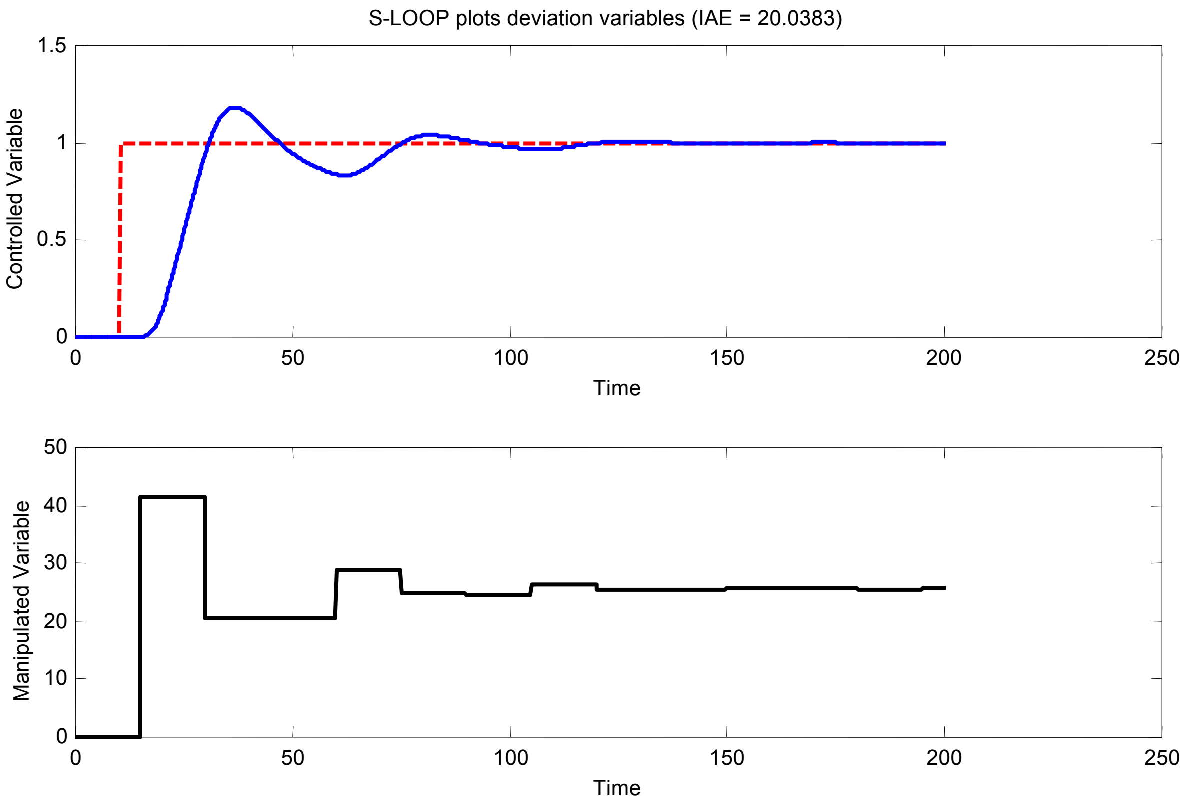
Tuning from chart

Kc = 20

TI = 14

Td = 2.35

IAE increased from 12.2 to 20+



CHAPTER 11: DIGITAL CONTROL

If the PID is no better in digital form, why did we spend decades of engineering time and billions of dollars converting the world's control to digital?

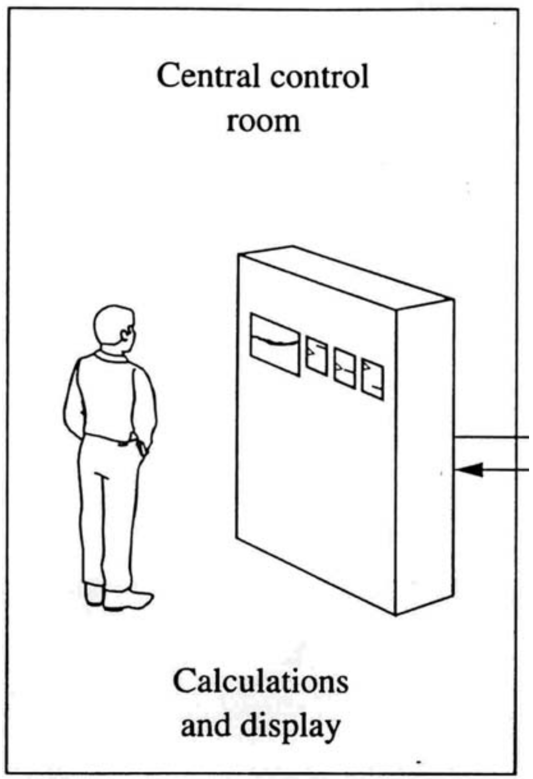
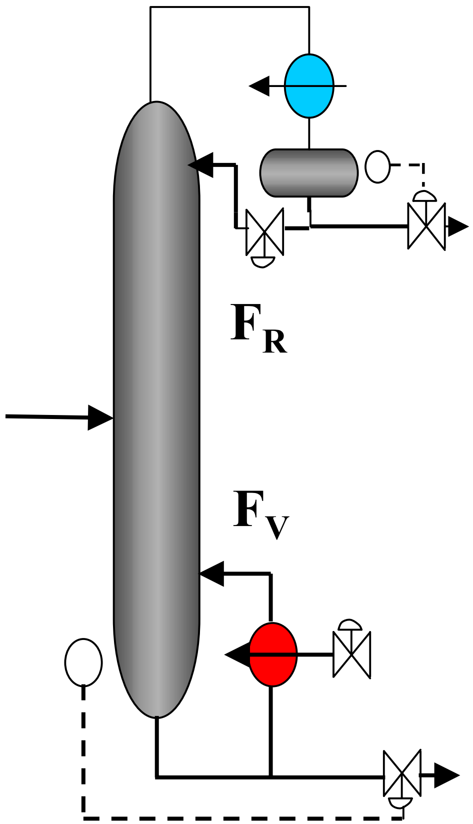
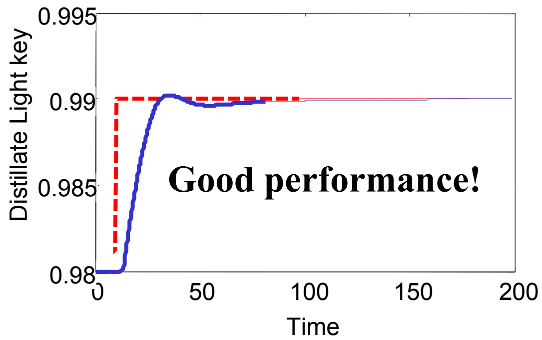


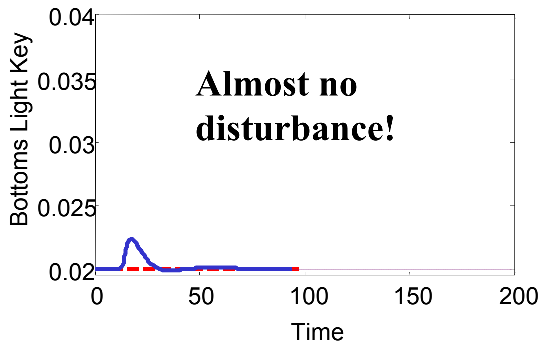
FIGURE 1.6

CHAPTER 11: DIGITAL CONTROL

Why did we convert the world's control to digital - Complex controllers







Improved performance can be achieved with algorithms that optimize the path to the set point, every controller execution!

(See Chapters 19 and 23)

CHAPTER 11: DIGITAL CONTROL

Why did we convert the world's control to digital - Process monitoring

We have a digital history of measurements for

- **Recall at any time for trouble shooting**
- **Calculation of process performance indicators, heat transfer coefficients, reactor yields, energy/kg of product, and so forth**
- **Excellent graphical displays with data in context of process schematic**

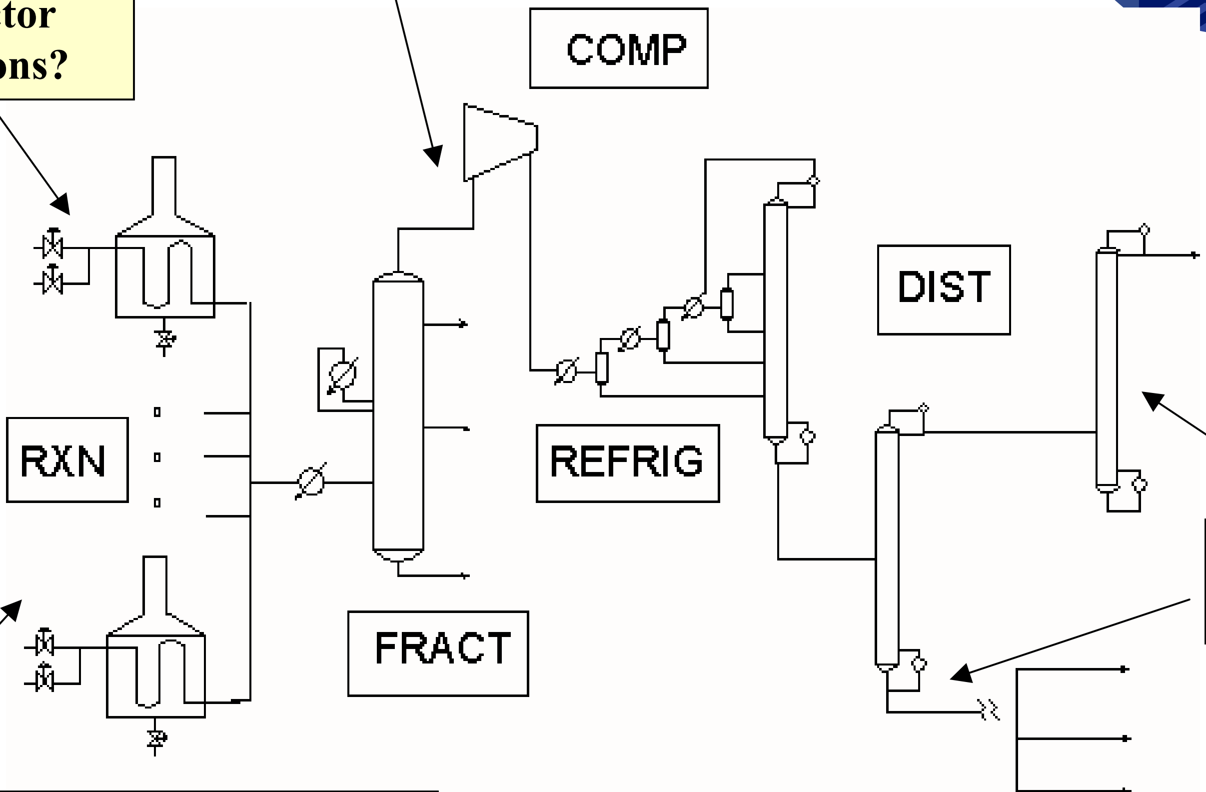
(See Chapter 26)

CHAPTER 11: DIGITAL CONTROL

Why did we convert the world's control to digital - Process optimization

Best suction pressure?

Best reactor conversions?



Best product/ recycle purities?

Best feed rates, each feed type

(See Chapter 26)

CHAPTER 11: DIGITAL CONTROL

Why did we convert the world's control to digital -Diagnostics

We have digital monitors at sensor, controller and valve!

- Compare signal to valve with actual valve position - report significant errors
- Diagnose problems with sensor (voltage, etc.)
- Do not take feedback control action on questionable loop - alarm operator

CHAPTER 11: DIGITAL CONTROL, WORKSHOP 1

1. Select all of the appropriate answers. Mechanical implementation of feedback control employs

- **a. Digital computation**
- **b. Analog computation**
- **c. Neither a nor b**
- **d. Both a and b**

2. A digital PID controller is operating "in automatic", i.e., it is calculating the signal to the final element. You are fine tuning the loop. You change the controller gain by -30% of its original value.

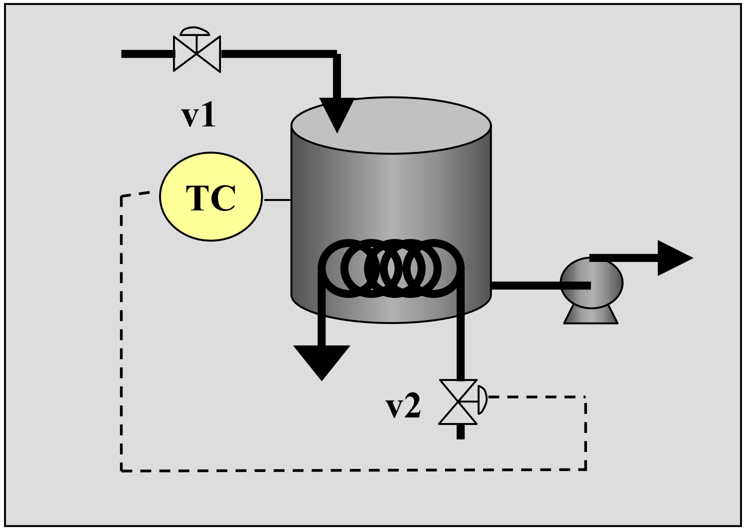
Describe what happens.

CHAPTER 11: DIGITAL CONTROL, WORKSHOP 2

You are tuning the temperature controller shown in the figure. You have determined the dynamic model below.

Determine the PID tuning for this loop for execution periods below and simulate the results using S_LOOP.

- **$\Delta t = 0.10$**
- **$\Delta t = 1.0$**
- **$\Delta t = 5.0$**



$$G_P(s) = \frac{T(s)}{v_2(s)} = \frac{-.53e^{-0.20\,s}}{10\,\mathbf{s}+1}$$

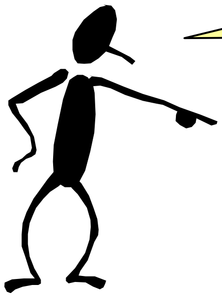
(All times are in minutes.)

CHAPTER 11: DIGITAL CONTROL, WORKSHOP 3

Develop a table with advantages and disadvantages for the six control equipment categories for many important issues.

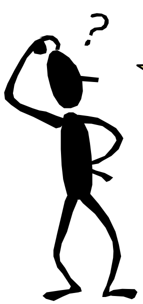
	reliability	speed	Many more!!
Manual operation			
Mechanical devices			
Pneumatic devices			
Electronic devices			
Digital calculations			
Digital calcs. & communication			

CHAPTER 11: DIGITAL CONTROL



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

- **Identify examples of analog and digital computation and signal transmission.**
- **Program a digital PID calculation**
- **Select a proper execution rate for a feedback controller.**
- **Tune a digital PID**



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 11: LEARNING RESOURCES

- **<u>SITE PC-EDUCATION WEB</u>**
  - Instrumentation Notes
  - Interactive Learning Module (Chapter 11)
  - Tutorials (Chapter 11)

- **Software Laboratory, S_LOOP**

  - You can simulate a PID loop with continuous of digital control to determine the effect of execution period.

CHAPTER 11: SUGGESTIONS FOR SELF-STUDY

1. **Find some process reaction curve plots in Chapters 3-5. Determine the maximum PID execution period. Then, for a controller execution period ten times the minimum, determine the tuning for PID and PI controllers using the tuning charts.**
2. **Using S_LOOP, simulate the system(s) in question 1.**
3. **Develop a flowchart for an excellent computer program to calculate the PID control. This should be a subroutine that can be called for every controller in the plant.**

CHAPTER 11: SUGGESTIONS FOR SELF-STUDY

4. **Take an inventory of your house and identify analog and digital control systems.**

5. **Develop a simulation that accepts a continuous signal and determines the output of a zero-order hold and first-order hold.**