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MENG366

Introduction to Control System

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What do these two have in common?

Tornado

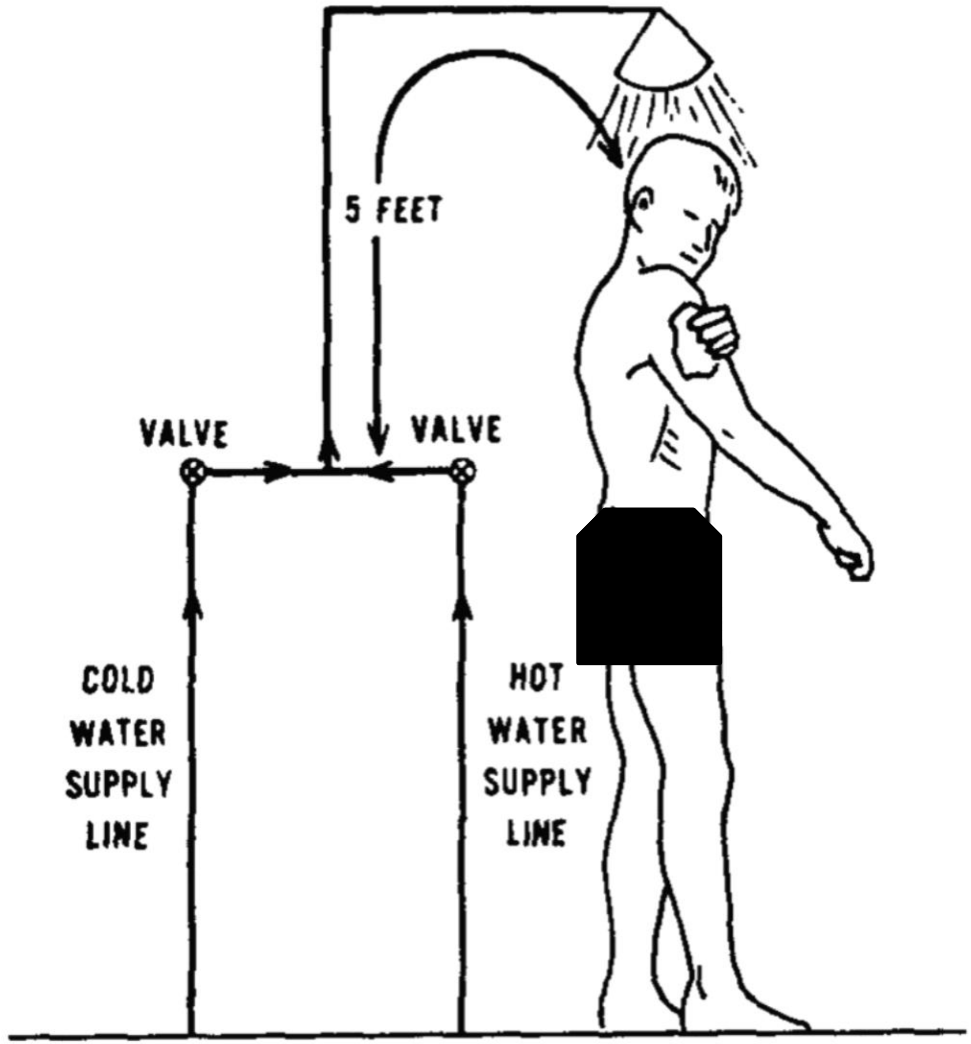
Boeing 777

- **Highly nonlinear, complicated dynamics!**
- **Both are capable of transporting goods and people over long distances**

BUT

- **One is controlled, and the other is not.**
- **Control is “the hidden technology that you meet every day”**
- **It heavily relies on the notion of “feedback”**

Basic Concepts of Feedback Control



Flow diagram for shower example.

Course Overview

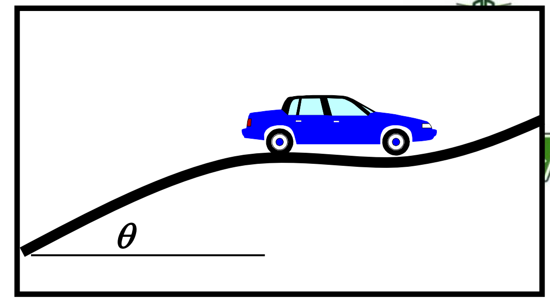
- One of the <u>most important</u> and <u>multi-disciplinary</u> courses you'll ever take
  - *Physics*
  - *Kinematics*
  - *Mathematics*
  - *Time and frequency response analysis*
  - *Engineering judgment*
- Leveraging <u>previous coursework</u> and preparing for <u>future coursework</u>
  - *Mechanical vibrations*
  - *Mechanics, electrical, electromechanical*
  - *Fluid-thermal*
  - *Calculus, differential equations, complex algebra*
  - *Measurements/instrumentation understanding*

Remember these?

- Emphasize combination of <u>theoretical</u> and <u>conceptual</u> understanding

Overview

Example: Vehicle speed control



1. MODEL:

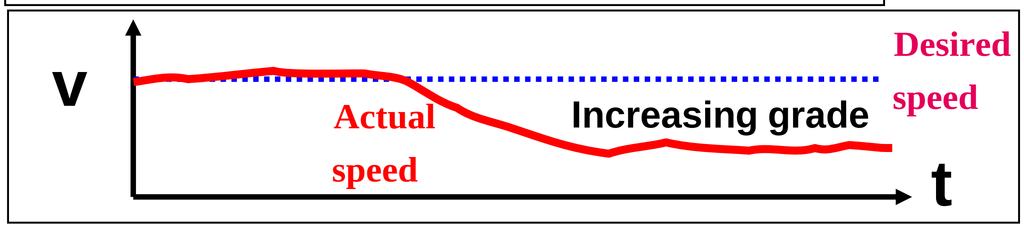
Inertia force; Traction: input, excitation; Friction: damping; Gravitation: disturbance

$$M\dot{v} = f_e(t) - Bv - Mg\sin\theta$$

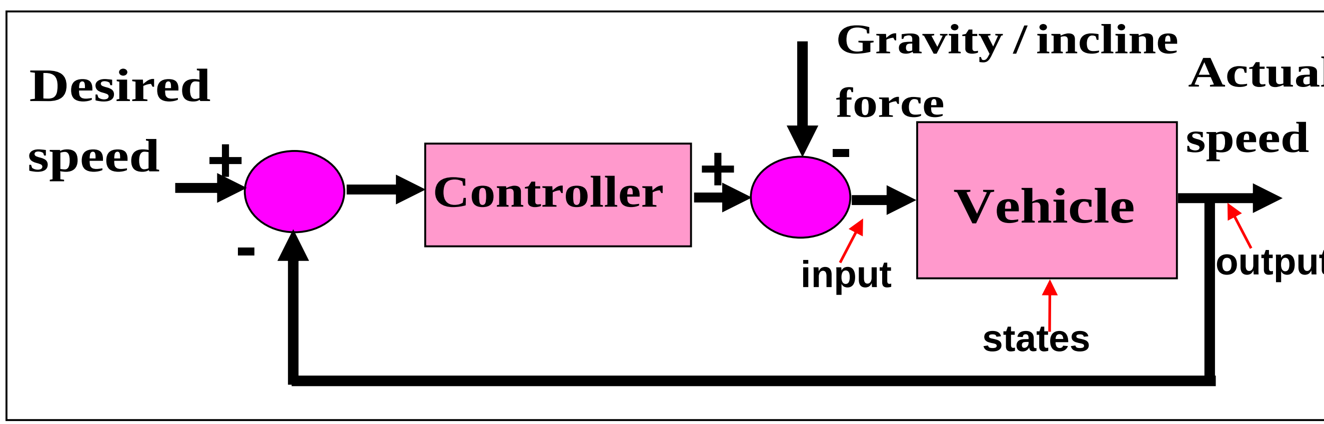
linearization

$$M\dot{v} + Bv \cong f_e(t) - Mg\theta$$

2. ANALYSIS:

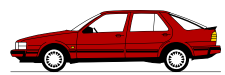


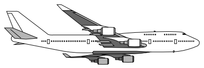
3. CONTROL:



Basic Concepts

- **System**





A *combination* of *components* acting together to perform *a specific objective*

- **Modeling**

A procedure to obtain a *model* describing *important* characteristics of system

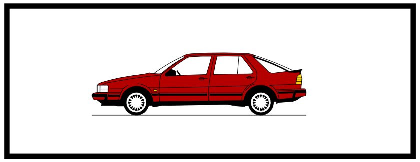
- **Analysis**

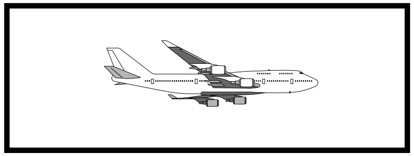
Investigation of *performance* of system, whose model is *known*, under specified conditions

Motivation for MENG366

Why should we care about modeling and analysis?

Explaining interesting Phenomenon	Component and Machine Design	Feedback Control Design and Adding Intelligence





Definitions Related to System

- ***Input*** — *A variable that excites a system*
  - *Inputs are not always known beforehand*
  - *Inputs are always responsible for problems in systems*

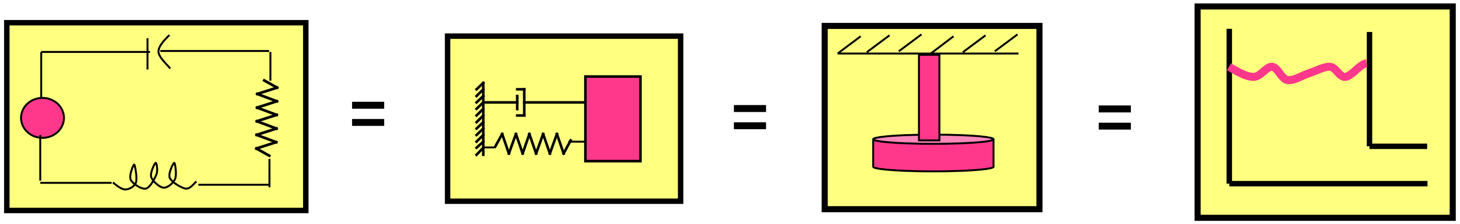
- ***Output*** — *A variable that we observe and consider important*
  - *Measurements/instrumentation*
  - *Not necessary what we want to know*

- ***State*** — *A variable that is used to describes the internal system dynamics*
  - *A set of states can be used to fully describe system's current situation.*
  - *With two identical sets of initial values of states, performance of a system is the same*
  - *Do you get all the states of system ?*

Interdisciplinary and System Nature of MENG366

Analogous systems

- ***Models are the same regardless of the physical domain of interest***



$y =$ Charge, $u =$ Voltage

$y =$ Transl. displ., $u =$ Force

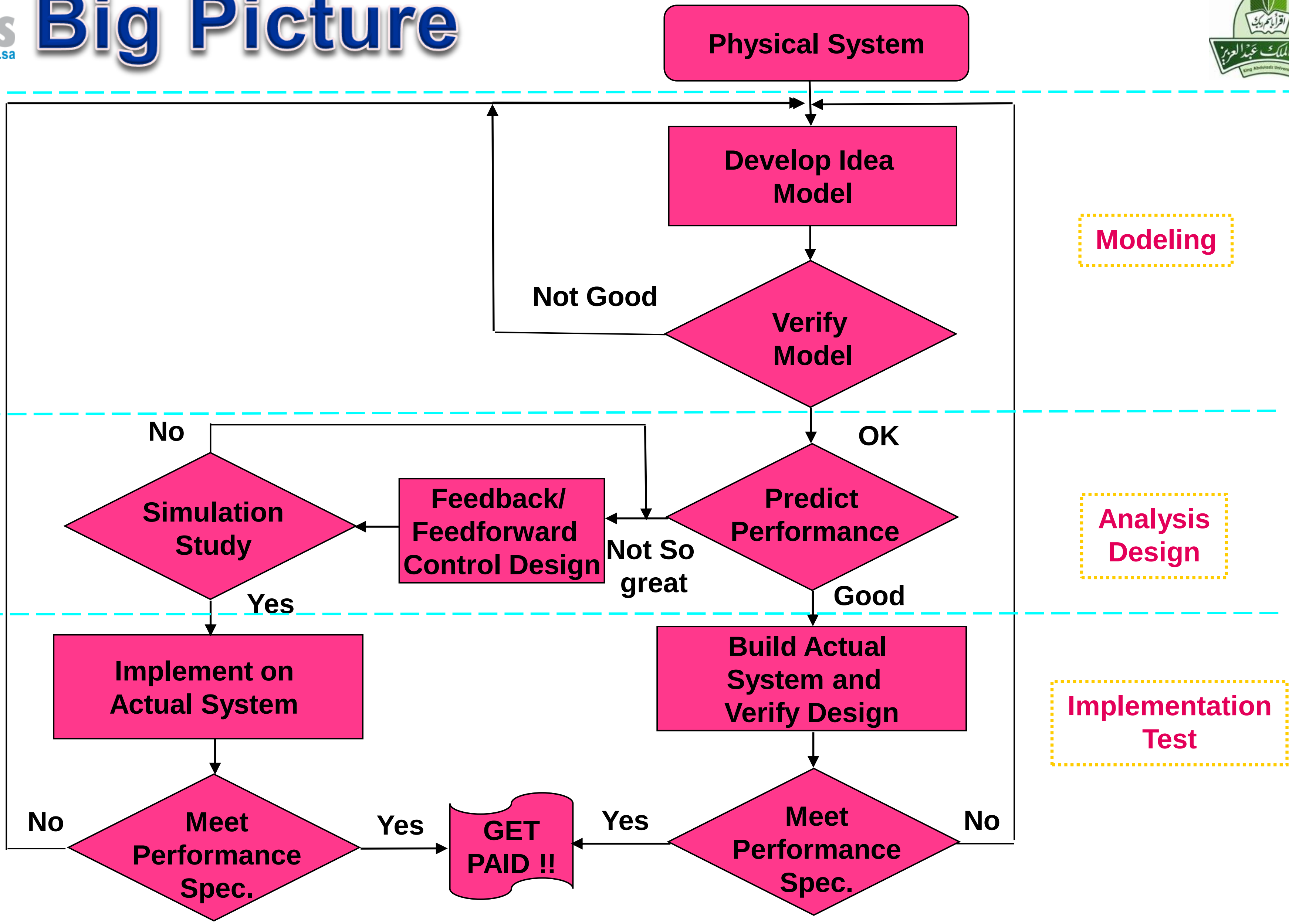
$y =$ Angular displ., $u =$ Torque

$y =$ Volume, $u =$ Pressure

u → $$\ddot{y} + \dot{y} + y = u(t)$$ → y

- ***We only need to understand how to analyze one model, but the results are applicable for four seemingly different types of physical systems!***

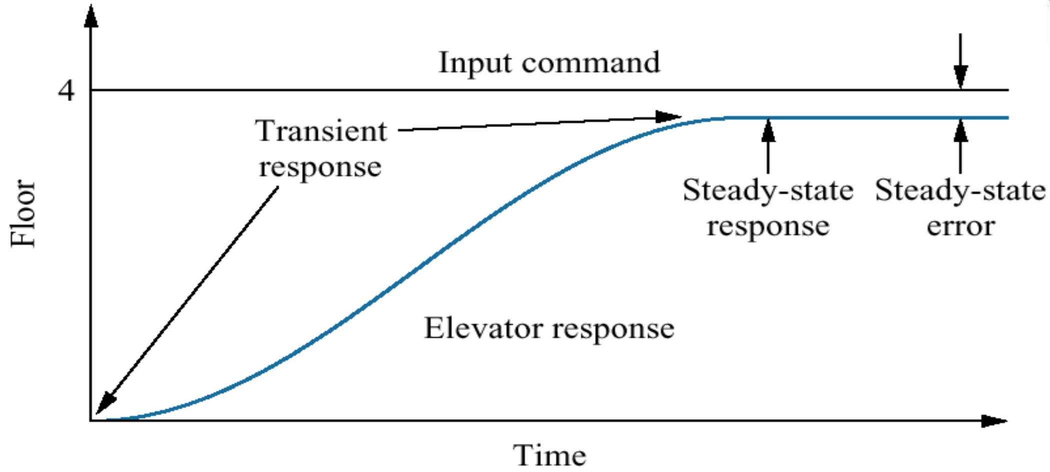
Big Picture



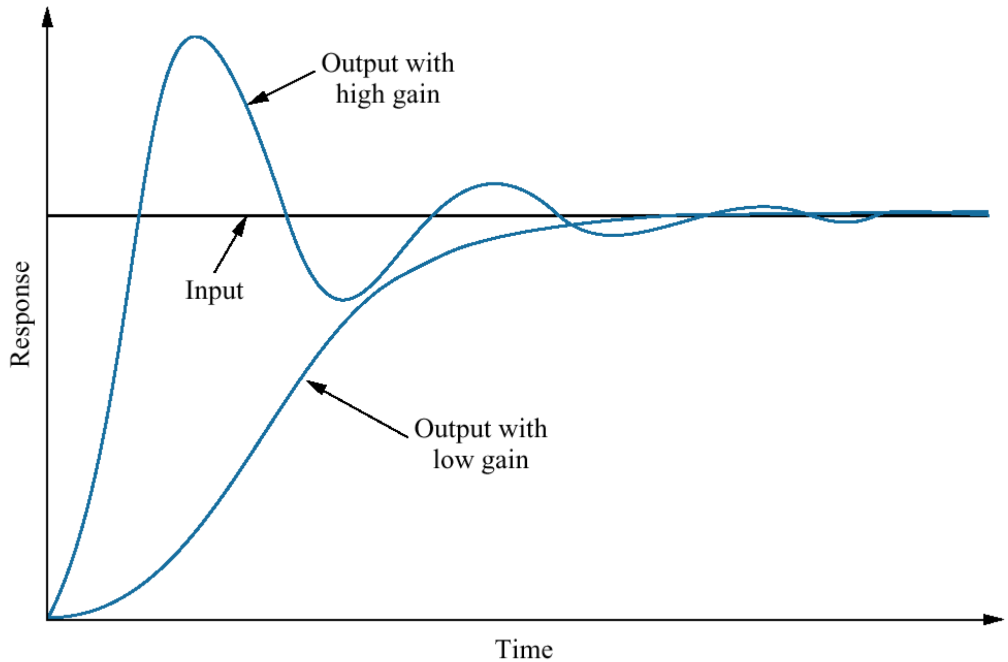
Physical System
Develop Idea Model
Not Good
Verify Model
Modeling
No
OK
Simulation Study
Feedback/ Feedforward Control Design
Not So great
Predict Performance
Analysis Design
Yes
Good
Implement on Actual System
Build Actual System and Verify Design
Implementation Test
No
Meet Performance Spec.
Yes
GET PAID !!
Yes
Meet Performance Spec.
No

Response: Input vs. Output

Input and output
(an elevator case)



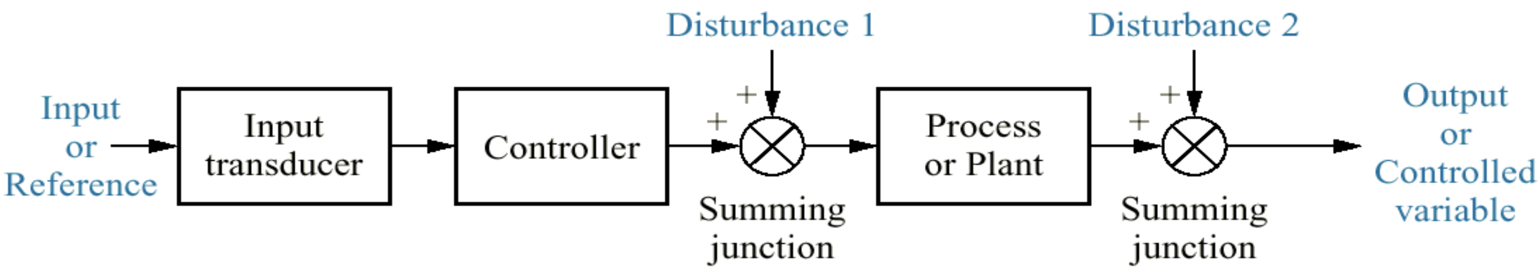
Response of a general position control system showing effect of high and low controller gain on the output response



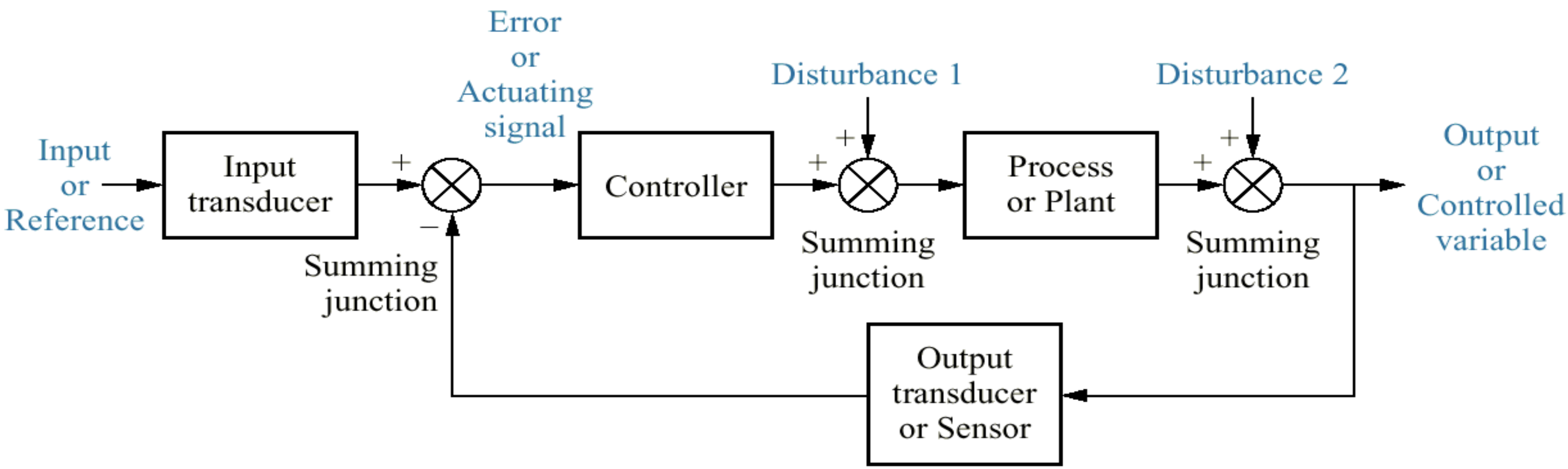
Two Types of Control Systems

- Open Loop
  - No feedback
  - Difficult to control output with accuracy
- Closed Loop
  - Must have feedback
  - Must have sensor on output
  - Almost always negative feedback

Open-loop vs. Closed-loop



(a)

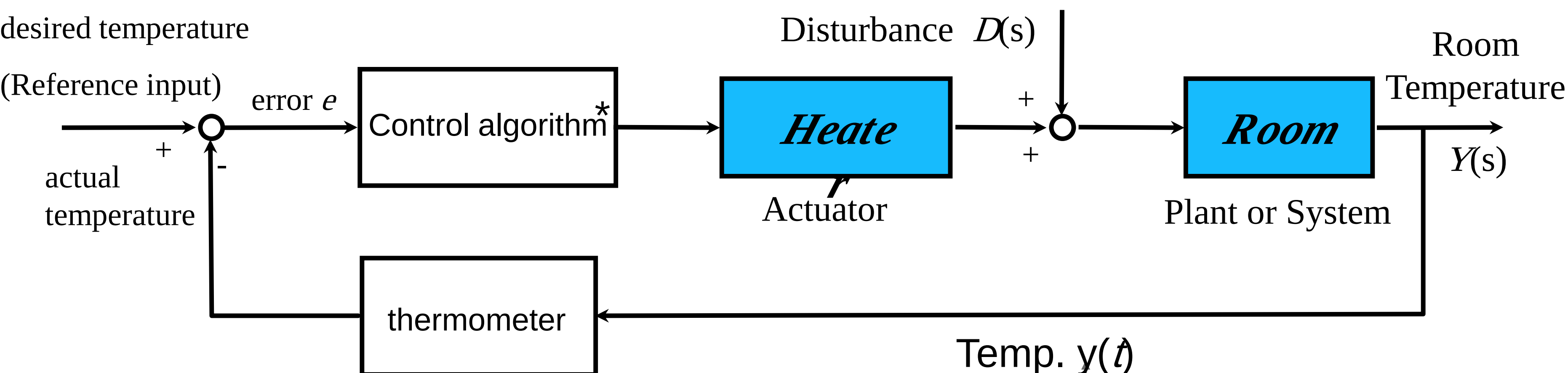


(b)

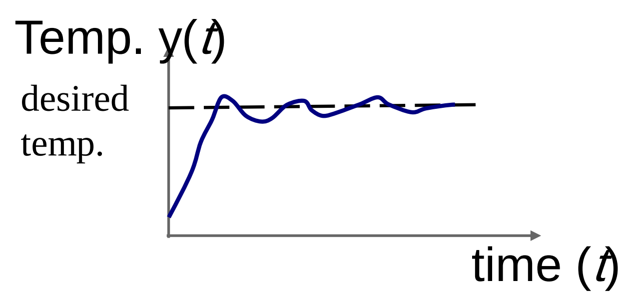
Open-Loop vs Closed-Loop

- **Closed-Loop (Feedback) Control**

  The control input $u(t)$ (or $U(s)$) is synthesized based on the a priori knowledge of the system (plant), the reference input r(t) (or $R(s)$) and the measurement of the actual output $y(t)$ (or $Y(s)$). For example the temperature control of this classroom:



*on-off controller: $\begin{cases} e > 0, \text{ turn on heater} \\ e < 0, \text{ turn off heater} \end{cases}$

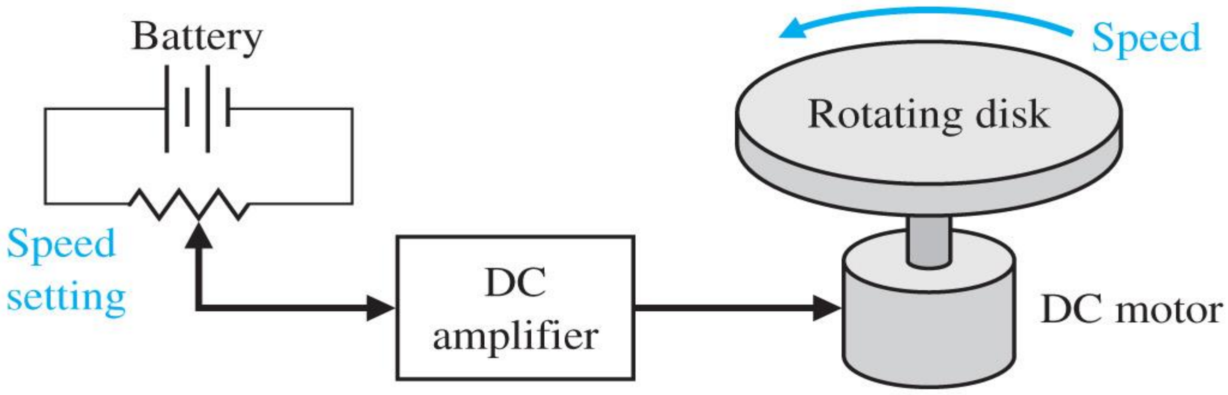


Open-loop control

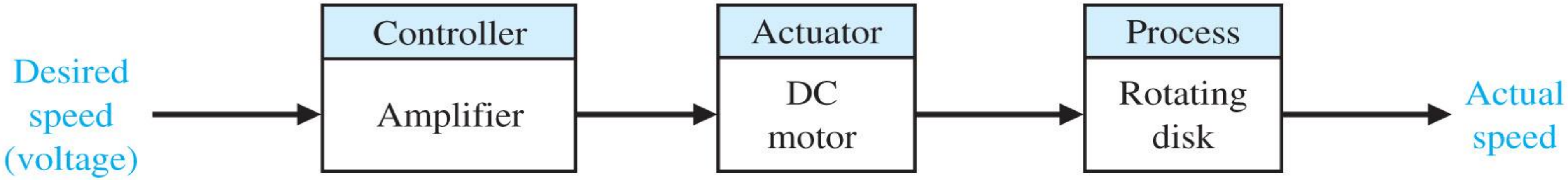
An open-loop control system utilizes an actuating device to control the process directly without using feedback.

A common example of an open-loop control system is an electric toaster in the kitchen.

Open-loop control



(a)

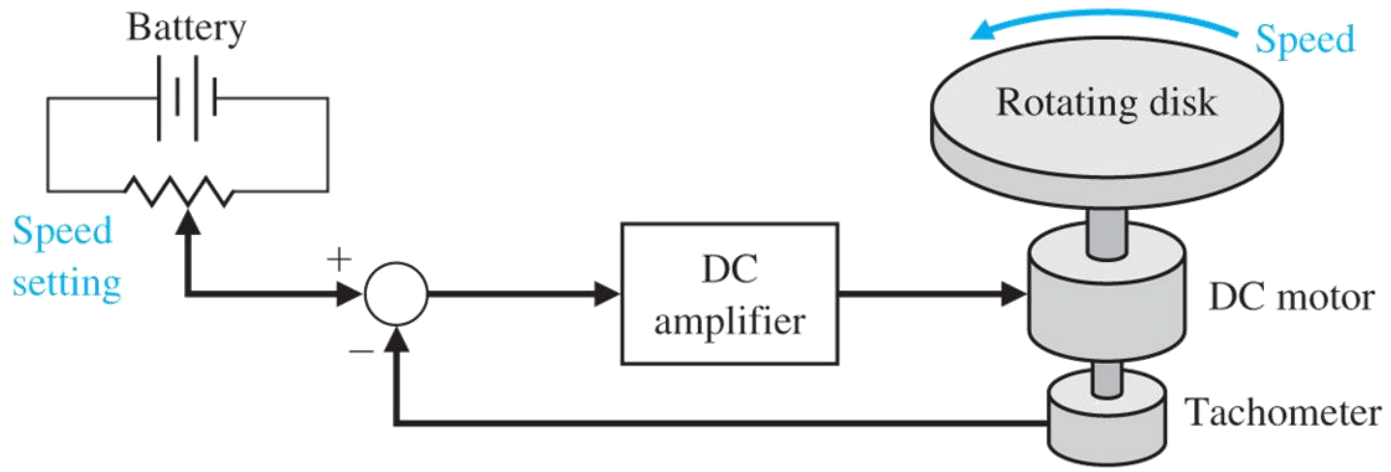


(b)

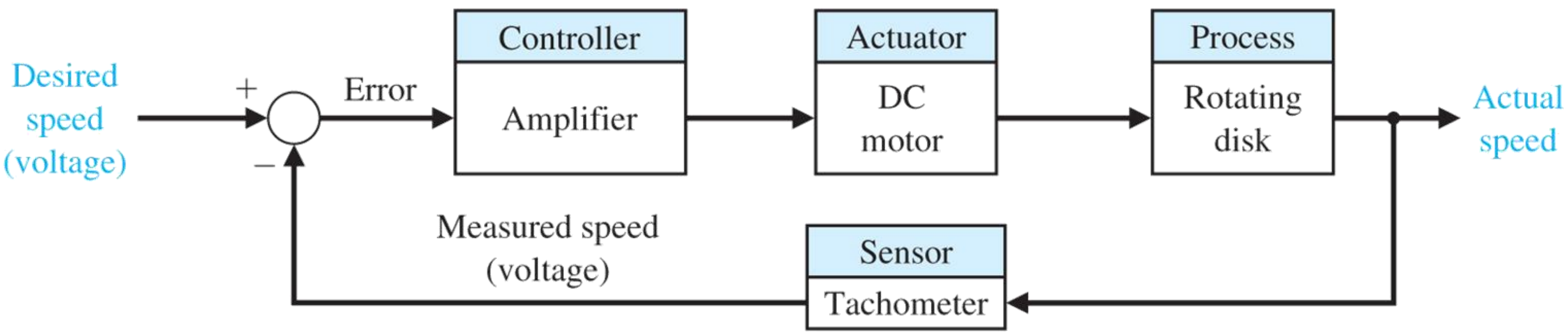
Closed-loop control

A closed-loop control system uses a measurement of the output and feedback of this signal to compare it with the desired output.

Negative Feedback Control System

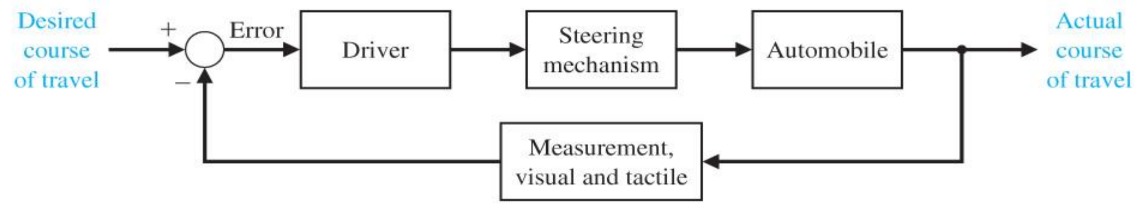


(a)

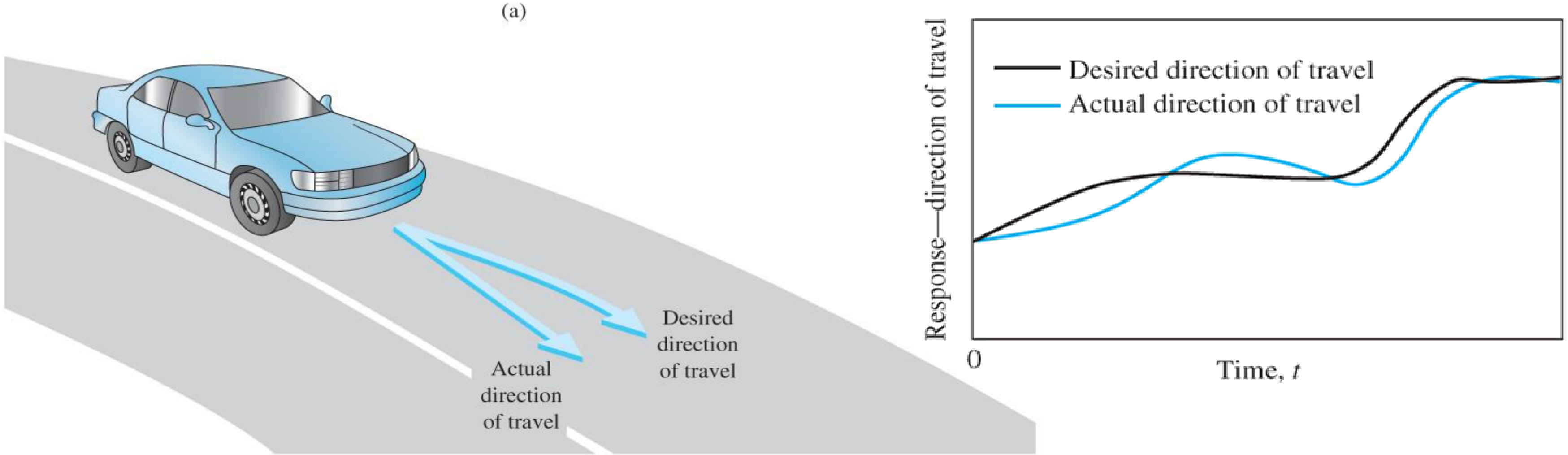


(b)

Closed-loop control



(a)



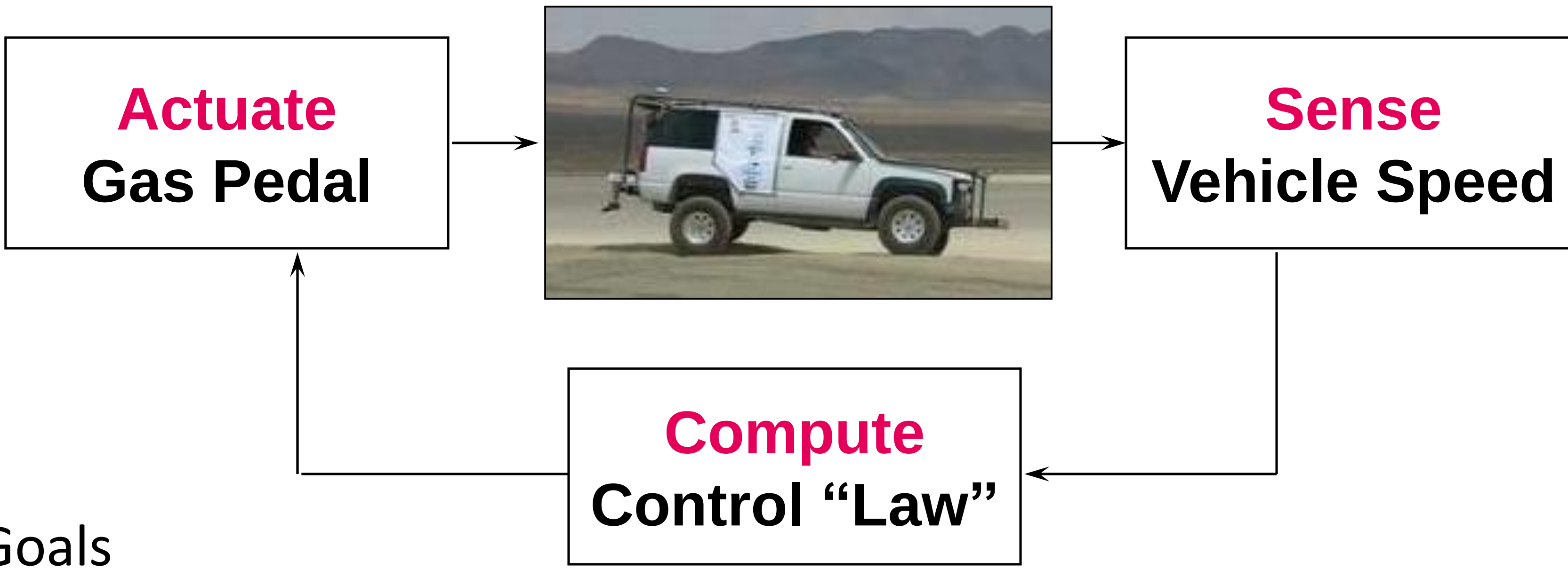
(b)

A person steering an automobile by looking at the auto’s location on the road and making the appropriate adjustments.

Closed-loop control

Control = Sensing + Computation + Actuation

In Feedback "Loop"



- Goals
  - Stability: system maintains desired operating point (hold steady speed)
  - Performance: system responds rapidly to changes (accelerate to 65 mph)
  - Robustness: system tolerates perturbations in dynamics (mass, drag, etc)

Manual control system

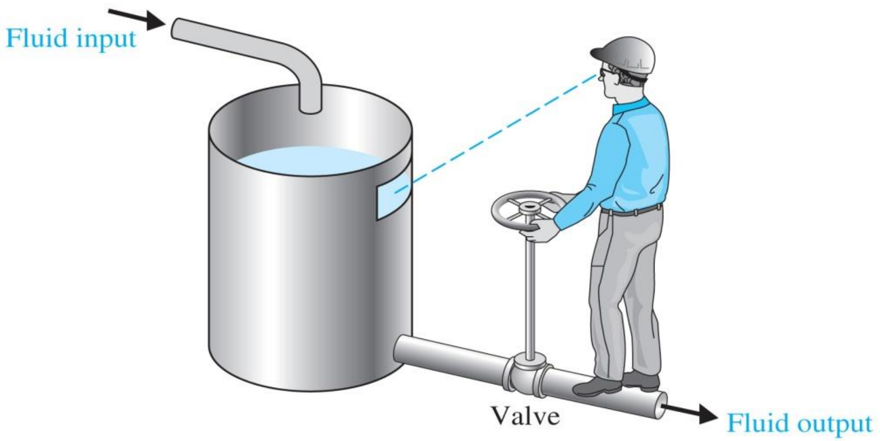


Figure: 01-08

Goal: **Regulate the level of fluid by adjusting the output valve.**

The input is a reference level of fluid and is memorized by operator.
The power amplifier is the operator.
The sensor is visual.
Operator compares the actual level with the desired level and opens or closes the valve (actuator).

The level of fluid in a tank control

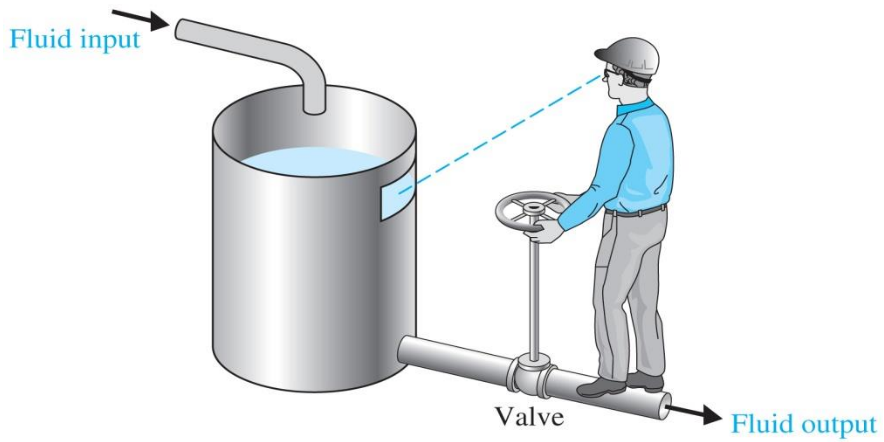
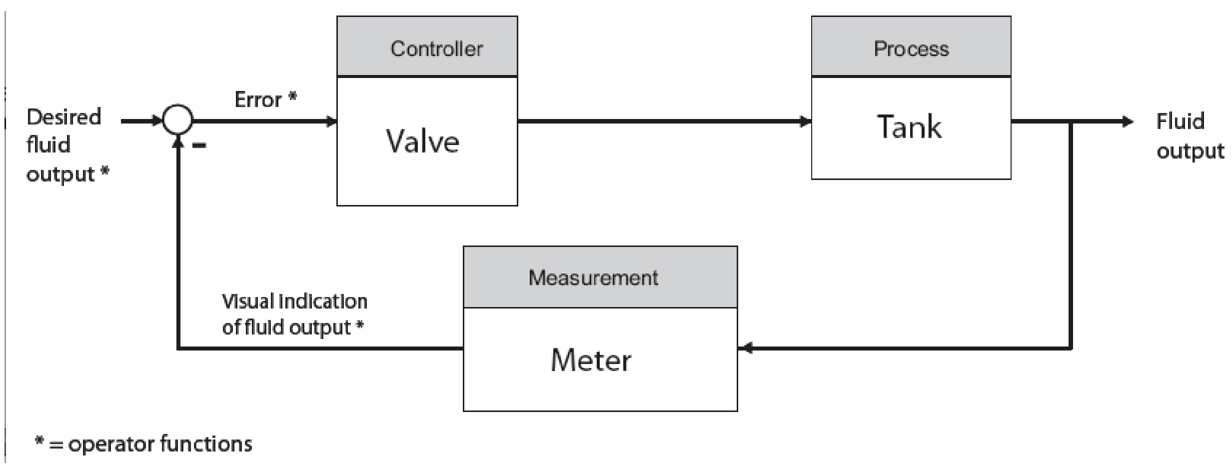


Figure: 01-08



Multivariable control system

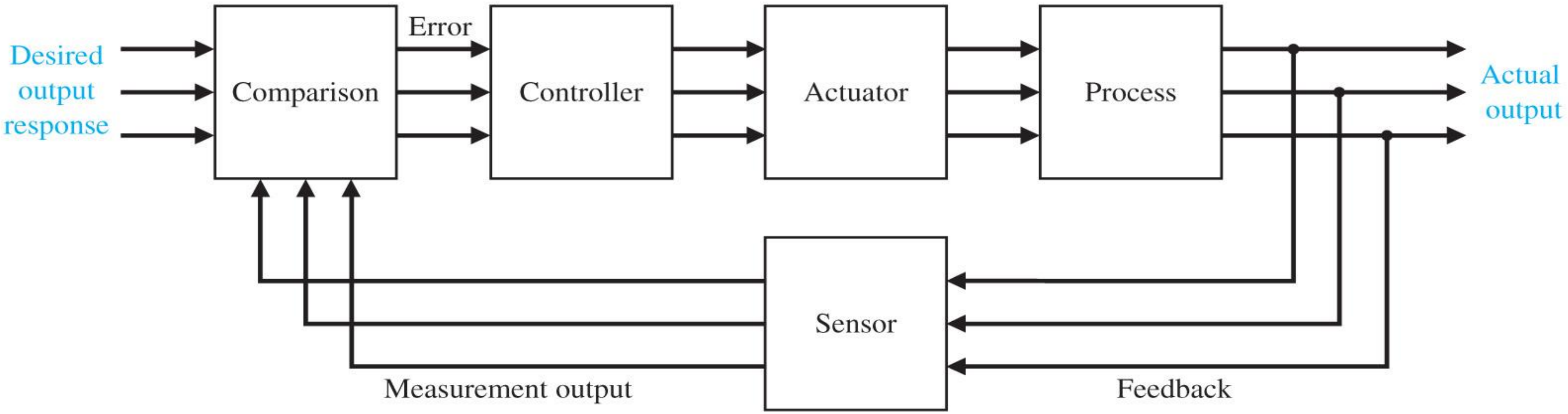
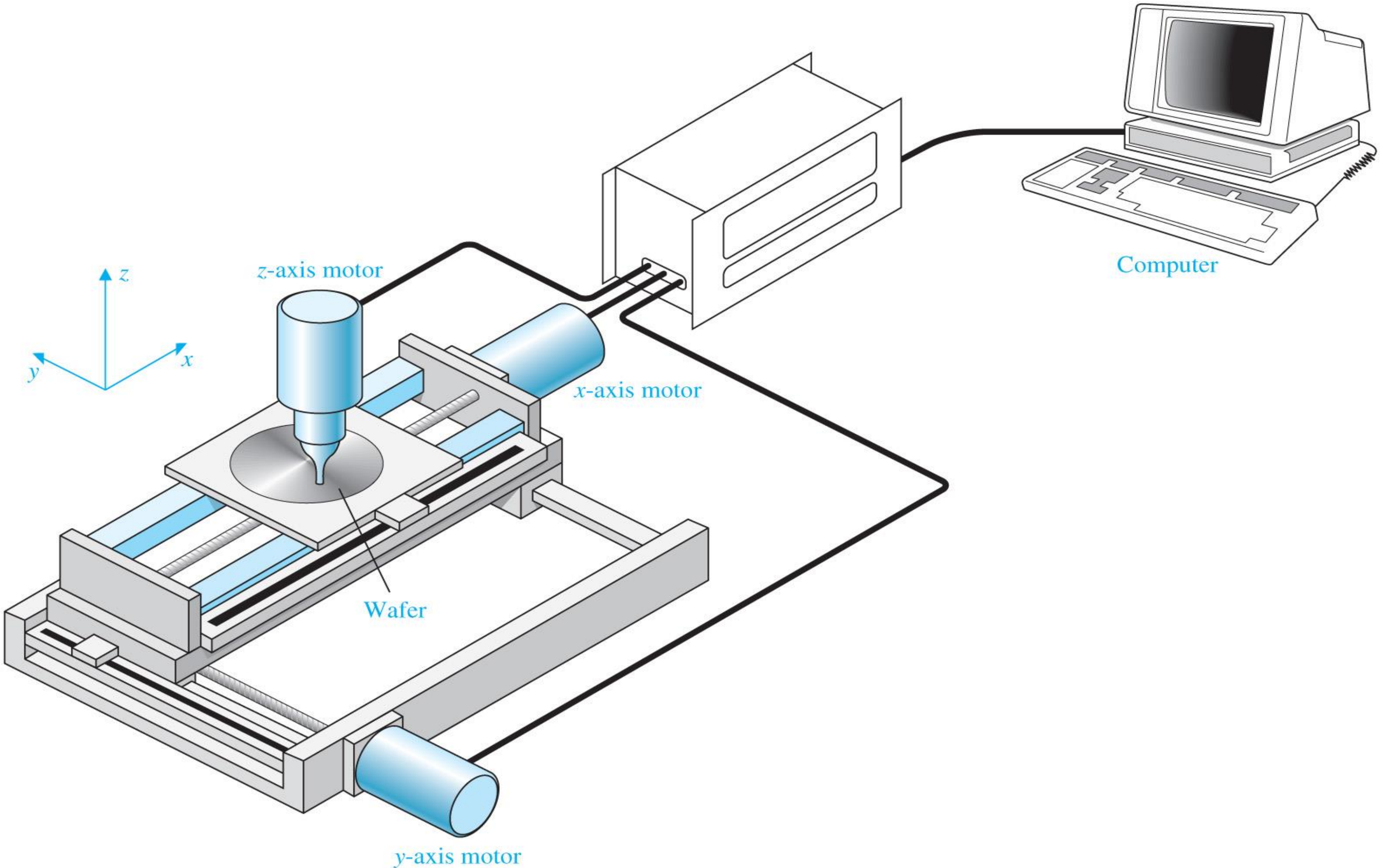


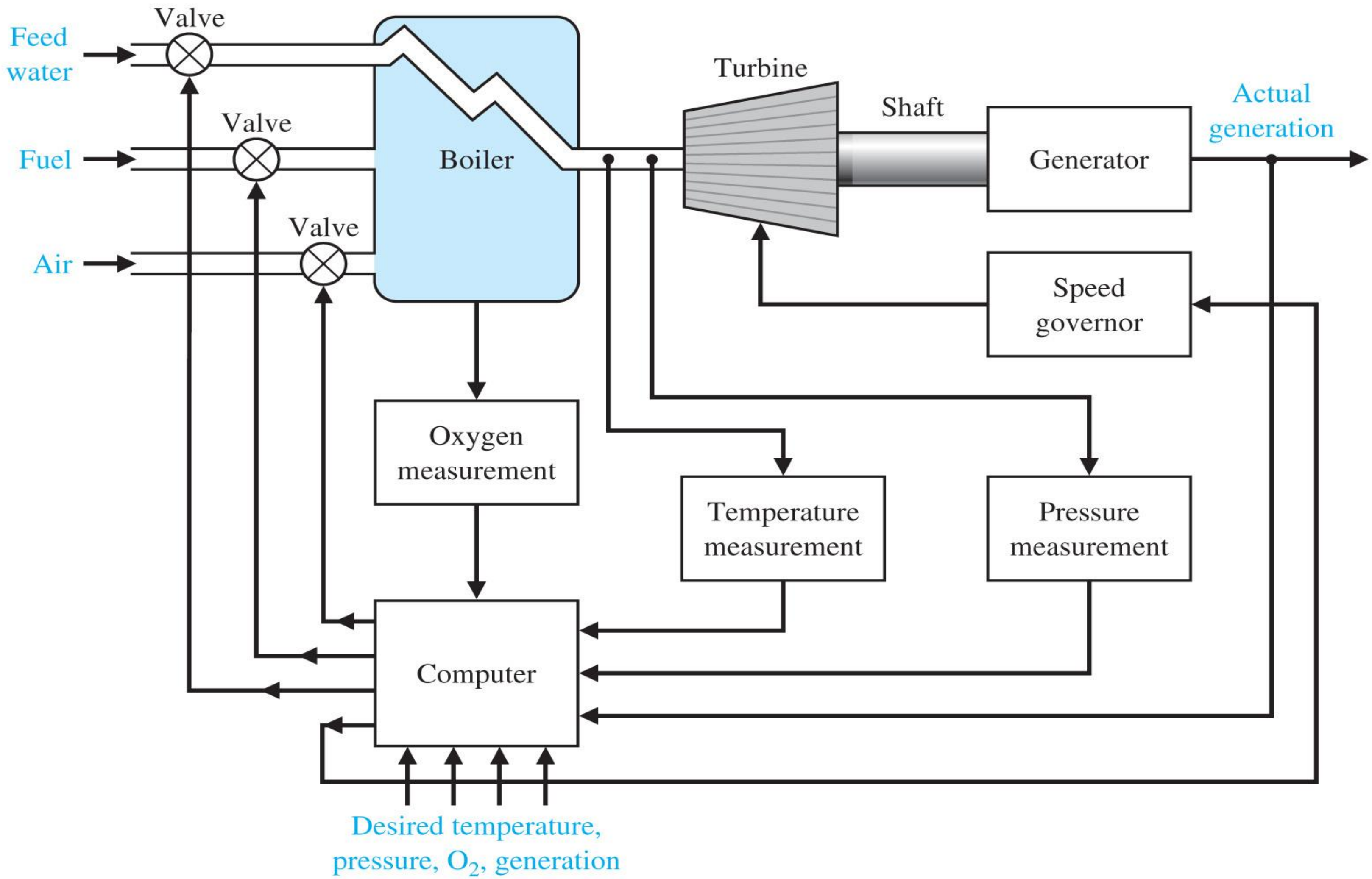
Figure: 01-04

Closed-loop control



A three-axis control system for inspecting individual semiconductor wafers with a highly sensitive camera.

Multivariable control system



Coordinated control system for a boiler-generator

Control system of the national income

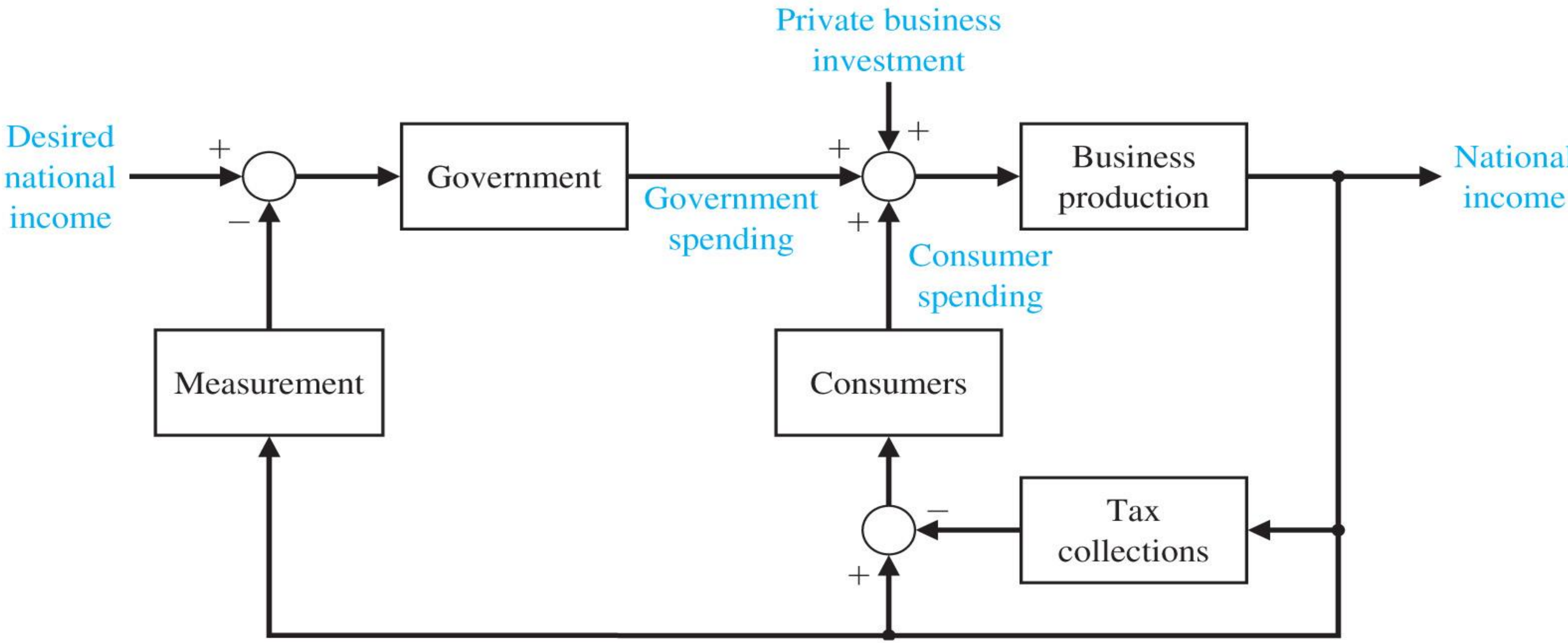


Figure: 01-13

Closed-loop control

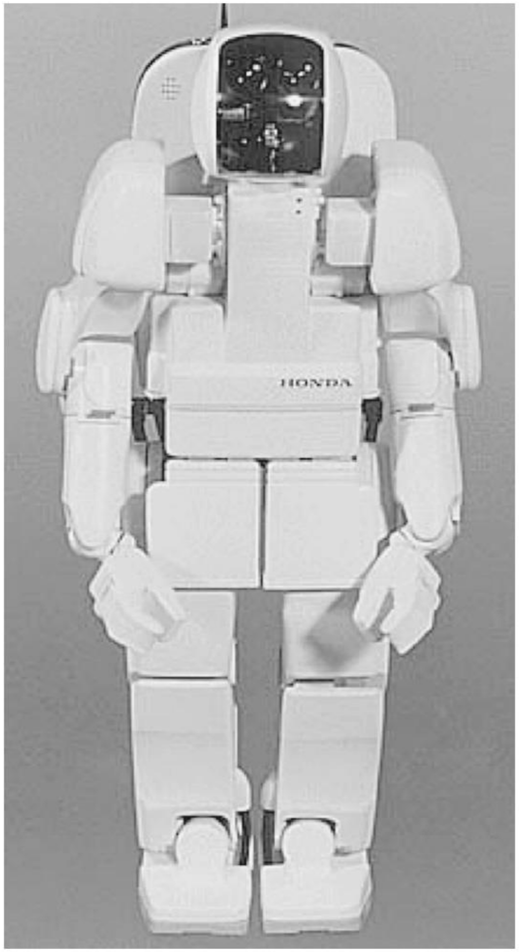


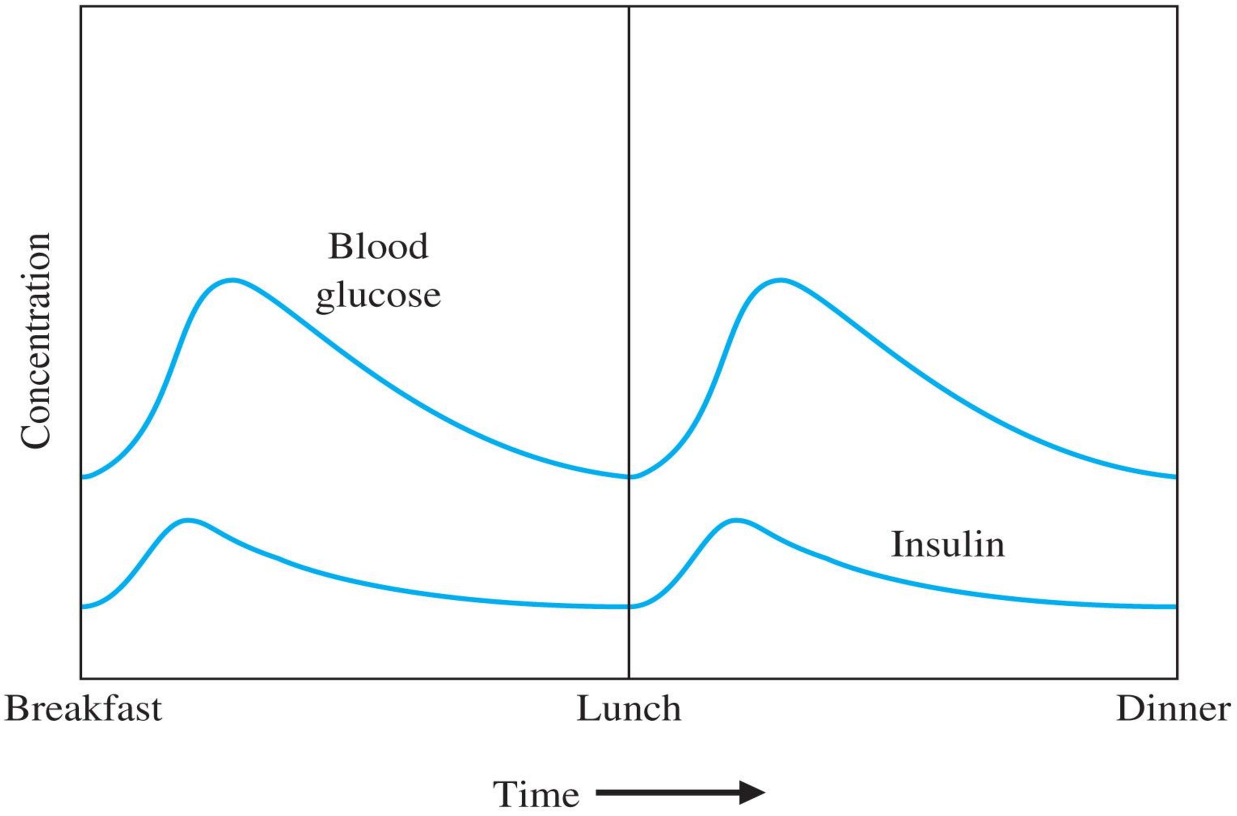
Figure: 01-09

A robot is a computer-controlled machine.

Industrial robotics is a particular field of automation in which the robot is designed to substitute for human labor.

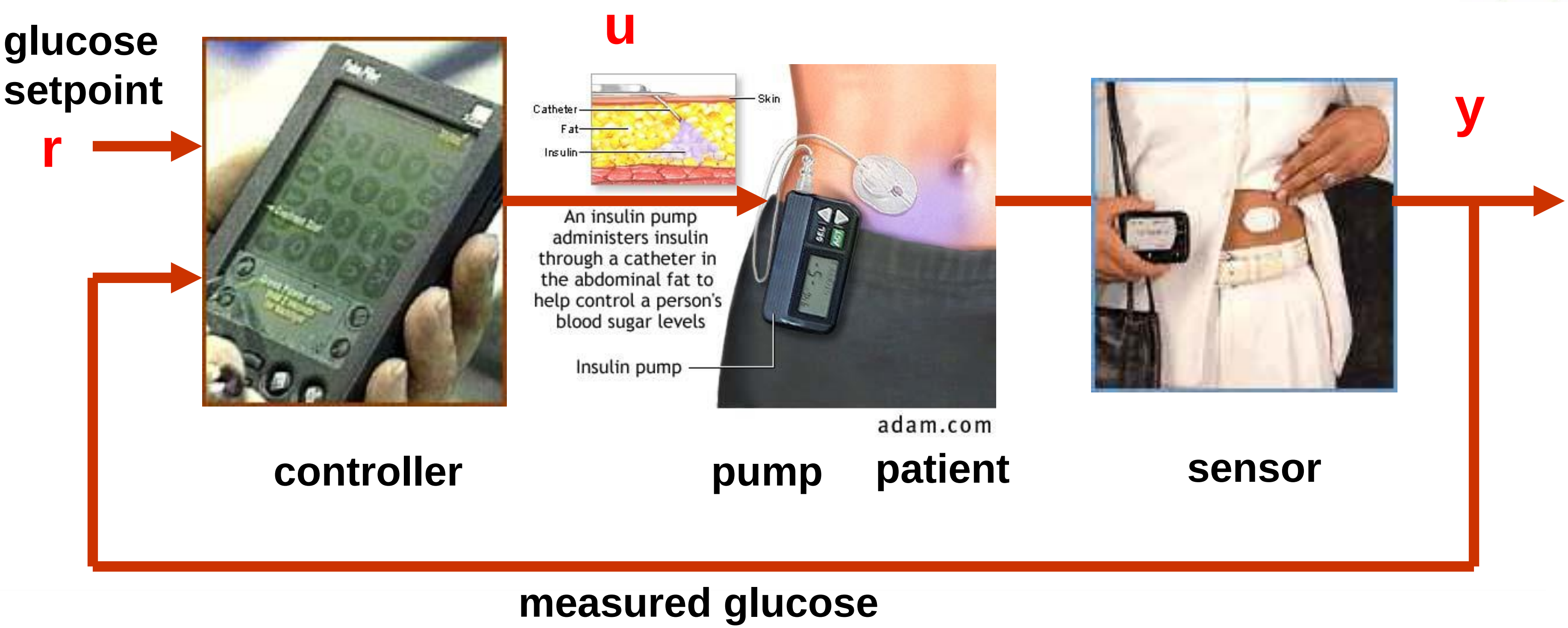
The Honda P3 humanoid robot.

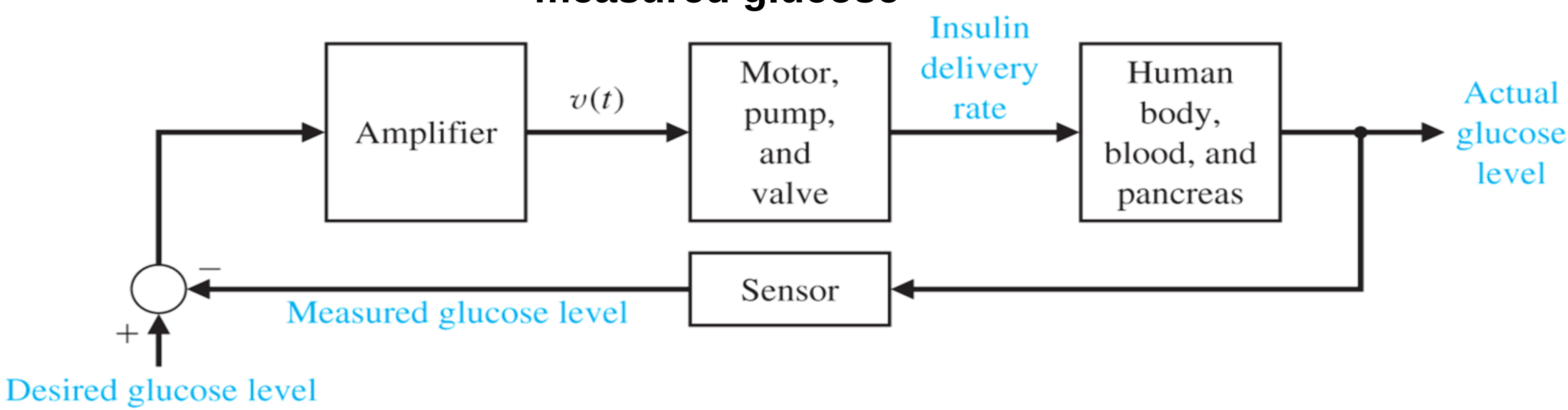
The blood glucose and insulin concentrations for a healthy person



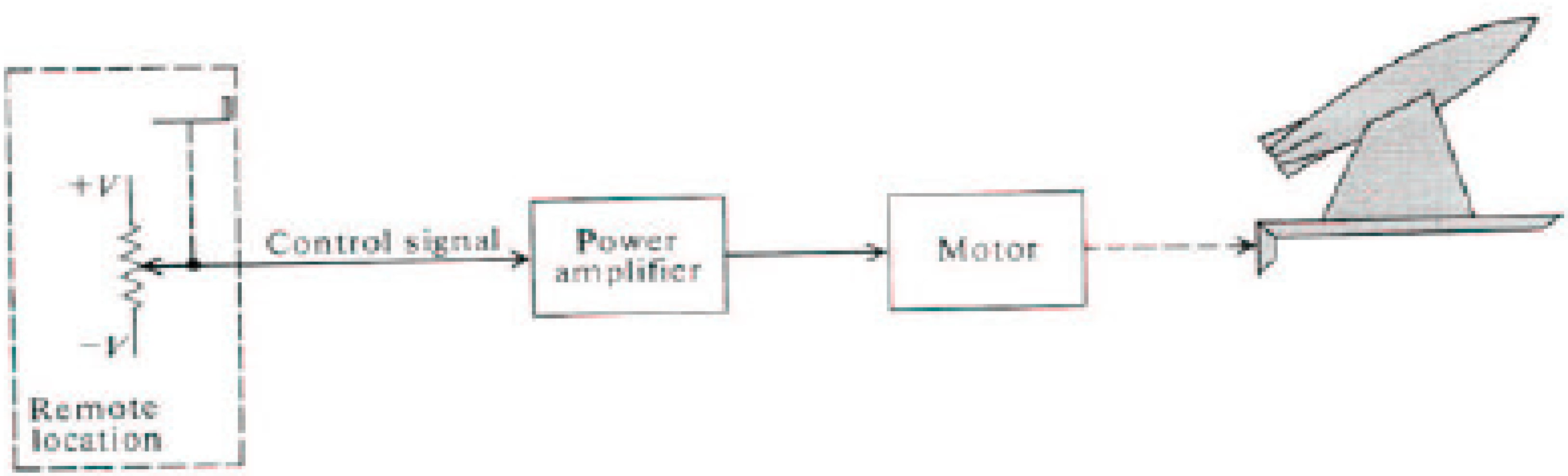
Automatic system can be used to regulate blood pressure, blood sugar level, and heart rate.

Closed-loop Artificial Pancreas



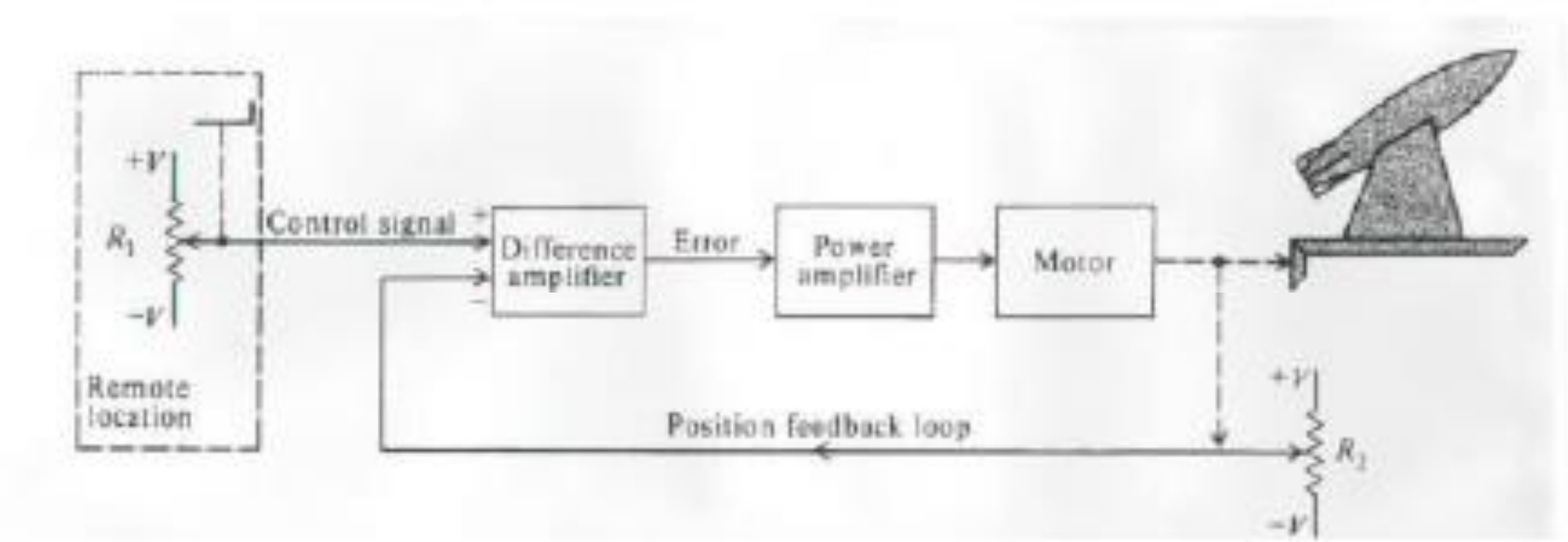


A position open loop control



The input is the desired angular position of the missile launcher, and the control system consists of potentiometer, power amplifier, motor, gearing between the motor and missile launcher, and missile launcher.

A position closed loop control



Should an error exists, it is amplified and applied to a motor drive which adjusts the output-shaft position until it agrees with the input-shaft position, and the error is zero.

Chemical composition control

In a chemical process control system, it is valuable to control the chemical composition of the product. To do so, a measurement of the composition can be obtained by using an infrared stream analyzer, as shown in FigureP1.3.The valve on the additive stream may be controlled.

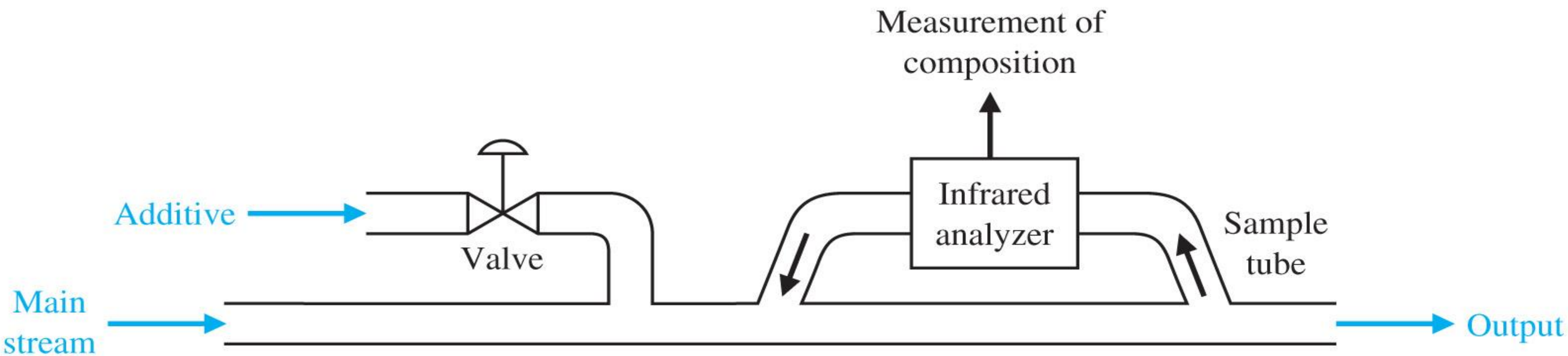
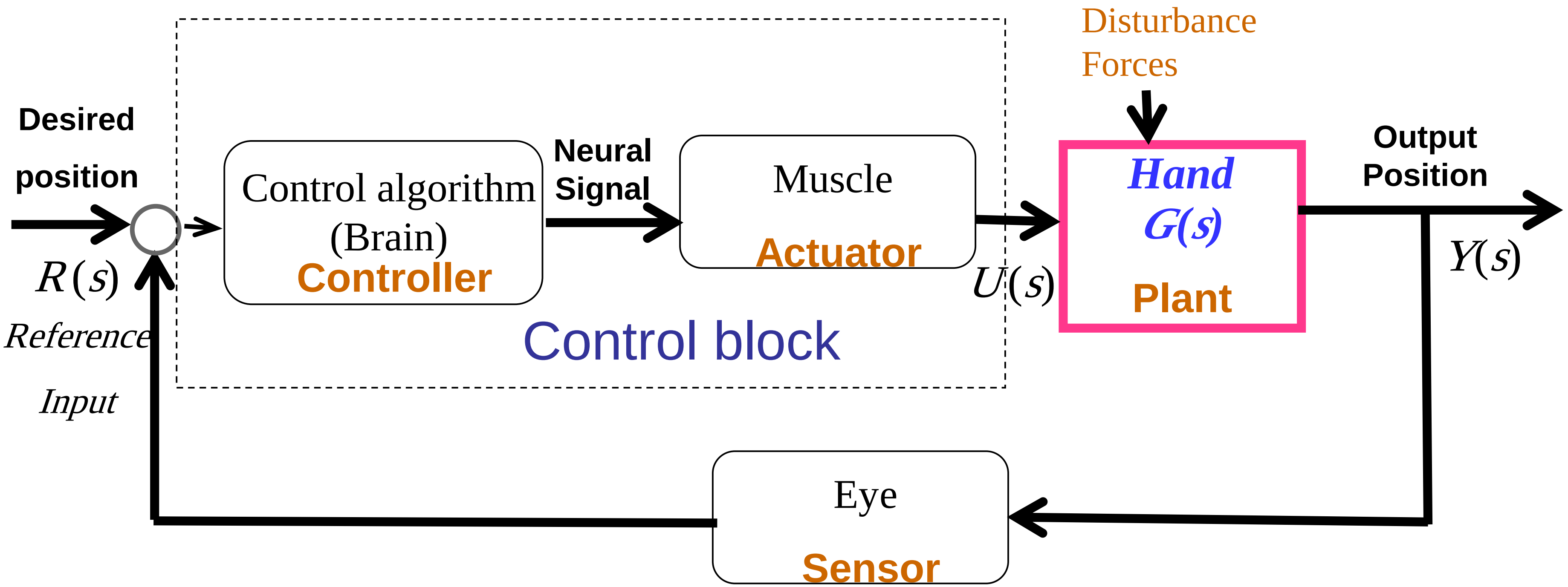


Figure: 01-27-04UNP1.3

Control System of Human Body



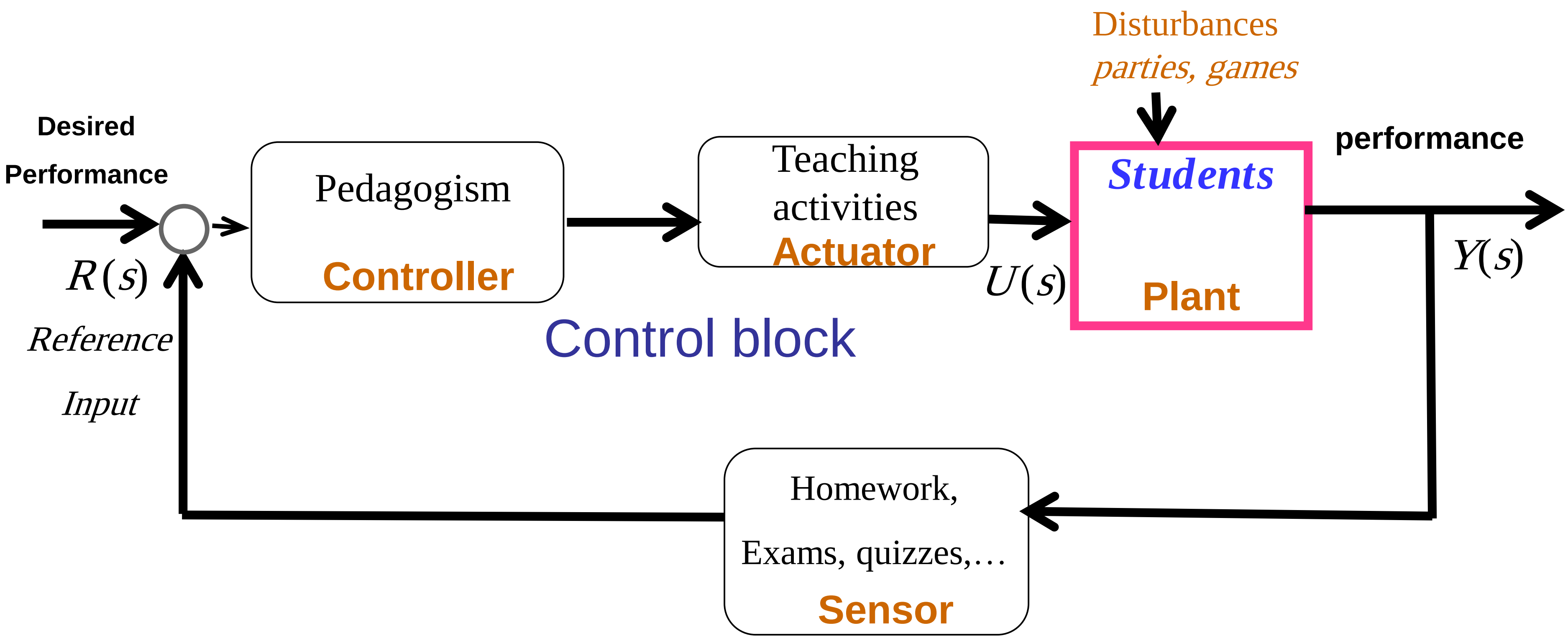
Open loop No Feedback

Closed loop With Feedback

Student-teacher learning process

- **Construct a feedback model of the learning process and identify each block of the system.**

Student-teacher learning process



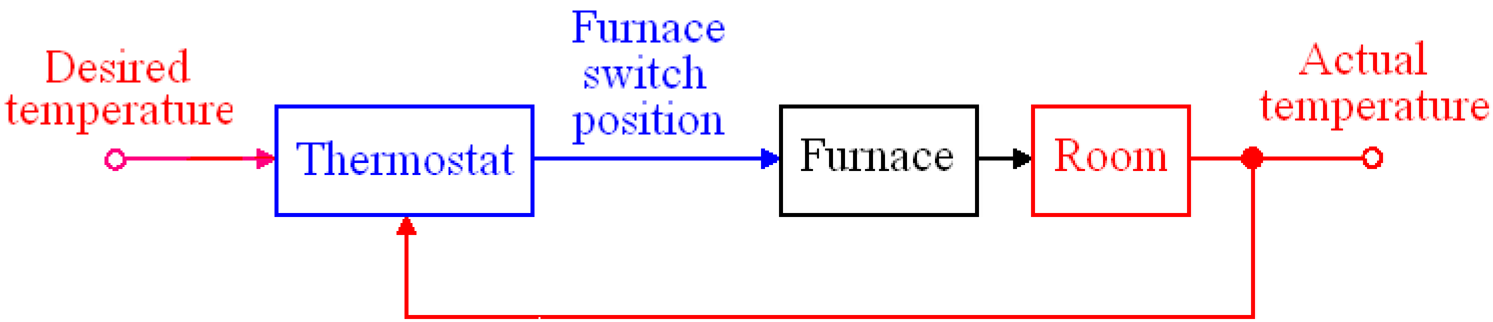
Open loop No Feedback *Blindly teaching ?!*

Closed loop With Feedback

SEE YOU

2:30

Heater



Question: Identify:

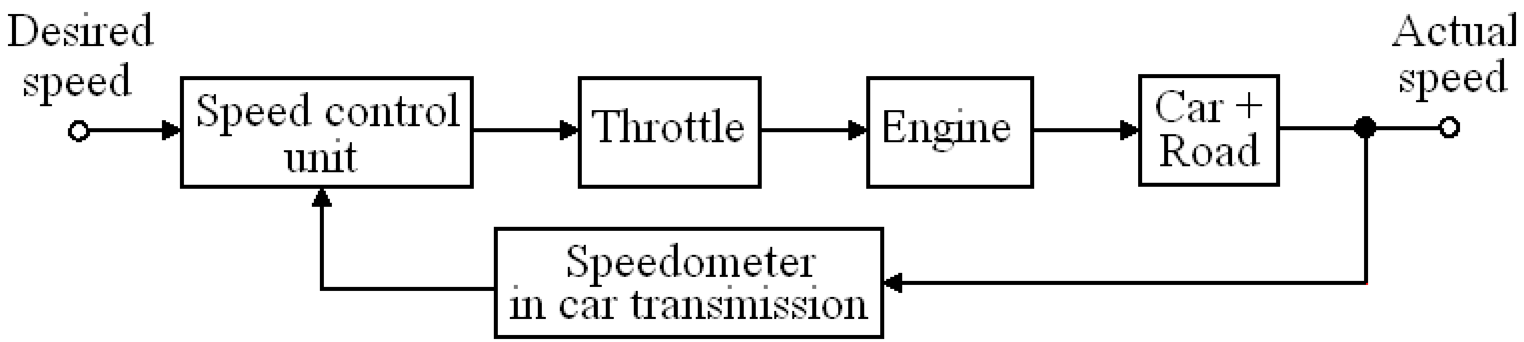
a) the process,

b) the control input variable,

c) the output variable,

d) the controller.

Cruise Control



Question: Identify:

a) the process,

b) the control input variable,

c) the output variable,

d) the controller.

Control System of Fluid Valve

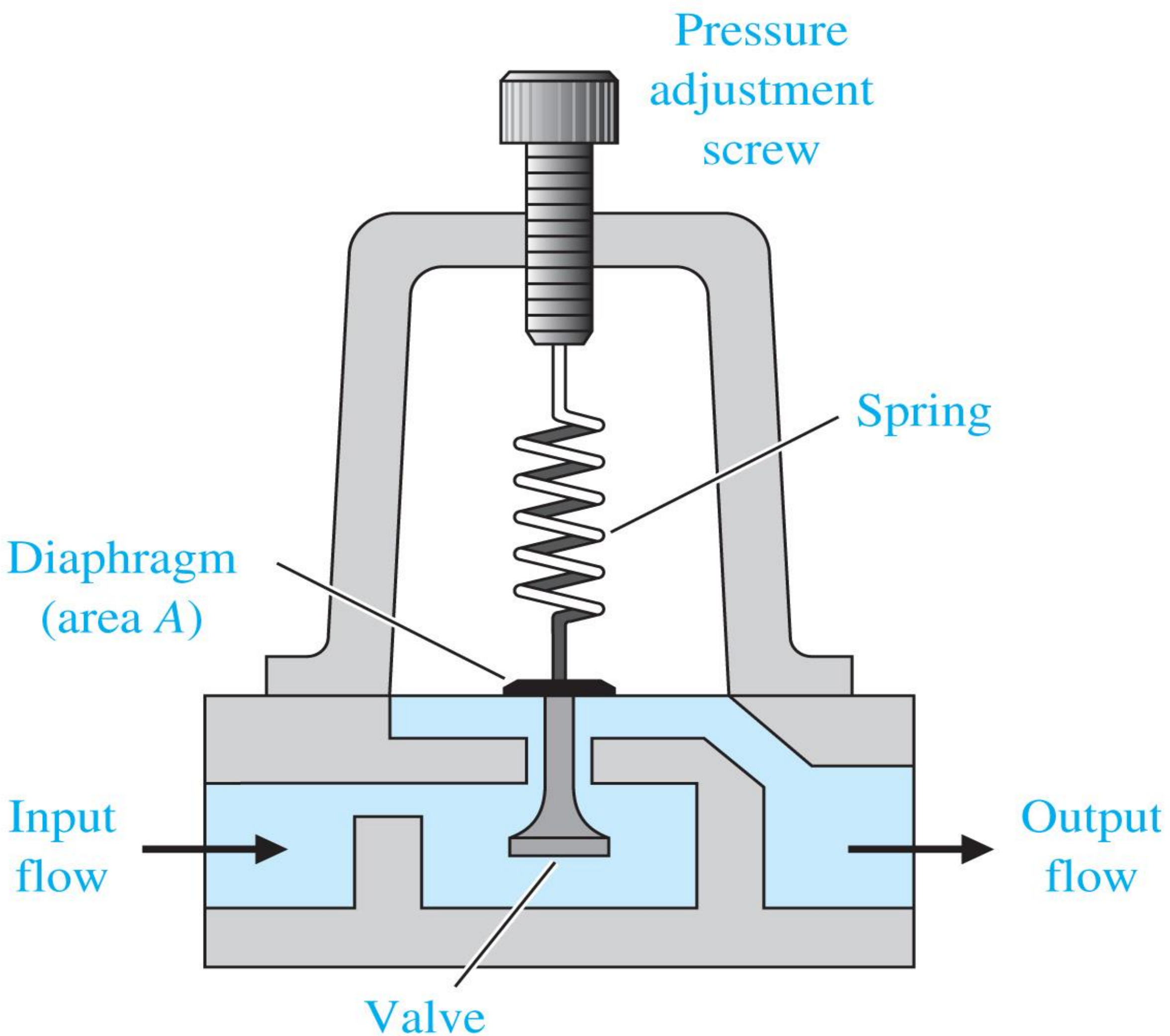
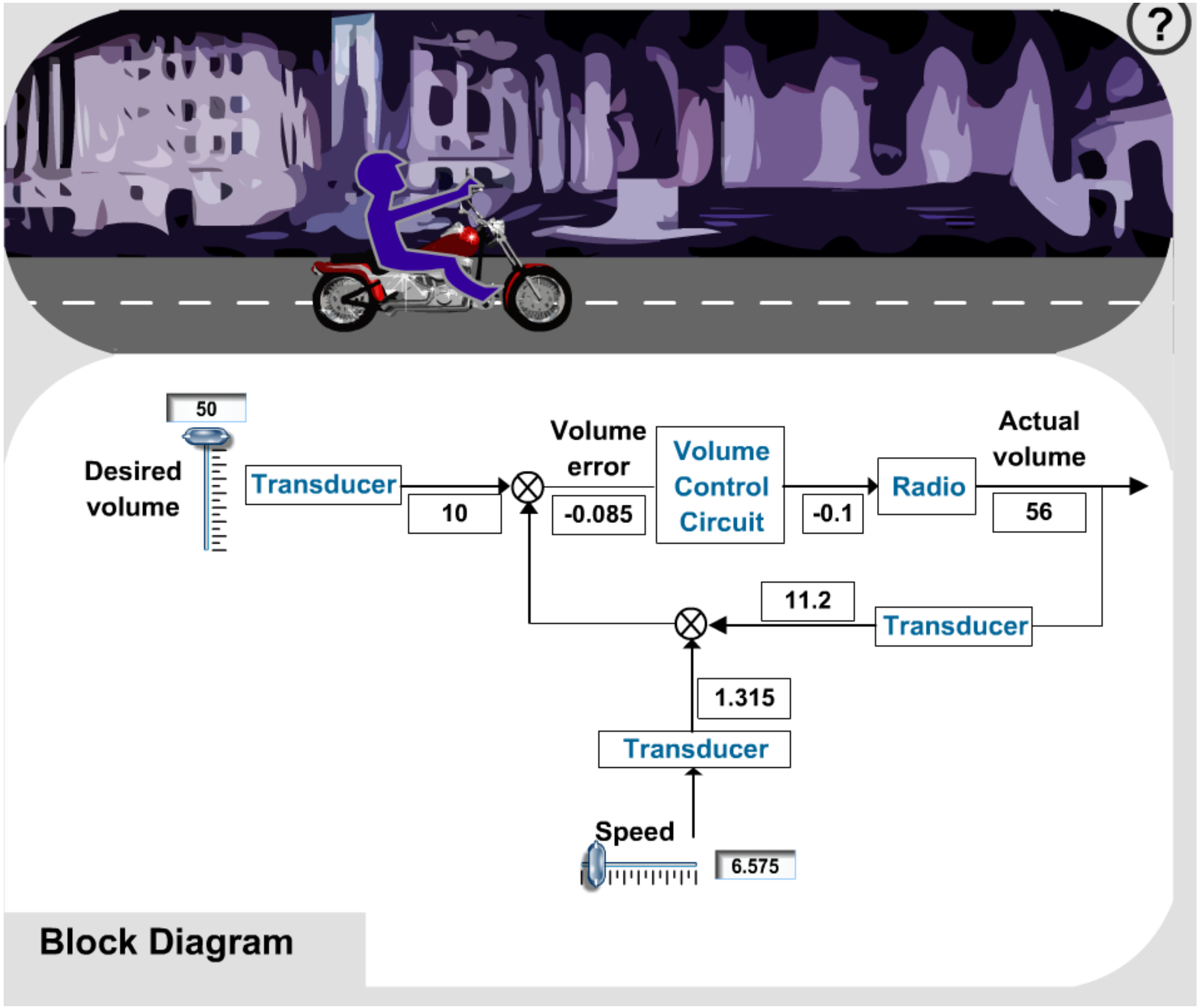


Figure: 01-27-11UNP1.18

Volume Control of Motorcycle

Volume Control of Motorcycle



Blending System

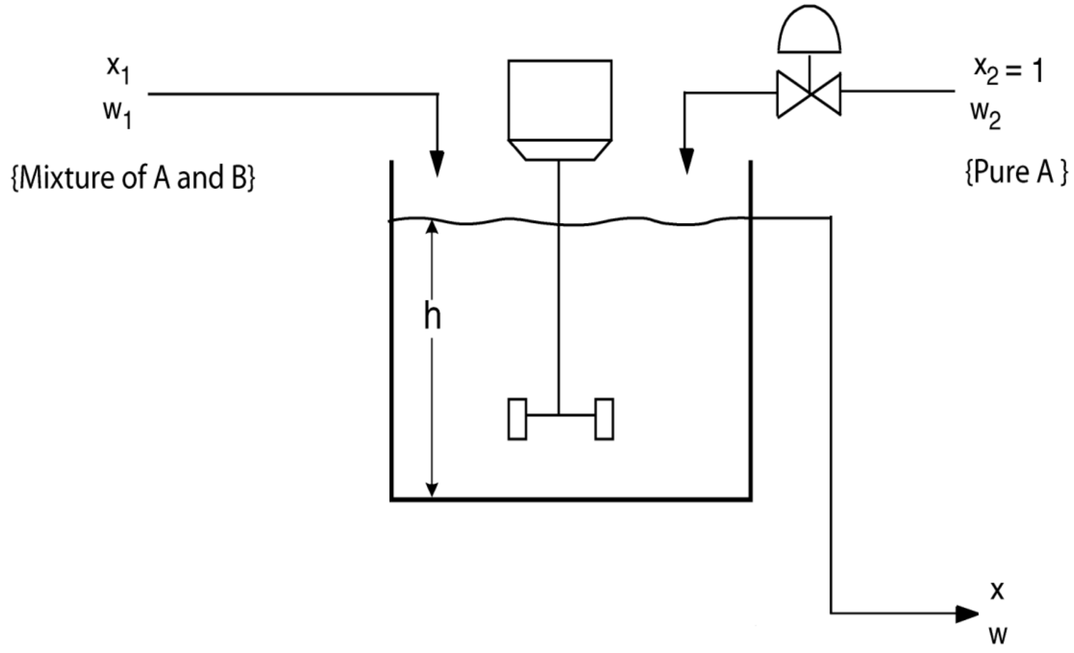


Figure 1.3. Stirred-tank blending system.

Notation:

- ***w_1, w_2* and w are mass flow rates**
- ***x_1, x_2* and *x* are mass fractions of component A**

Blending System

Assumptions:

1. w_1 is constant
2. x_2 = constant = 1 (stream 2 is pure A)
3. Perfect mixing in the tank

Control Objective:

Keep x at a desired value (or "set point") x_{sp}, despite variations in $x_1(t)$. Flow rate w_2 can be adjusted for this purpose.

Terminology:

- Controlled variable (or "output variable"): x
- Manipulated variable (or "input variable"): w_2
- Disturbance variable (or "load variable"): x_1

Blending System

Design Question. **What value of** $\overline{w}_2$ **is required to have** $\overline{x} = x_{SP}$?

Overall balance:

$$0 = \overline{w}_1 + \overline{w}_2 - \overline{w} \qquad (1\text{-}1)$$

Component A balance: $\overline{x} = x_{SP}$

$$\overline{w}_1\overline{x}_1 + \overline{w}_2\overline{x}_2 - \overline{w}\,\overline{x} = 0 \qquad (1\text{-}2)$$

(The overbars denote nominal steady-state design values.)

- **At the design conditions,** $\overline{x} = x_{SP}$ **. Substitute Eq. 1-2, and** $\overline{x}_2 = 1$ **, then solve Eq. 1-2 for** $\overline{w}_2$ **:**

$$\overline{w}_2 = \overline{w}_1 \frac{x_{SP} - \overline{x}_1}{1 - x_{SP}} \qquad (1\text{-}3)$$

Blending System

- **Equation 1-3 is the design equation for the blending system.**
- **If our assumptions are correct, then this value of $\overline{w}_2$ will keep $\overline{x}$ at x_{SP} . But what if conditions change?**

Control Question. Suppose that the inlet concentration x_1 changes with time. How can we ensure that x remains at or near the set point x_{SP}?

As a specific example, if $x_1 > \overline{x}_1$ and $w_2 = \overline{w}_2$, then $x > x_{SP}$.

Some Possible Control Strategies:

Method 1. ***Measure x and adjust w_2.***

- **Intuitively, if *x* is too high, we should reduce w_2;**

Blending System

- **Manual control vs. automatic control**
- **Proportional feedback control law,**

$$w_2(t) = \bar{w}_2 + K_c\left[x_{SP} - x(t)\right] \qquad (1\text{-}4)$$

1. **where K_c is called the controller gain.**
2. **$w_2(t)$ and $x(t)$ denote variables that change with time t.**
3. **The change in the flow rate, $w_2(t) - \bar{w}_2$, is proportional to the deviation from the set point, $x_{SP} - x(t)$.**

Blending System

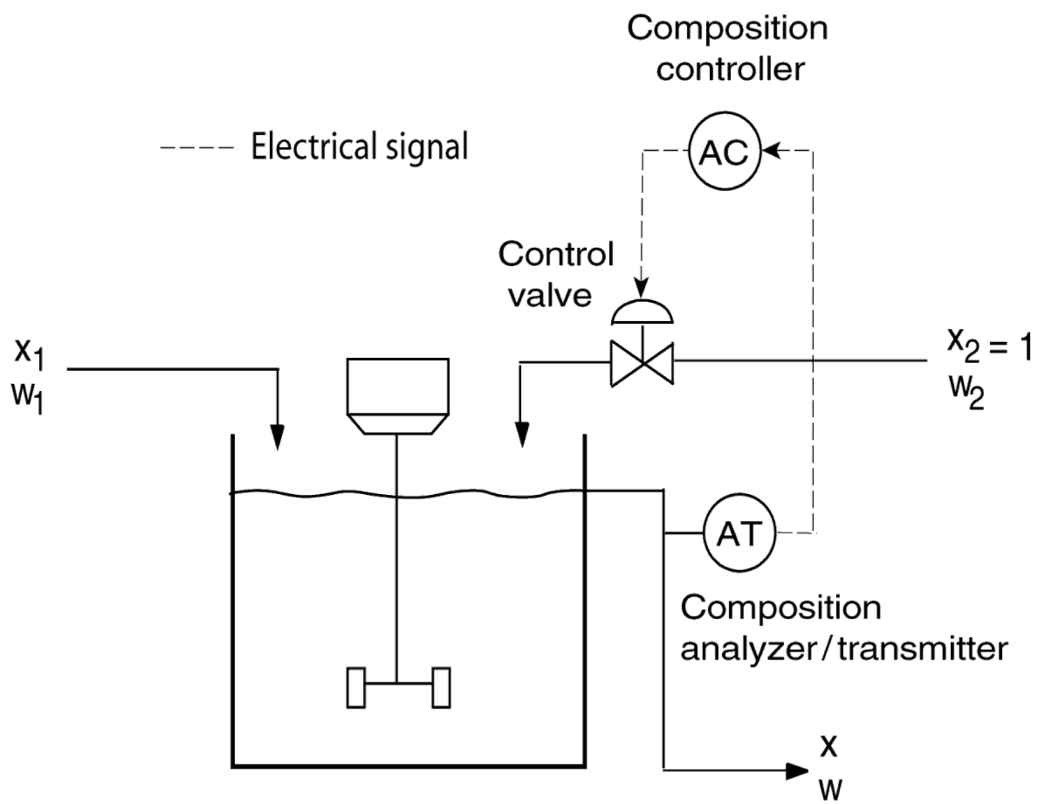


Figure 1.4. Blending system and Control Method 1.

Method 2. *Measure x_1 and adjust w_2.*

- Thus, if x_1 is greater than $\bar{x}_1$, we would decrease w_2 so that $w_2 < \bar{w}_2$;

- One approach: Consider Eq. (1-3) and replace $\bar{x}_1$ and $\bar{w}_2$ with $x_1(t)$ and $w_2(t)$ to get a control law:

$$w_2(t) = \bar{w}_1 \frac{x_{SP} - x_1(t)}{1 - x_{SP}} \qquad (1\text{-}5)$$

Blending System

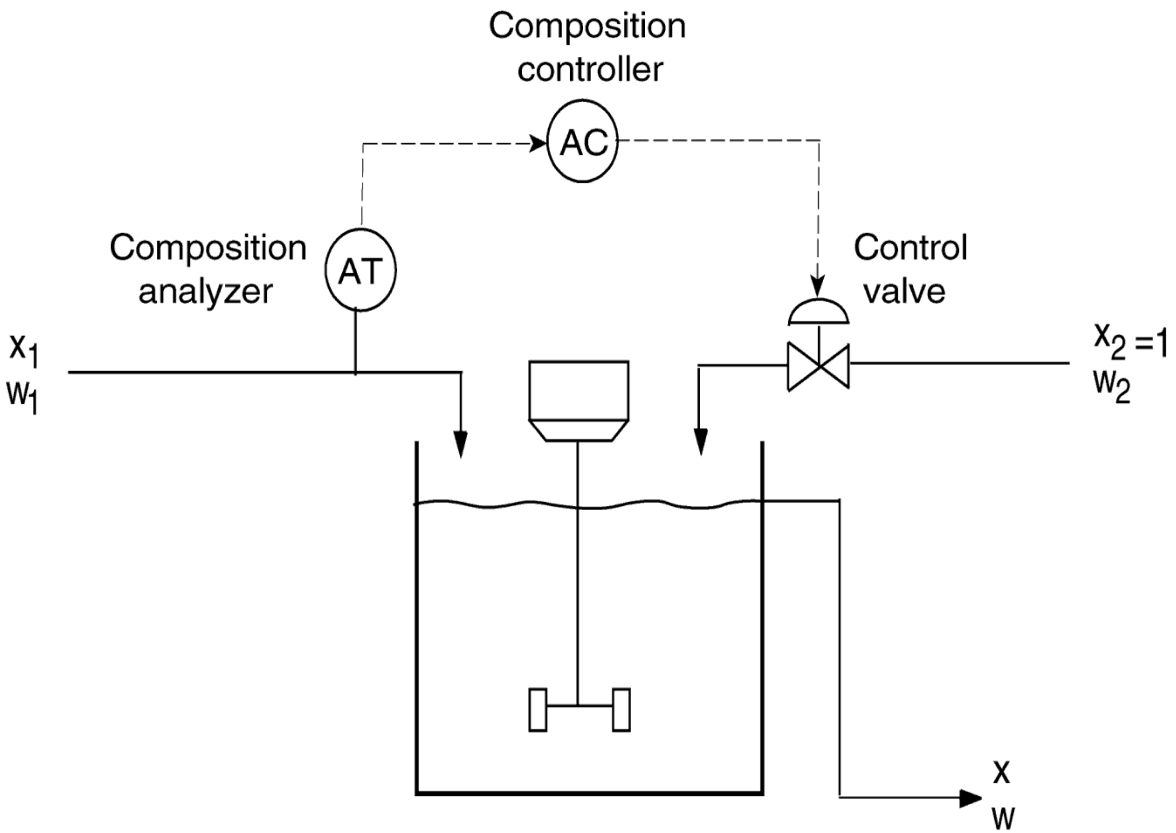


Figure 1.5. Blending system and Control Method 2.

Blending System

- Because Eq. (1-3) applies only at steady state, it is not clear how effective the control law in (1-5) will be for transient conditions.

Method 3. ***Measure x_1 and x, adjust w_2.***

- This approach is a combination of Methods 1 and 2.

Method 4. ***Use a larger tank.***

- If a larger tank is used, fluctuations in x_1 will tend to be damped out due to the larger capacitance of the tank contents.
- However, a larger tank means an increased capital cost.

Classification of Control Strategies

Table. 1.1 Control Strategies for the Blending System

Method	*Measured Variable*	*Manipulated Variable*	*Category*
1	x	w_2	*FB*[a]
2	x_1	w_2	*FF*
3	x_1 and x	w_2	*FF/FB*
4	-	-	*Design change*

Feedback Control:

- **Distinguishing feature: measure the controlled variable**