# MEC 411: Control System Design and Analysis

## (Fall 2023)

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# Ch1: Introduction to Control Systems

Contents:

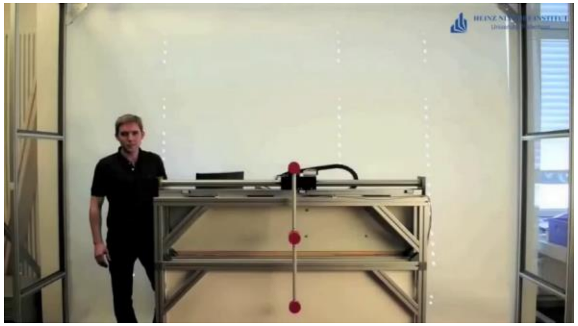
# Introduction

# Manual & Automatic Control

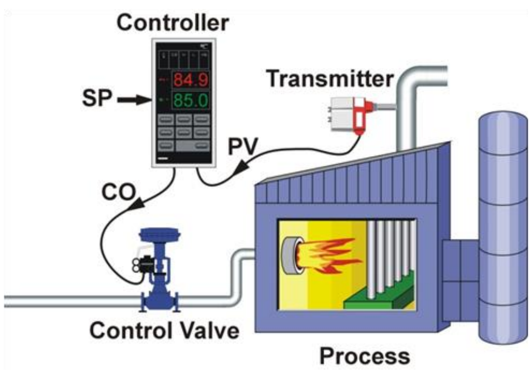
- A system that involve a person controlling a machine is called **Manual Control** (e.g., driving an automobile)

- A system that involves machines only is called **Automatic Control**.

**Automatic Control** is essential in any field of engineering and science like space-vehicle systems, robotic systems, modern manufacturing systems, and any industrial operations involving control of temperature, pressure, humidity, flow, etc.

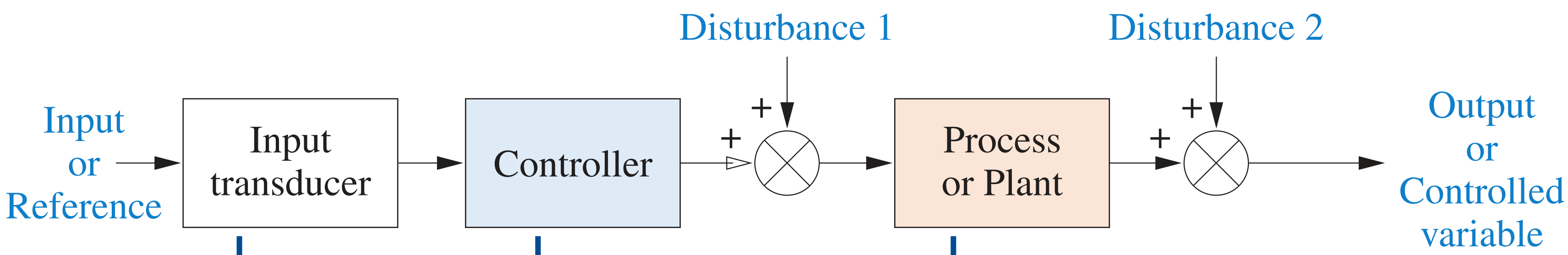


Inverted Pendulum



# Block Diagram

A **Block Diagram** is an intuitive/graphical way of representing a system. It shows us how the systems are <u>interconnected</u> and how the signal flows between them.

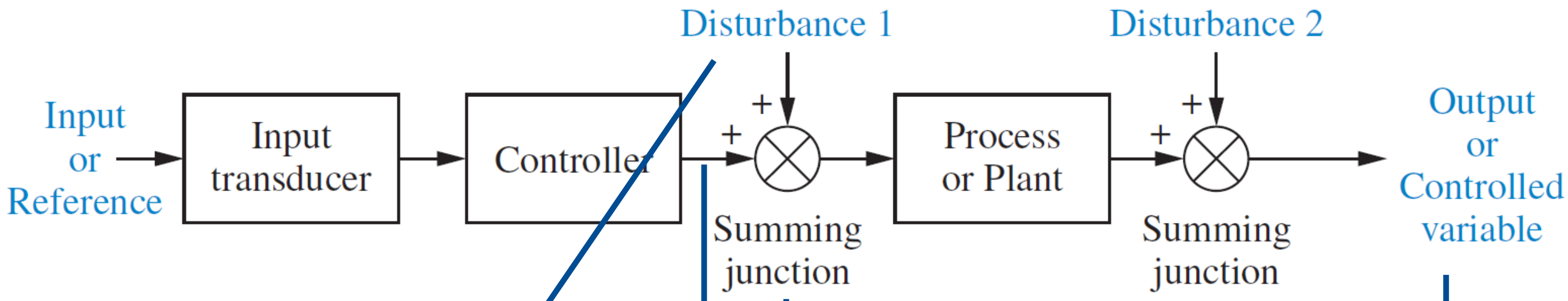



**Input Transducer** converts the form of the input to that used by the controller.

**Plant** is any "physical object" to be controlled (e.g., a mechanical device, a heating furnace, a spacecraft). **Process** is any "operation" to be controlled (e.g., chemical, economic, and biological processes).

**Controller** can be a software or a hardware (electrical e.g., using op-amps, or mechanical e.g., centrifugal governor).

# Block Diagram




**Disturbance** is a signal that tends to adversely affect the system performance.

**Control Effort Signal**

**Controlled Variable** is the quantity or condition that is measured and controlled and is normally the output of the system.

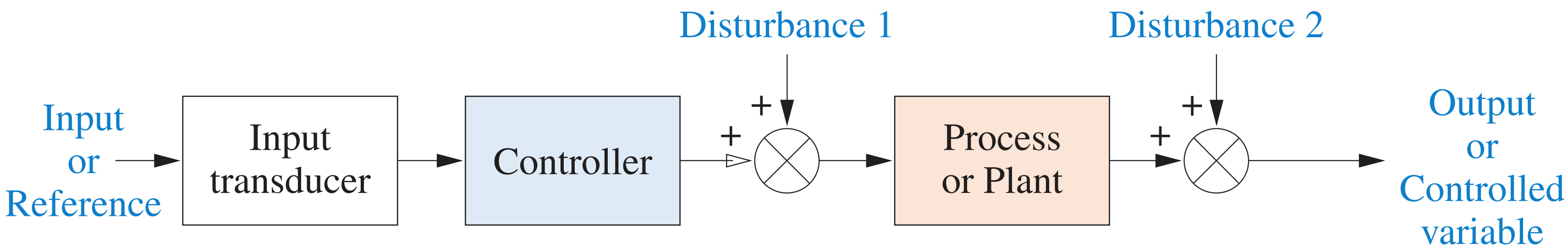
**Summing Junction** is algebraic sum of input signals using associated signs.

# Control Systems Configurations

# Open-Loop Control System

Two major configurations of control systems: **Open-Loop** and **Closed-Loop**.

**Open-Loop Control System** is the system in which the output is not fed back for comparison with the reference input. Hence, the output has no effect on the control effort.

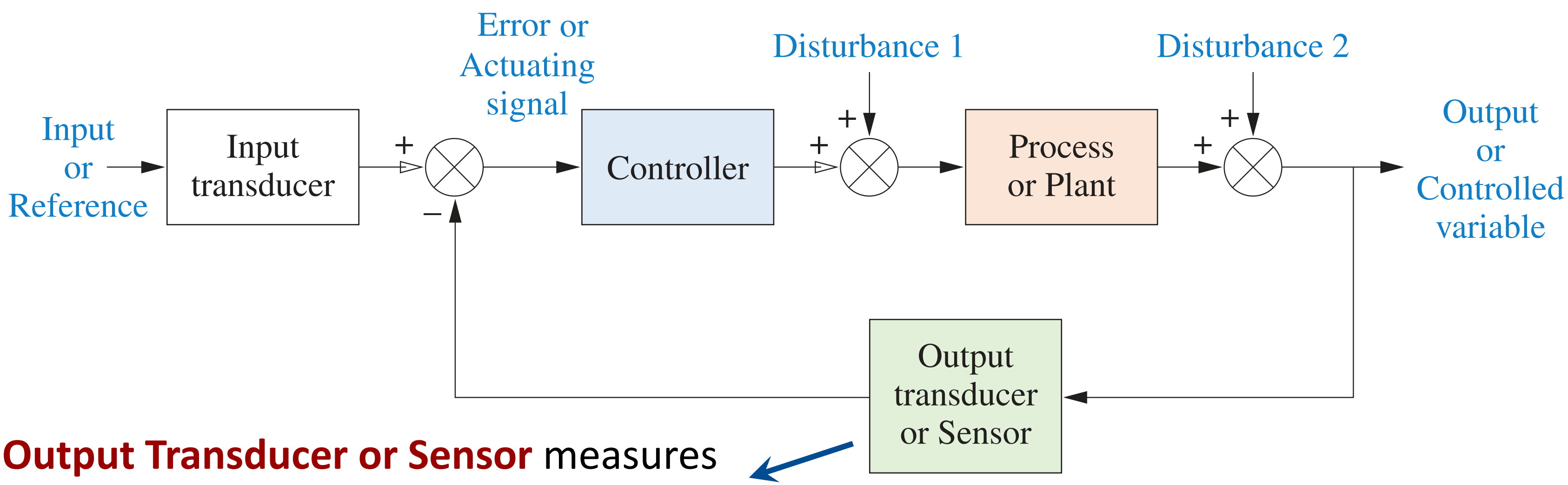



[*Ex. 1*] **Washing Machine**: Soaking, washing, and rinsing operate on a time basis and the machine does not measure the output signal, i.e., cleanliness of the clothes.

[*Ex. 2*] **Toaster**: Heating operates on a time basis and the toaster does not measure the output signal, i.e., the color of the toast.

# Closed-Loop Control System

**Closed-Loop or Feedback Control System** is the system in which the output is measured and fed back, and the difference between the system output and reference input (i.e, error) is used as a means of control. Hence, the output has effect on the control effort.



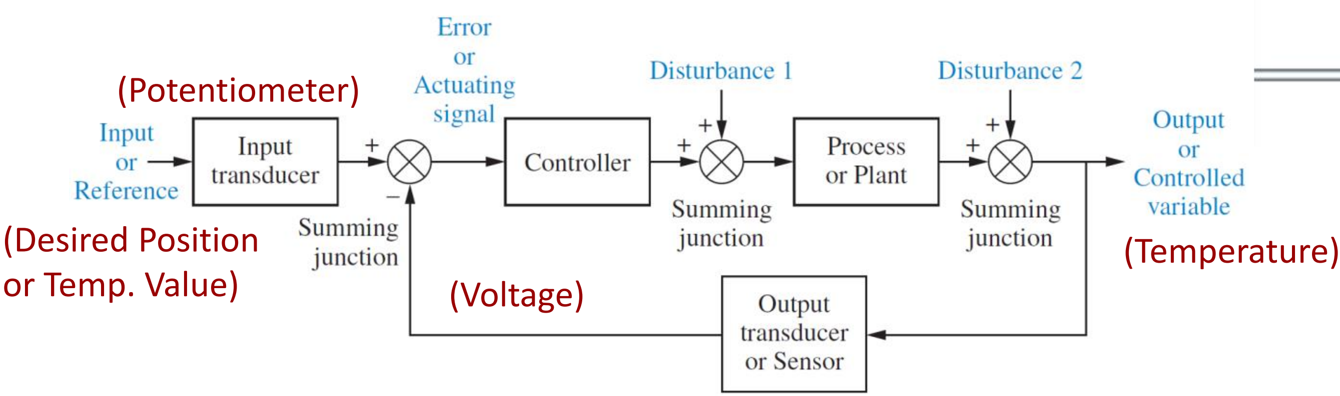

**Output Transducer or Sensor** measures the output response and converts it into the form used by the controller.

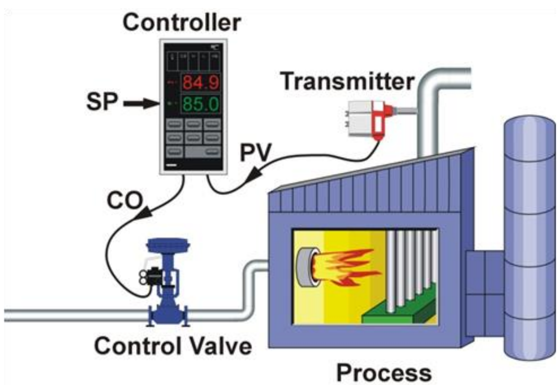
- The feedback can drive the system toward the desired performance in the presence of unpredictable disturbances.

# Examples of Closed-Loop Control Systems

### 1. Temperature Control System of an Electric Furnace:

Assume that a controller uses electrical signals to operate valves of a temperature control system. The input position can be converted to a voltage by a potentiometer, a variable resistor, and the output temperature can be converted to a voltage by a thermistor, a device whose electrical resistance changes with temperature.

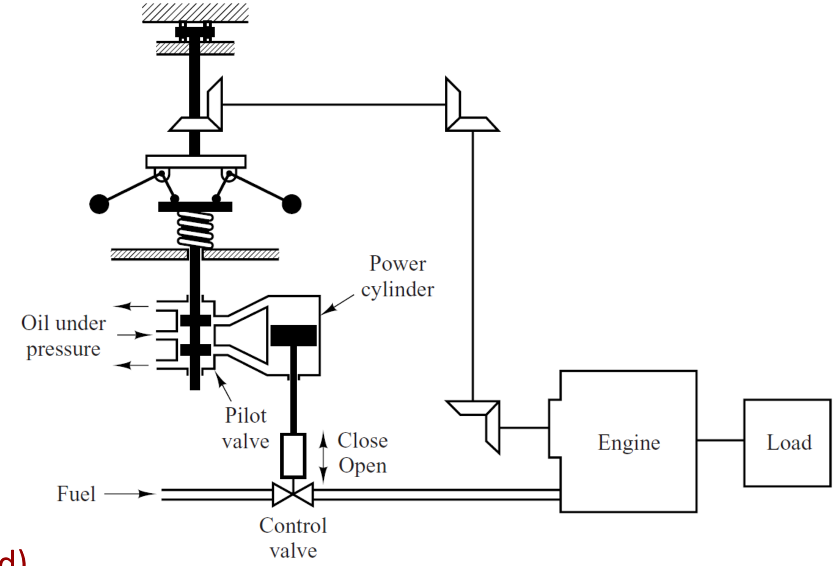


# Examples of Closed-Loop Control Systems

## 2. Speed Control System (James Watt’s Centrifugal Governor):

The amount of fuel admitted to the engine is adjusted according to the difference between the desired and the actual engine speeds by using the speed governor.

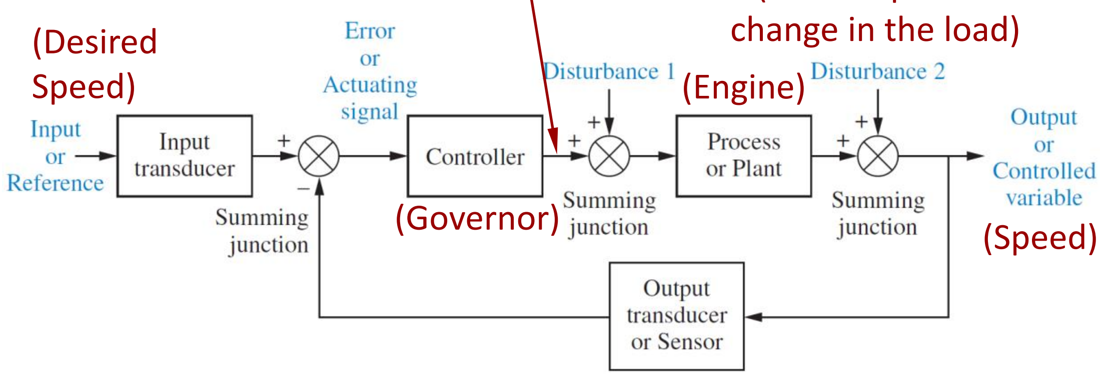



(Position/status of control valve controlling the amount of fuel)

(An unexpected change in the load)

(Desired Speed)

(Engine)




(Governor)

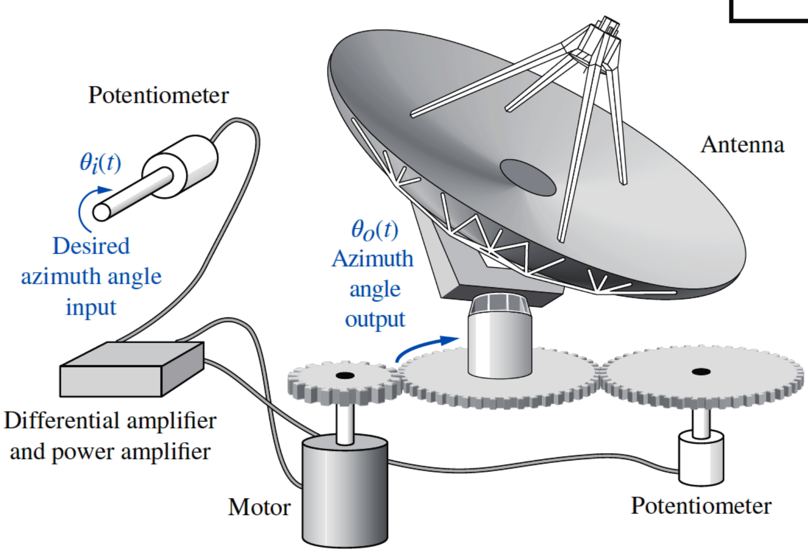
(Speed)

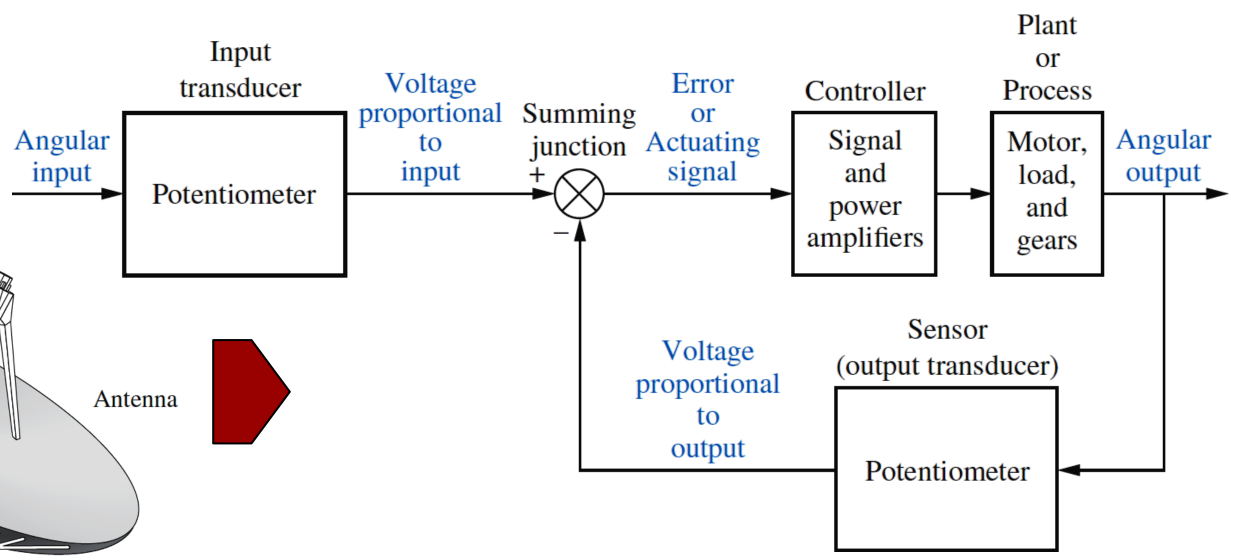

(Governor)

# Examples of Closed-Loop Control Systems

## 3. Position Control System of an Antenna:

**Purpose** : To have the angle output, $\theta_o(t)$, follow the input angle of the potentiometer, $\theta_i(t)$.



# Closed-Loop vs Open-Loop Control Systems

**Open-Loop**:

- The accuracy of the system depends on calibration. Thus, it performs better when the relationship between the input and output is known.
- It is convenient when measuring the output is hard or expensive.
- In the presence of disturbances, the system will not perform the desired task.
- Its construction and maintenance is simple, easy, and inexpensive.
- Its stability is not a major problem.

**Closed-Loop**:

- It has the advantage of greater accuracy.
- It is relatively insensitive to external disturbances and internal variations in system parameters.
- It is more complex and expensive than open-loop system.
- Its stability is a major problem because the controller may cause oscillation in the output value.

❖ The control systems engineer must consider the **trade-off** between the simplicity and low cost of an open-loop system and the accuracy and higher cost of a closed-loop system.

# Objectives of Control Systems

# Control Systems Objectives

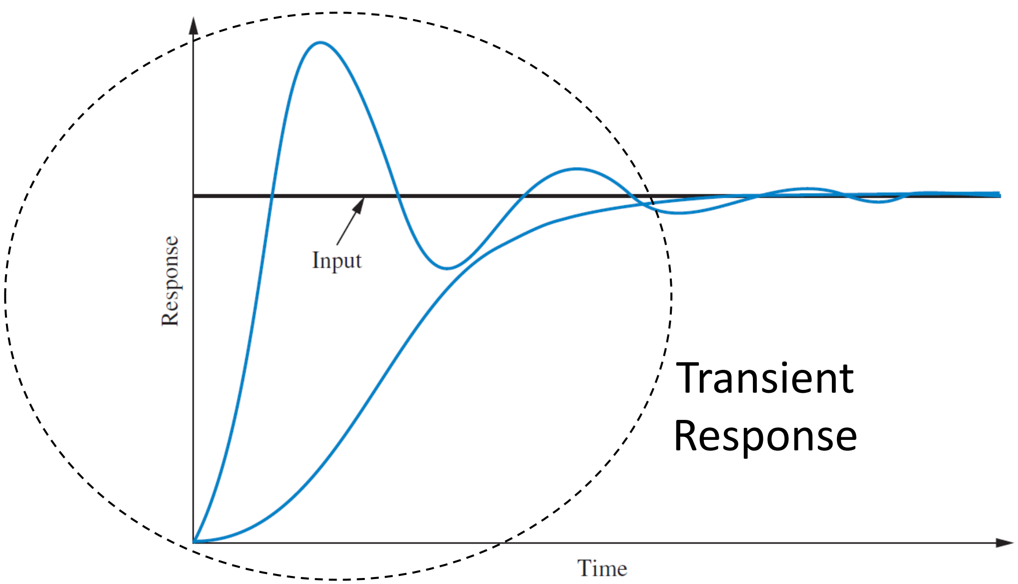
Major objectives of **Analysis** and **Design** of control systems are:

(for determining a system's performance)

(for creating or changing a system's performance)

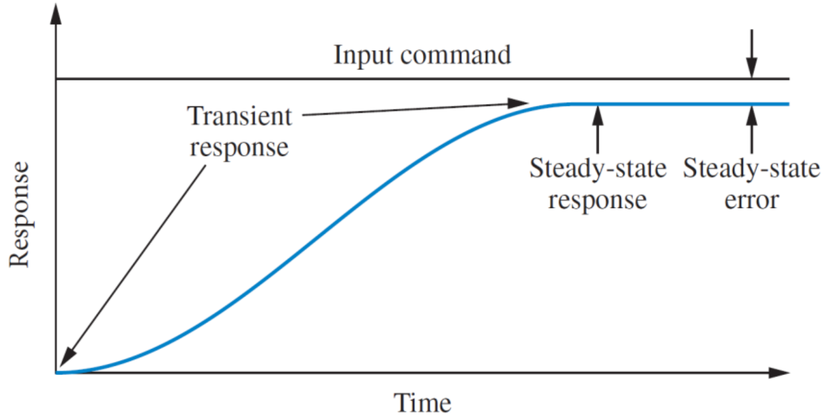
- Producing the desired **Transient Response**.

[***Ex.***] An elevator arrives at a floor with an appropriate speed.

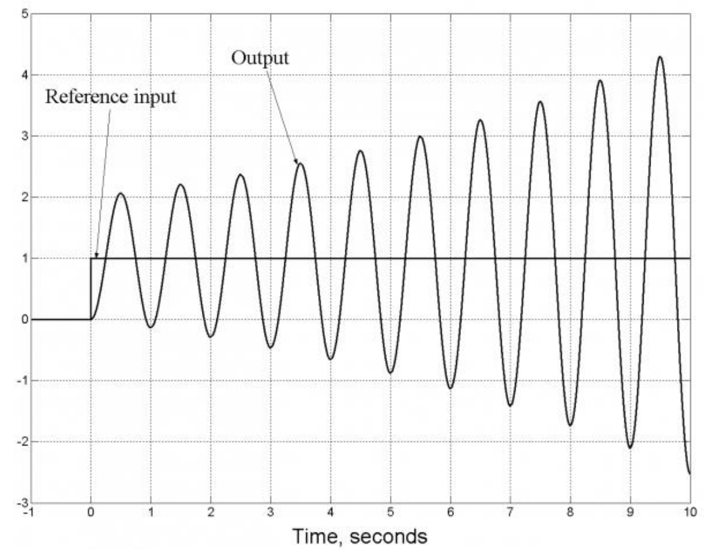


# Control Systems Objectives

- Reducing **Steady-State Error**.
[***Ex.***] An elevator stops exactly at a desired floor.




- Achieving **Stability**.
[***Ex.***] An elevator doesn't crash into the floor or exit through the ceiling.




(What are causes of Instability?)

# Control Systems Objectives

**Instability** may have two causes:

1. The system being controlled may be unstable itself. For example, the Segway vehicle will simply fall over if the control is turned off.
2. Addition of feedback to the system may itself drive the system unstable.

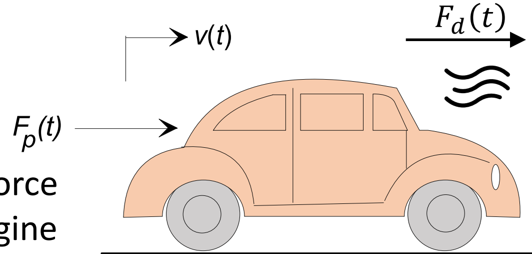
**Other Objectives:**

- Disturbance rejection
- Robustness
- Sensitivity of system performance to changes in parameters
- ...

# A Motivational Example

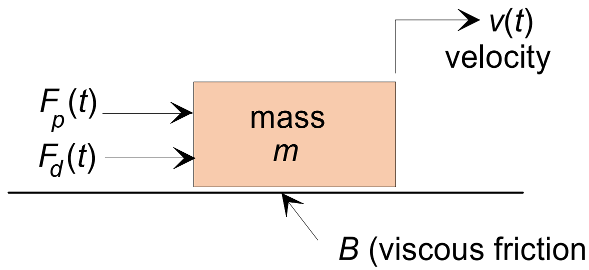
# Car Cruise Control

A simplified dynamic model of the car in the presence of disturbance, e.g., wind or incline:

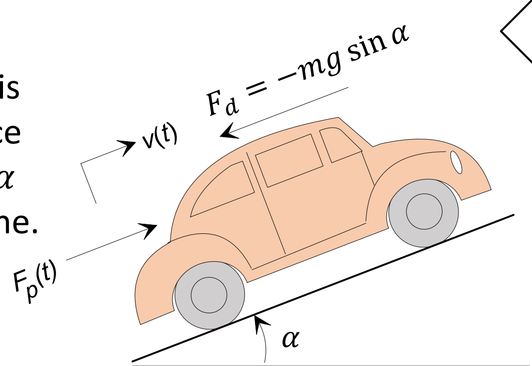



disturbance force from the environment (it can be + or -)

propulsive force from the engine




On the incline, there is a constant disturbance force $F_d = -mg\sin\alpha$ acting down the incline.

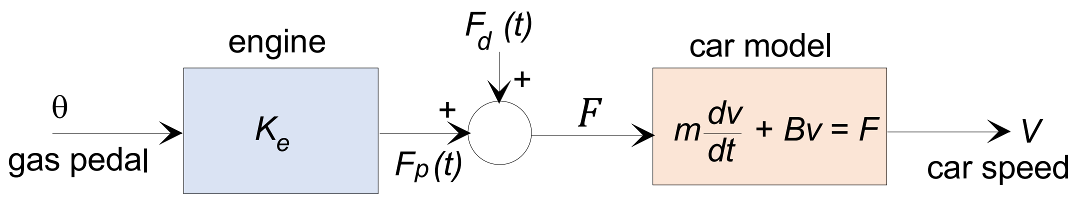



$$m\frac{dv}{dt} = F_p(t) + F_d(t) - Bv$$

Assume that $F_p(t) = K_e\theta(t)$ where $\theta(t)$ is gas-pedal depression and $K_e$ is a constant.

$$m\frac{dv}{dt} + Bv = K_e\theta(t) + F_d(t)$$

# Open-Loop Control



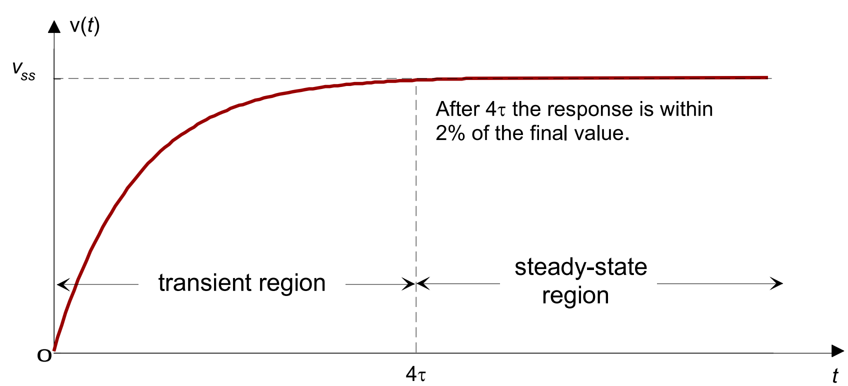

The response to a step in the command $\theta(t)$ with $v(0) = 0$ and in the presence of constant disturbance (i.e., $F_d(t) = \bar{F}_d$).

$$\theta(t) = \begin{cases} \bar{\theta} & t \geq 0 \\ 0 & t < 0 \end{cases}$$

$$\frac{m}{B}\frac{dv}{dt} + v = \frac{K_e}{B}\bar{\theta} + \frac{1}{B}\bar{F}_d \longrightarrow v(t) = -v_{ss}e^{-\frac{t}{\tau}} + v_{ss} \quad \text{where} \quad \tau = \frac{m}{B}, v_{ss} = \frac{K_e}{B}\bar{\theta} + \frac{\bar{F}_d}{B}$$

Note that disturbance is usually unknown!

Steady-state (final) speed:

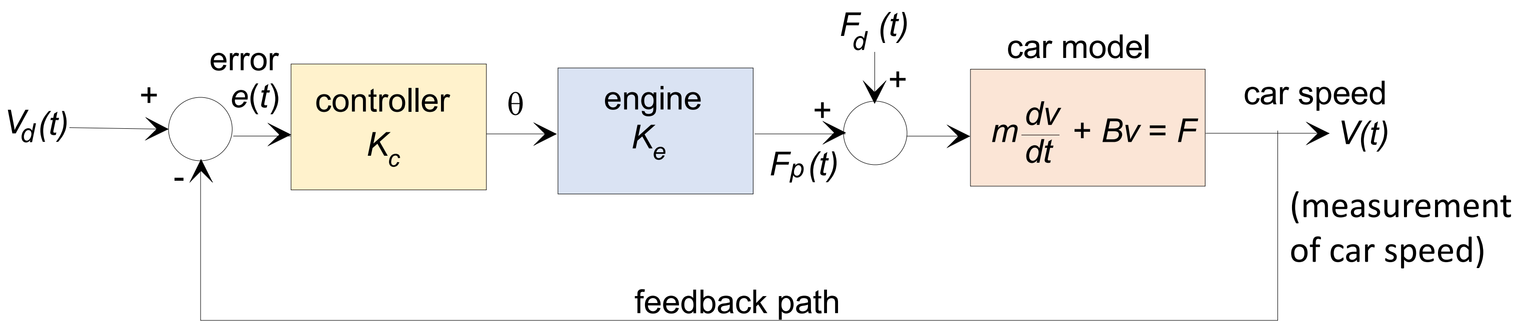


# Closed-Loop Control:
# A Proportional (P) Controller

**Goals**:

- Maintain the speed of a car at a desired value $v_d(t)$ in the presence of external disturbances/forces (such as wind gusts, gravitational forces on an incline, etc.).
- Improve the dynamic response of the car as the driver steps on the gas.

Let's choose a **Proportional (P) controller** (where the control effort is proportional to the error):




error: $e(t) = v_d(t) - v(t)$

control effort: $\underbrace{\theta(t) = K_c}_{\text{controller gain}} e(t) = K_c\big(v_d(t) - v(t)\big)$ (the gas pedal is depressed by an amount proportional to the error)

# Closed-Loop Control: A Proportional (P) Controller

$$\frac{m}{B}\frac{dv}{dt}+v=\frac{K_e}{B}\theta(t)+\frac{1}{B}F_d(t)\xrightarrow{\theta(t)=K_c\left(v_d(t)-v(t)\right)}\frac{m}{B+K_cK_e}\frac{dv}{dt}+v=\frac{K_cK_e}{B+K_cK_e}v_d(t)+\frac{1}{B+K_cK_e}F_d(t)$$

(closed-loop equation)

The response to a step in the command $v_d(t)$ with $v(0)=0$ and in the presence of constant disturbance (i.e., $F_d(t)=\bar{F}_d$).

$$v_d(t)=\begin{cases}v_d & t\geq 0\\ 0 & t<0\end{cases}$$

$$\frac{m}{B+K_cK_e}\frac{dv}{dt}+v=\frac{K_cK_e}{B+K_cK_e}v_d+\frac{1}{B+K_cK_e}\bar{F}_d\longrightarrow v(t)=-v'_{ss}e^{-\frac{t}{\tau'}}+v'_{ss}$$

$$\tau'=\frac{m}{B+K_cK_e}=\frac{B\tau}{B+K_cK_e},\qquad v'_{ss}=\frac{K_cK_ev_d}{B+K_cK_e}+\frac{\bar{F}_d}{B+K_cK_e}$$

By increasing the controller gain $K_c$,

- the impact of the disturbance is reduced,
- $\tau$ decreases (i.e., the car responds more quickly to changes in the gas pedal),
- $v_{ss}\rightarrow v_d$.