北航 自动化科学与电气工程学院
School of Automation Science And Electrical Engineering

自动化控制原理 A(上)

Principles of Automatic Control A(I)

教　　材

Modern Control Engineering

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Courseware: available in Course Center
https://course.e.buaa.edu.cn/opencourse/course/detail/13936
Course hours/Credits: 48/3.5
Grading policy: Final exam (70%), midterm test (20%), attendance and assignments (10%)
Prerequisite courses: Advanced mathematics, Linear algebra, Complex variable function, Integral transformation, Circuit analysis, Electronic technology fundamentals, C language programming
Classroom discipline: If one fails to attend more than 8 times, he or she will be disqualified from final exam.

Chapter 1

Introduction to Control Systems

Outline

- What is a control system?
- What is an automatic control system? What is a closed-loop system? What is an open-loop system?
- How to describe a system?
- What are the basic requirements for a control system?

1-1 Introduction

Automatic control has played a vital role in the advance of engineering and science. For example:

- Space-vehicle systems
- Missile-guidance systems
- Robotic systems
- Flight control systems
- Numerical control of machine tools in the manufacturing industries ....

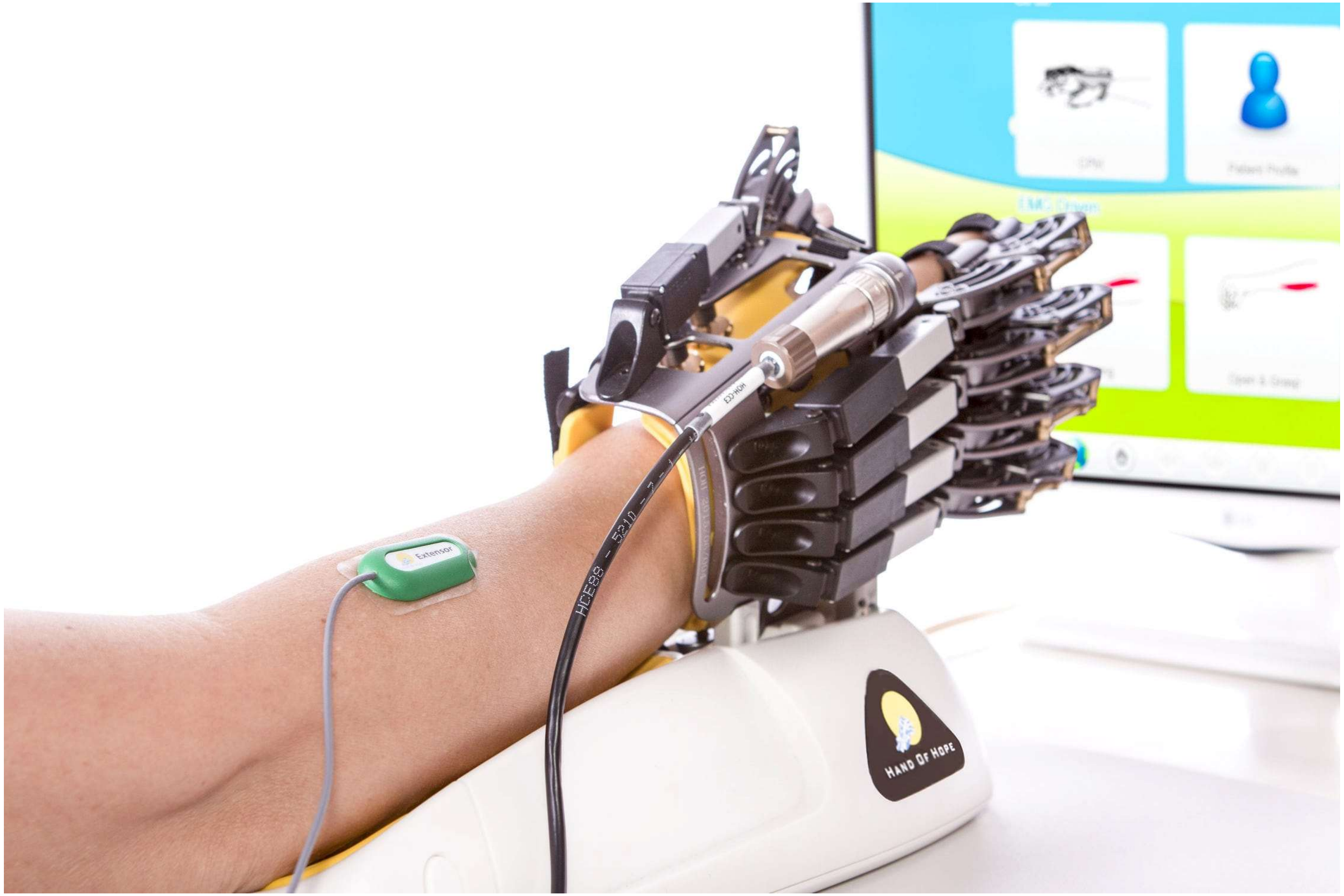
The physical quantities to be controlled are different according to the tasks assigned to a control system, such as angle of pitch, yaw angle, roll angle, velocity, displacement, pressure, humidity, viscosity, flow in the process industries and so on.

A Computerized Numerical Control (CNC) Turning Center

One of the computerized numerical control (CNC) panels

Rendezvous and docking between Tianzhou-1 and Tiangong-2

Control panel of an autopilot system

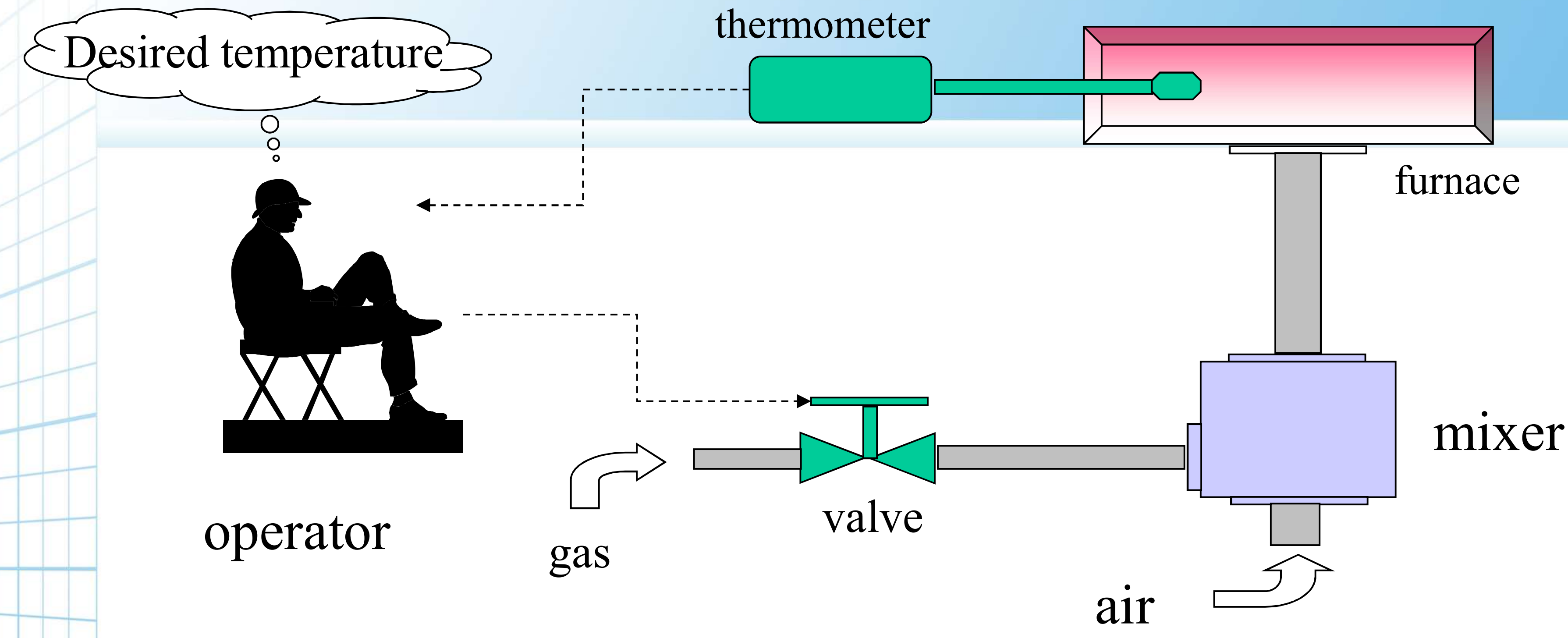


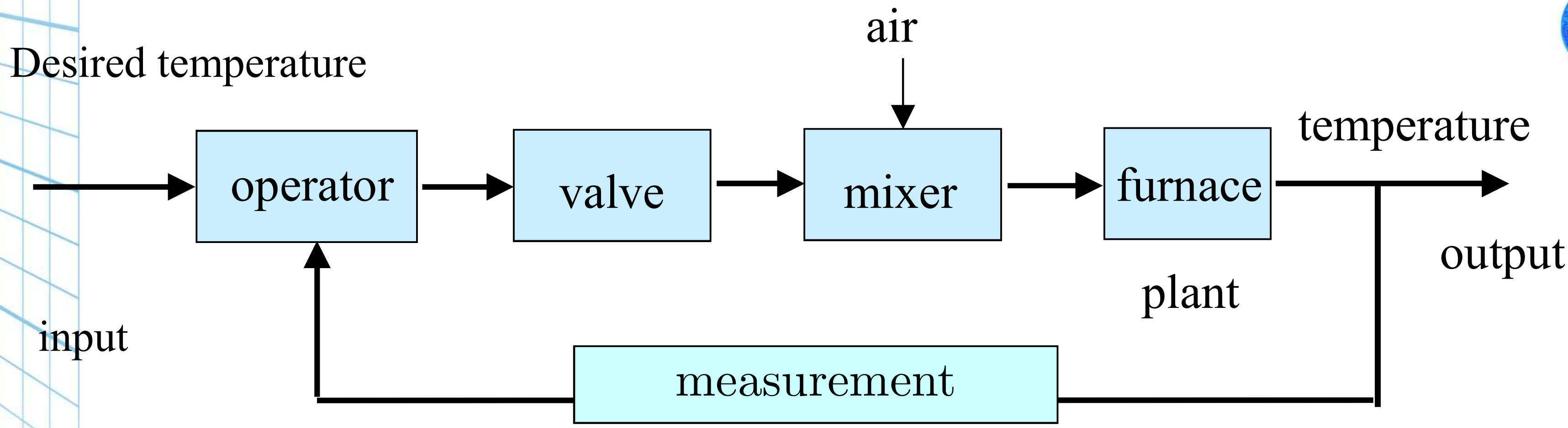
Rehabilitation robotics

1. What is a control system?

Definition: A control system is a device or a set of devices to regulate the behavior of other devices or system for the purpose of achieving certain objective.

Example. Temperature Control System





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Definitions of some basic terminologies:

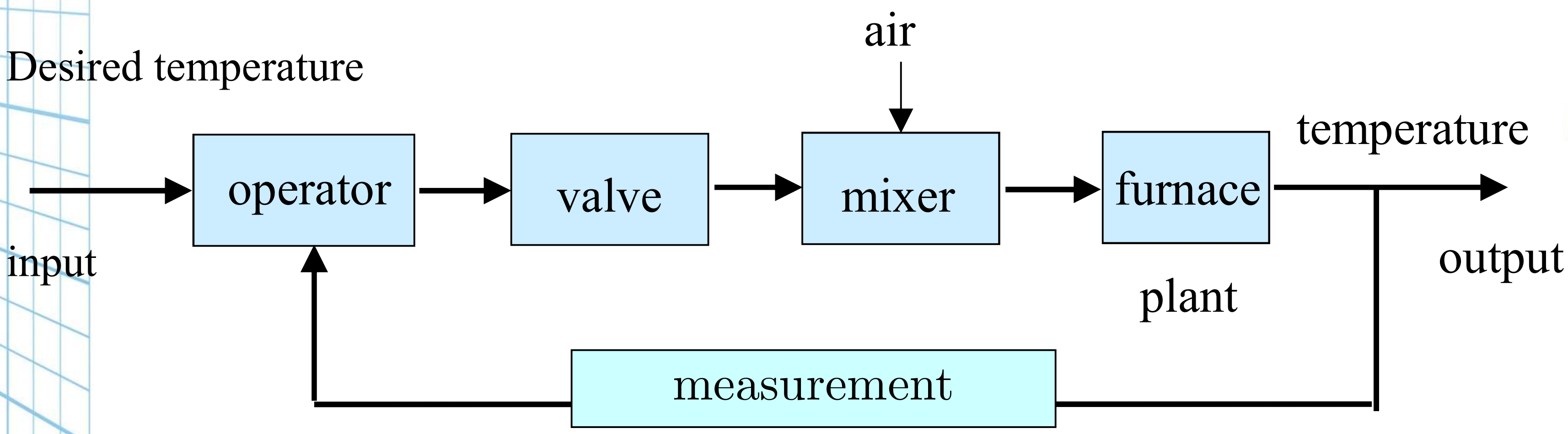
Plant: A physical object to be controlled.

System: A system is a combination of components that act together and perform a certain objective.

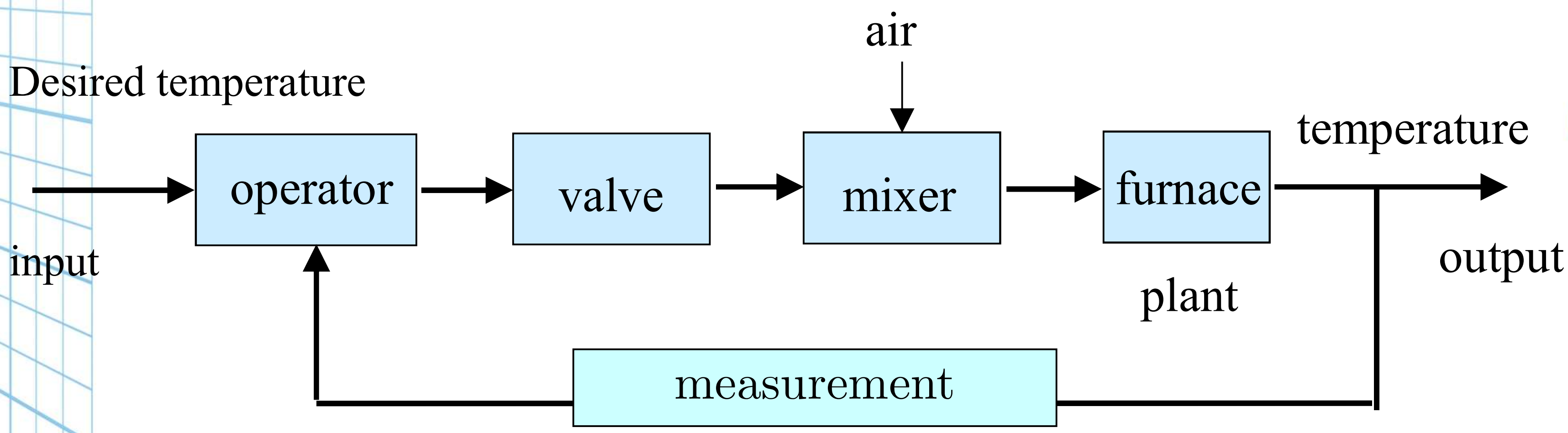
Controlled variable and control signal: The controlled variable is the quantity that is measured and controlled.

The control signal is the quantity that is varied by the controller so as to affect the value of the controlled variable.

Disturbances: A disturbance is a signal that tends to adversely affect the value of the output of a system.



Feedback: Feedback control refers to an operation that, in the presence of disturbances, tends to reduce the difference between the output and the input of a system and does so on the basis of the difference.



In other words, **control** means measuring the value of the controlled variable of the system and applying the control signal to the system to correct or limit deviation of the measured value from a desired value.

Example. Furnace temperature control system

Plant: Furnace

Controlled variable: Temperature of the furnace T_c

Reference signal: Desired temperature T_r

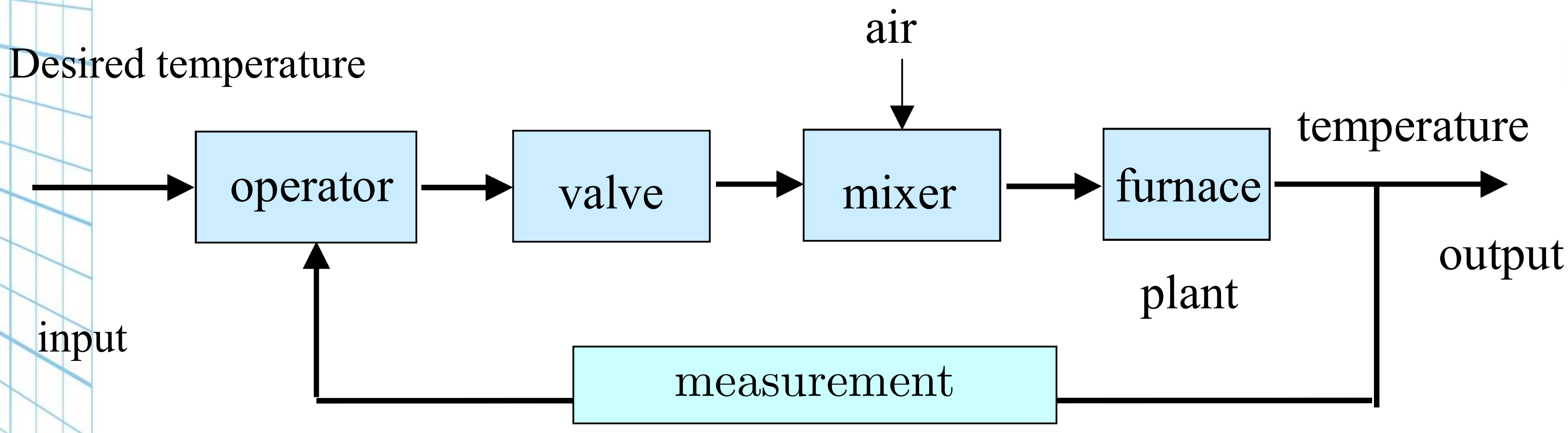
Control objective: To make T_c track T_r through the controller as soon as possible.

Control actions analysis:

1) If $T_c = T_r$, no control actions are needed for the operator;
2) If $T_c < T_r$ $\rightarrow$valve$\uparrow$ $\rightarrow$Gas$\uparrow$$\rightarrow$ $T_c\uparrow$$\rightarrow$ $T_c = T_r$;
3) If $T_c > T_r$ $\rightarrow$valve$\downarrow$ $\rightarrow$Gas$\downarrow$$\rightarrow$ $T_c\downarrow$$\rightarrow$ $T_c = T_r$.

This is a Feedback Control (Closed-loop Control):

A person could be assigned the task of sensing the actual value of the output and comparing it with the command input. If the output does not meet the desired value, the person can alter the valve to achieve this value.



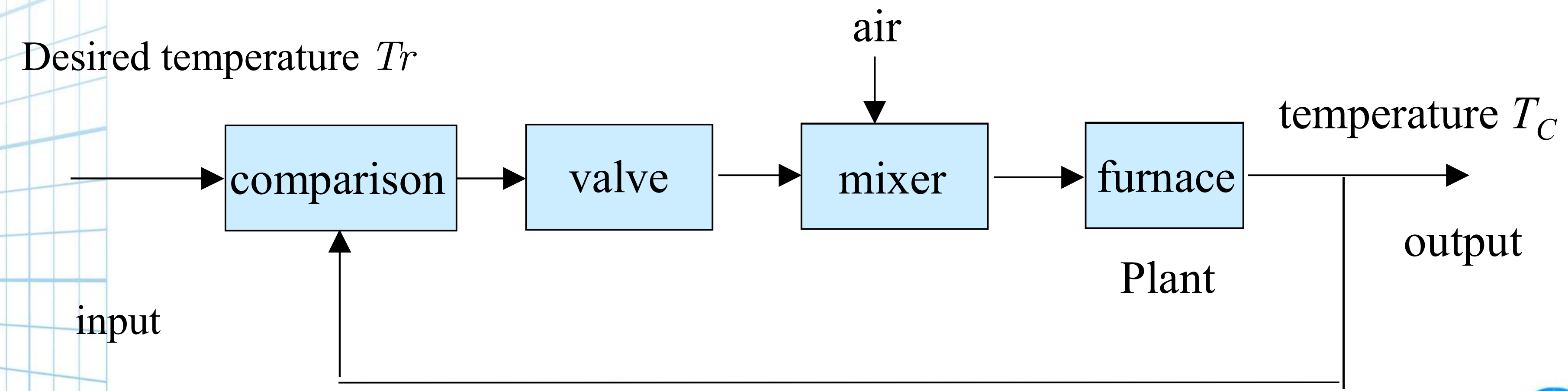
2. What is an automatic control system?

If the operator above is replaced by a computer or a device that does not depend on direct human intervention, the system is called an **automatic control system**.

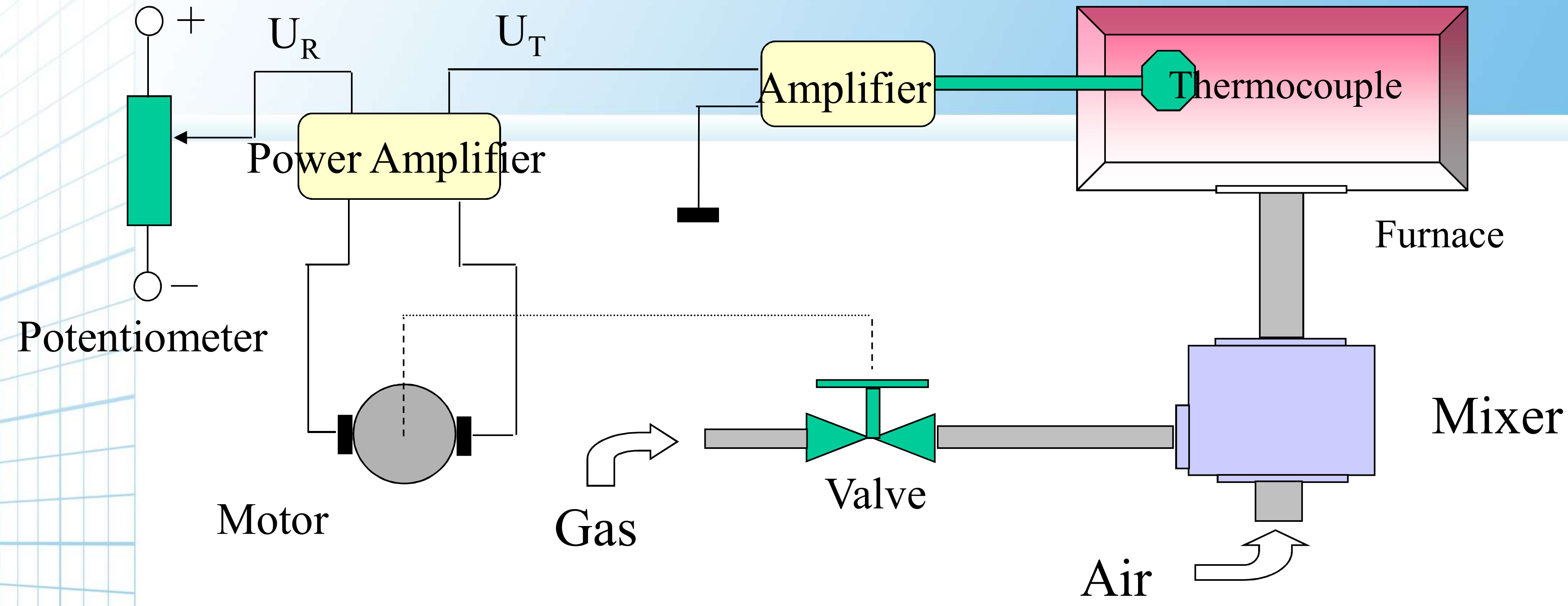
Roughly speaking,
an automatic control system is a closed-loop control system that requires no operator action.

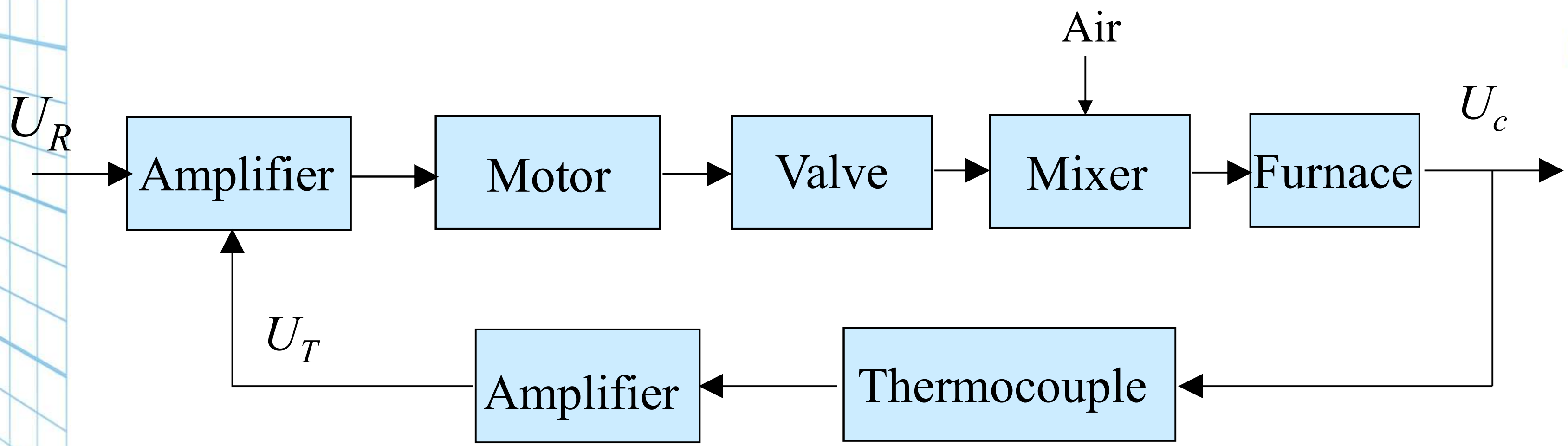
Example. Automatic furnace temperature control system

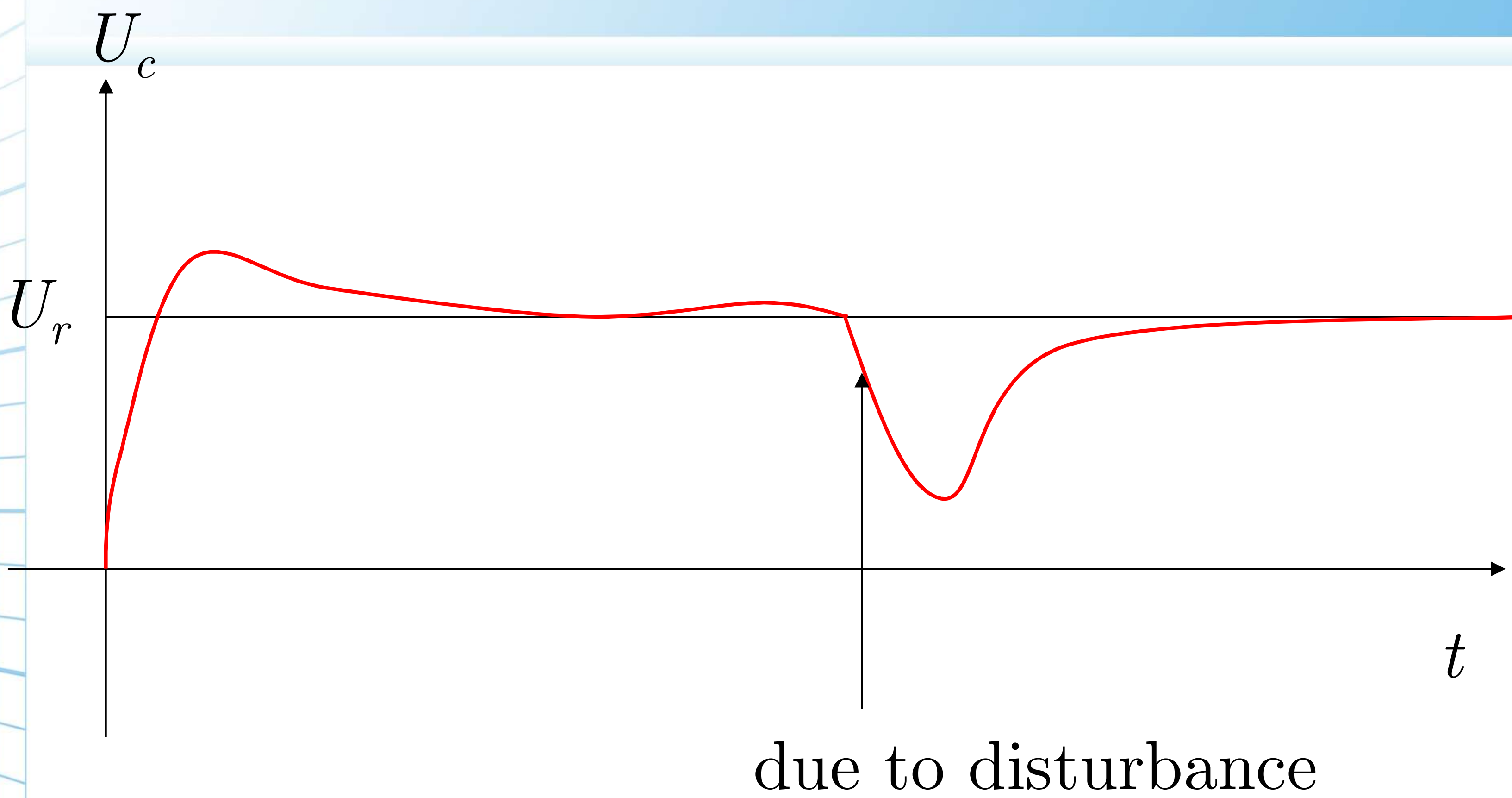
Analysis: What does the operator do?



The operator performs a comparison, that is, an algebraic operation $T_r - T_c$, and then tunes the valve to change the value of T_c. Such control processes can be replaced by an automatic controller.


+
U_R
U_T
Amplifier
Thermocouple
Power Amplifier
−
Potentiometer
Furnace
Mixer
Motor
Gas
Valve
Air


Air
U_R
Amplifier
Motor
Valve
Mixer
Furnace
U_c
U_T
Amplifier
Thermocouple


U_c
U_r
t
due to disturbance

1-2 Examples of control systems

Example. Speed control system

Controlled plant: Engine

Controlled variable: Actual engine speed U_c

Reference signal: Desired engine speed U_r

Control objective: To make U_c track U_r through a controller as soon as possible even if disturbances exist.

Control actions analysis:

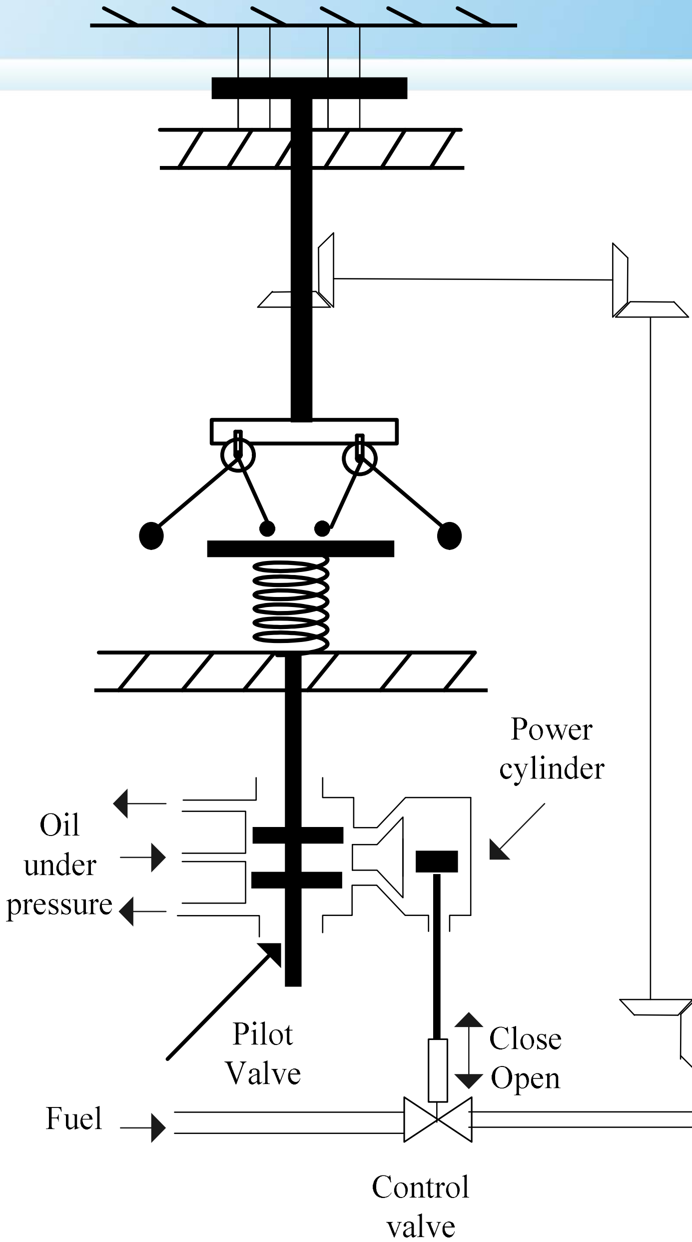
1. If $U_c = U_r$, no pressured oil will flow into either side of the power cylinder;

2. If $U_c < U_r$

$\rightarrow F_c\downarrow \rightarrow$ valve$\downarrow$

Fuel$\uparrow \rightarrow U_c\uparrow \rightarrow$

$U_c = U_r$

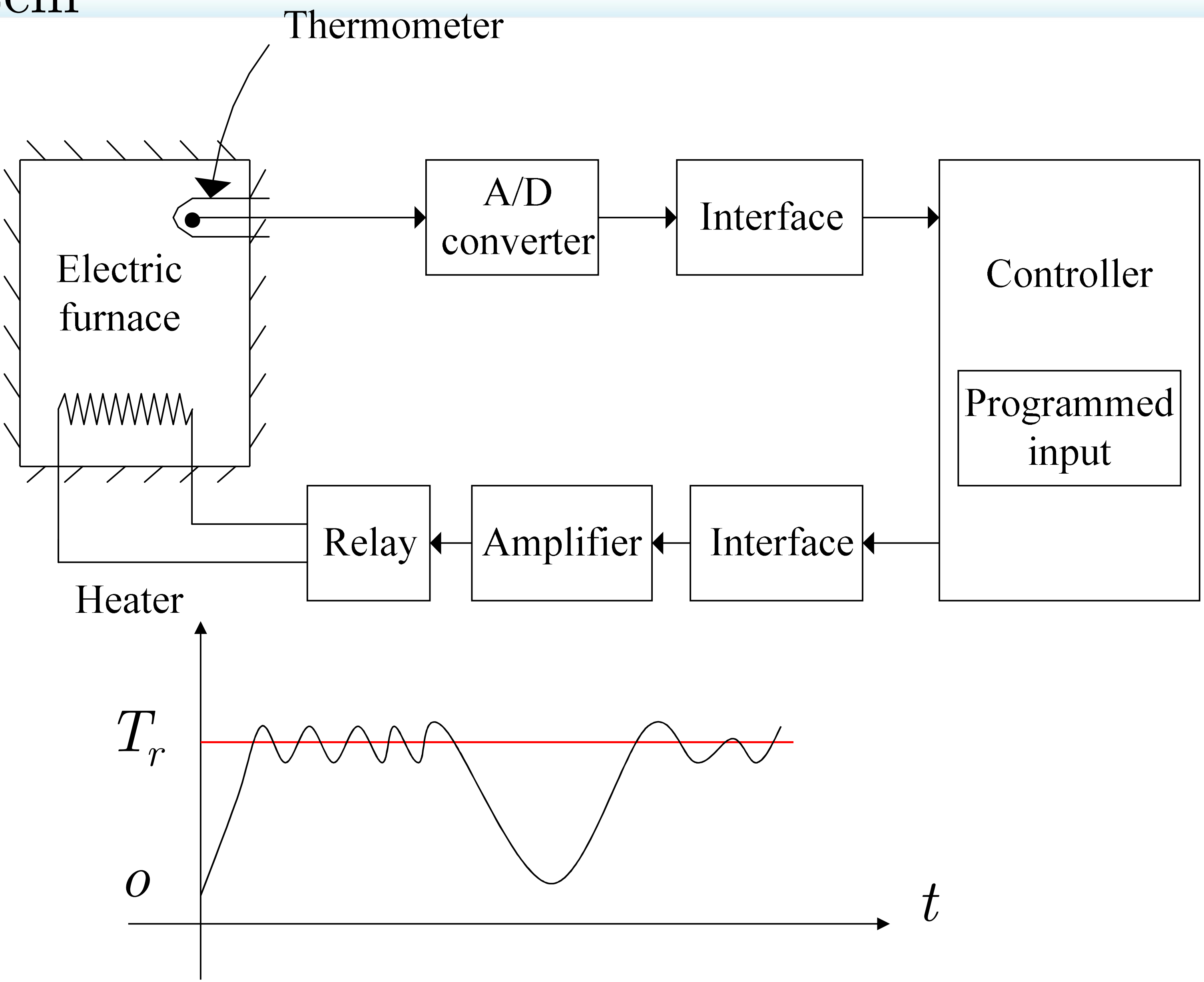


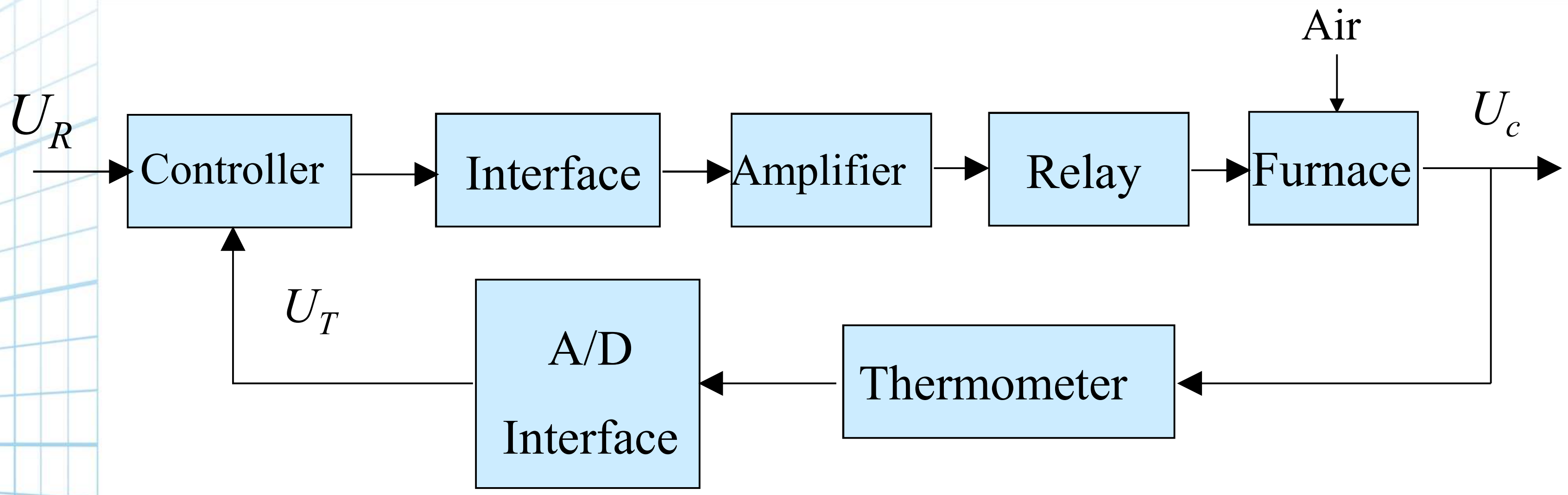
The sequence of actions may be stated as follows: The speed governor is adjusted such that, at the desired speed, no pressured oil will flow into either side of the power cylinder.

If the actual speed drops below the desired value due to disturbance, then the decrease in the centrifugal force of the speed governor causes the control valve to move downward, supplying more fuel, and the speed of the engine increases until the desired value is reached.

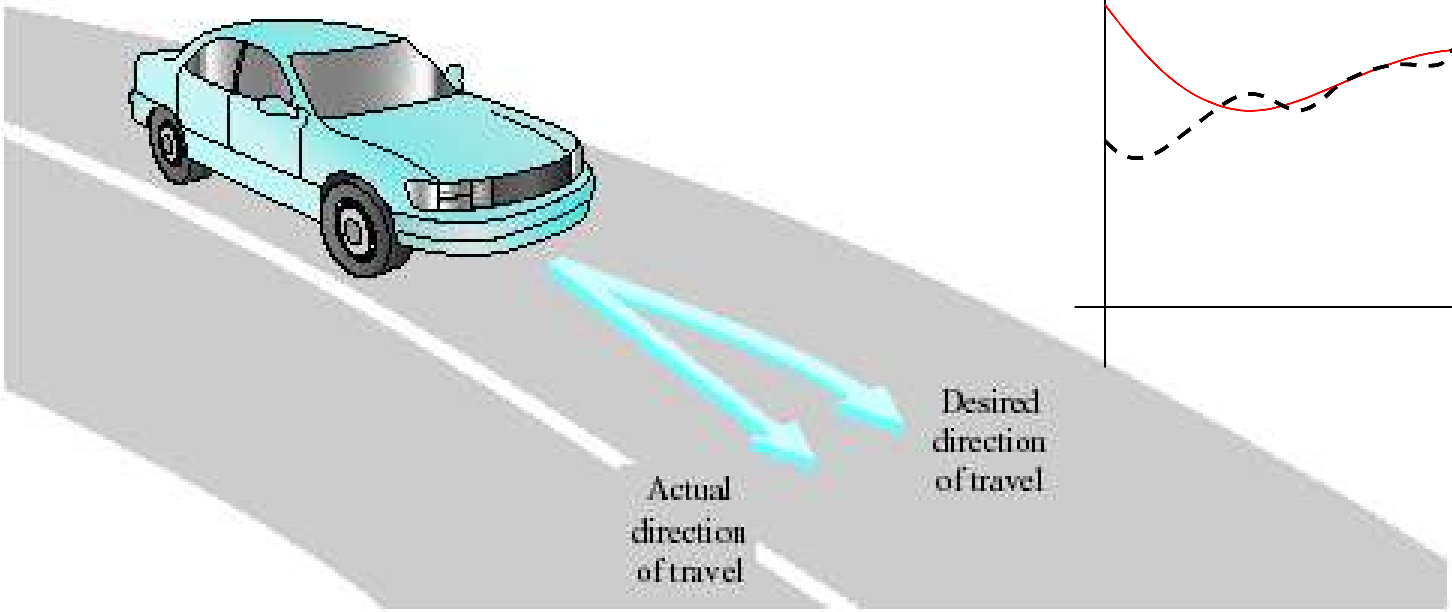
By the same fashion, we can analyze the case when the speed of the engine increases above the desired value.

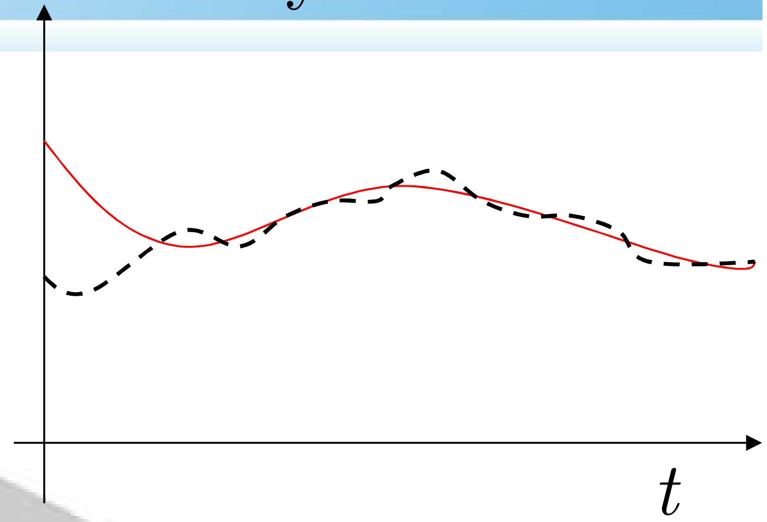
Example. Computer control of furnace temperature system

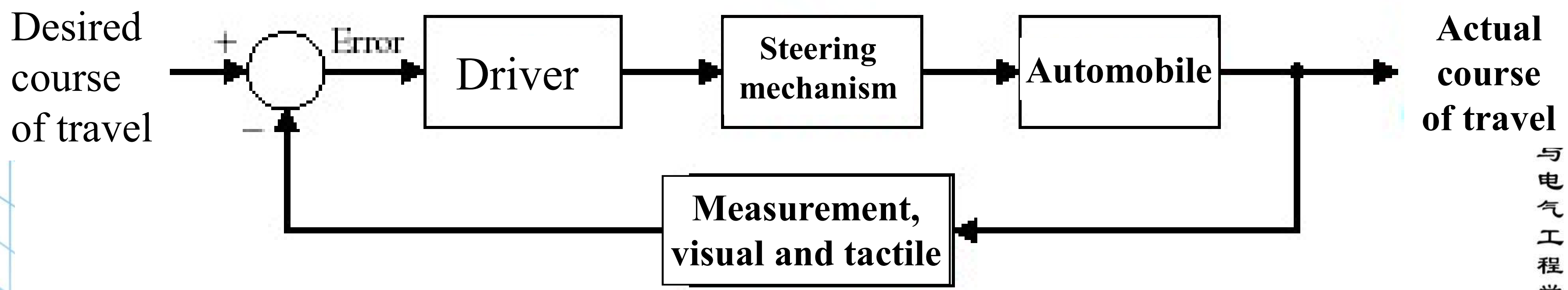



Air
U_R
Controller
Interface
Amplifier
Relay
Furnace
U_c
U_T
A/D
Interface
Thermometer

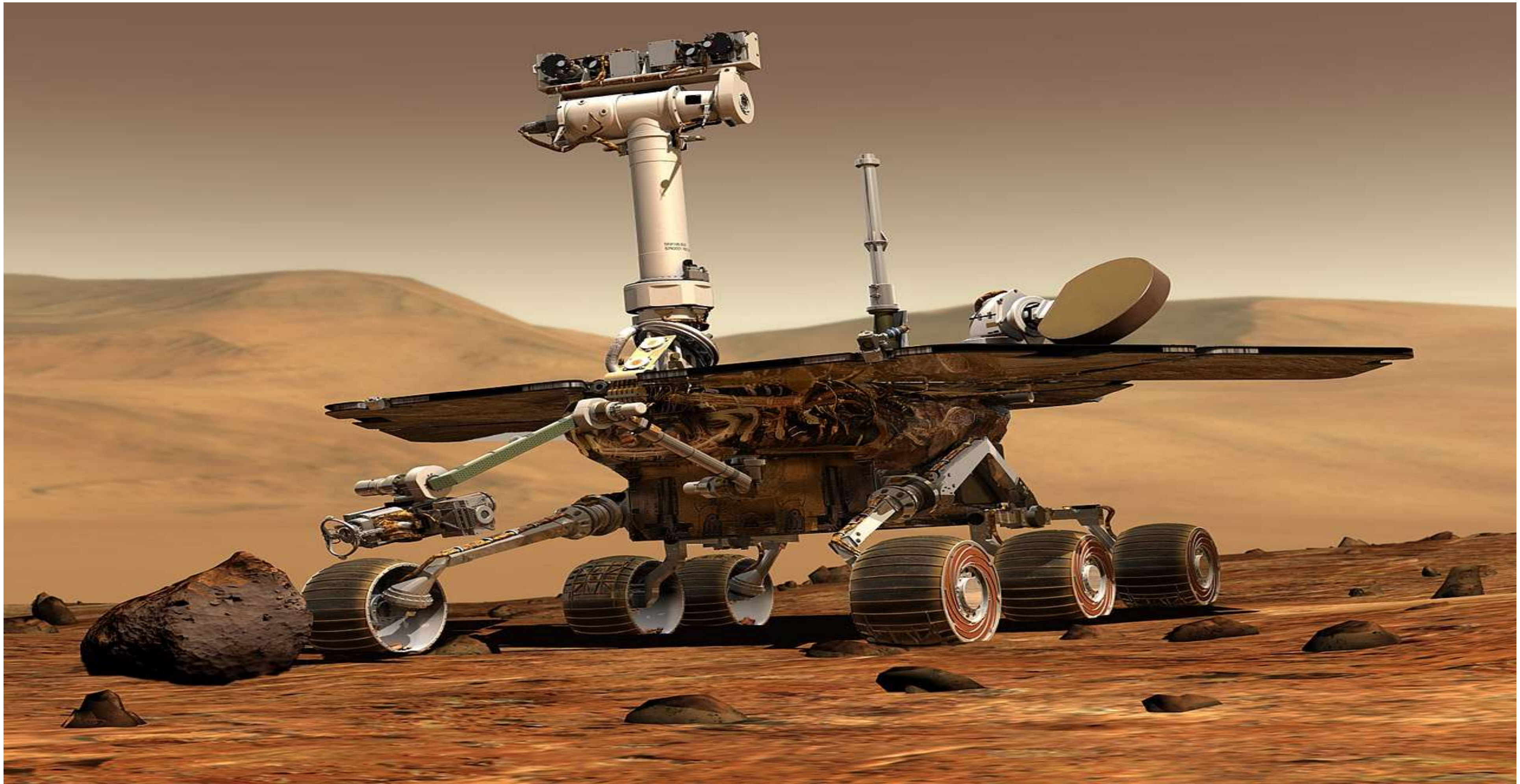
Example. Automobile steering control system







Unmanned aerial vehicle (UAV). Generally the UAV is controlled by ground operators. One significant challenge is to develop control systems which will avoid in-air collisions.



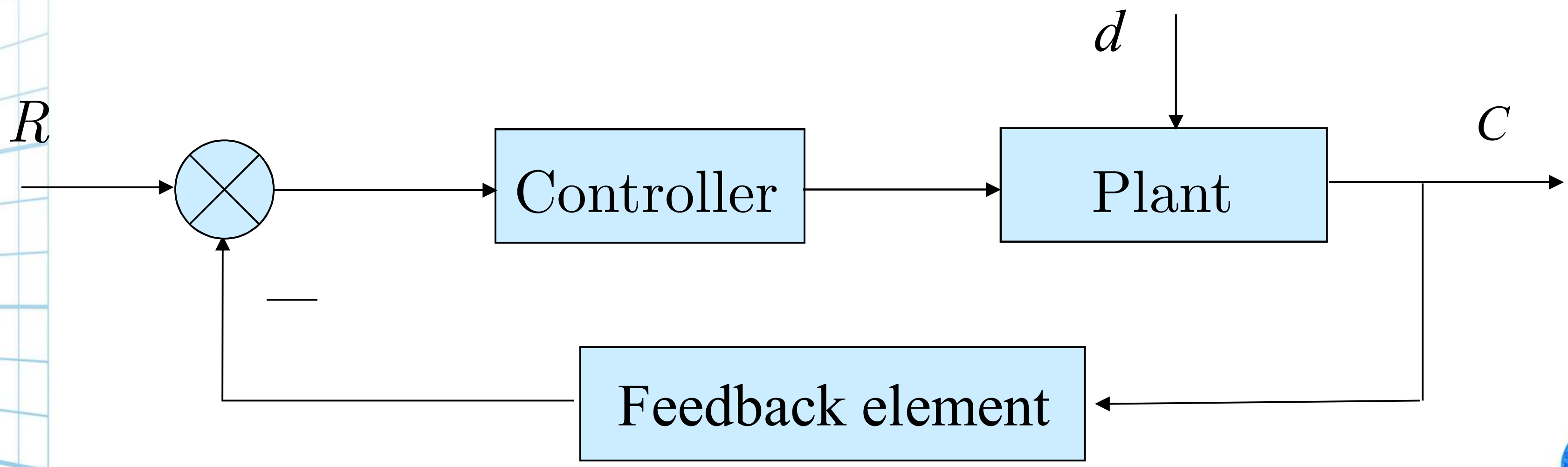
Solar-powered Mars rover *Spirit*. The vehicle can be controlled from Earth by sending it path commands, $r(t)$. The system is operated with feedback, whose goal is to operate the rover with modest effects from disturbances such as rocks.

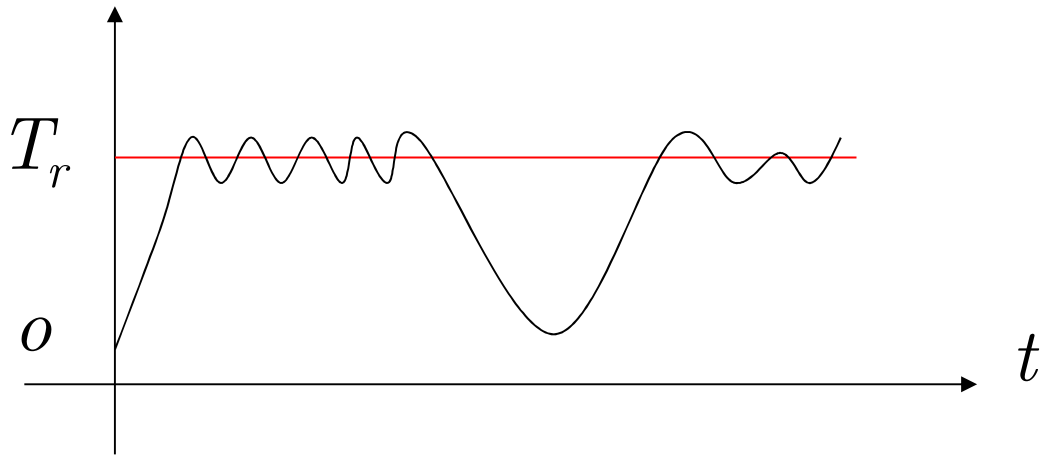
1-3 Closed-loop control versus open-loop control

1. Closed-loop (Feedback) control systems

Definition: A system that maintains a prescribed relationship between the output and the reference input by comparing them and using the **difference** as a means of control is called **feedback control system**.

The advantage of the closed-loop systems is their ability to recover from external, unwanted disturbances.





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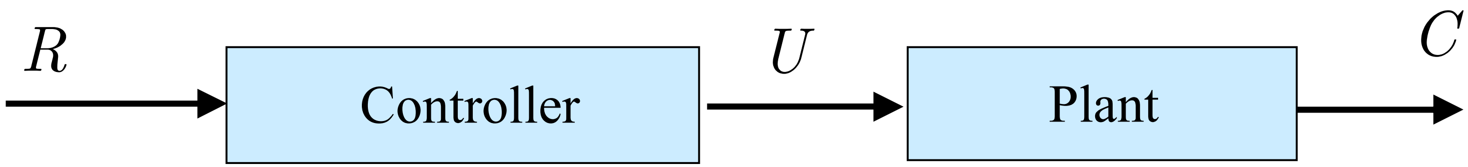
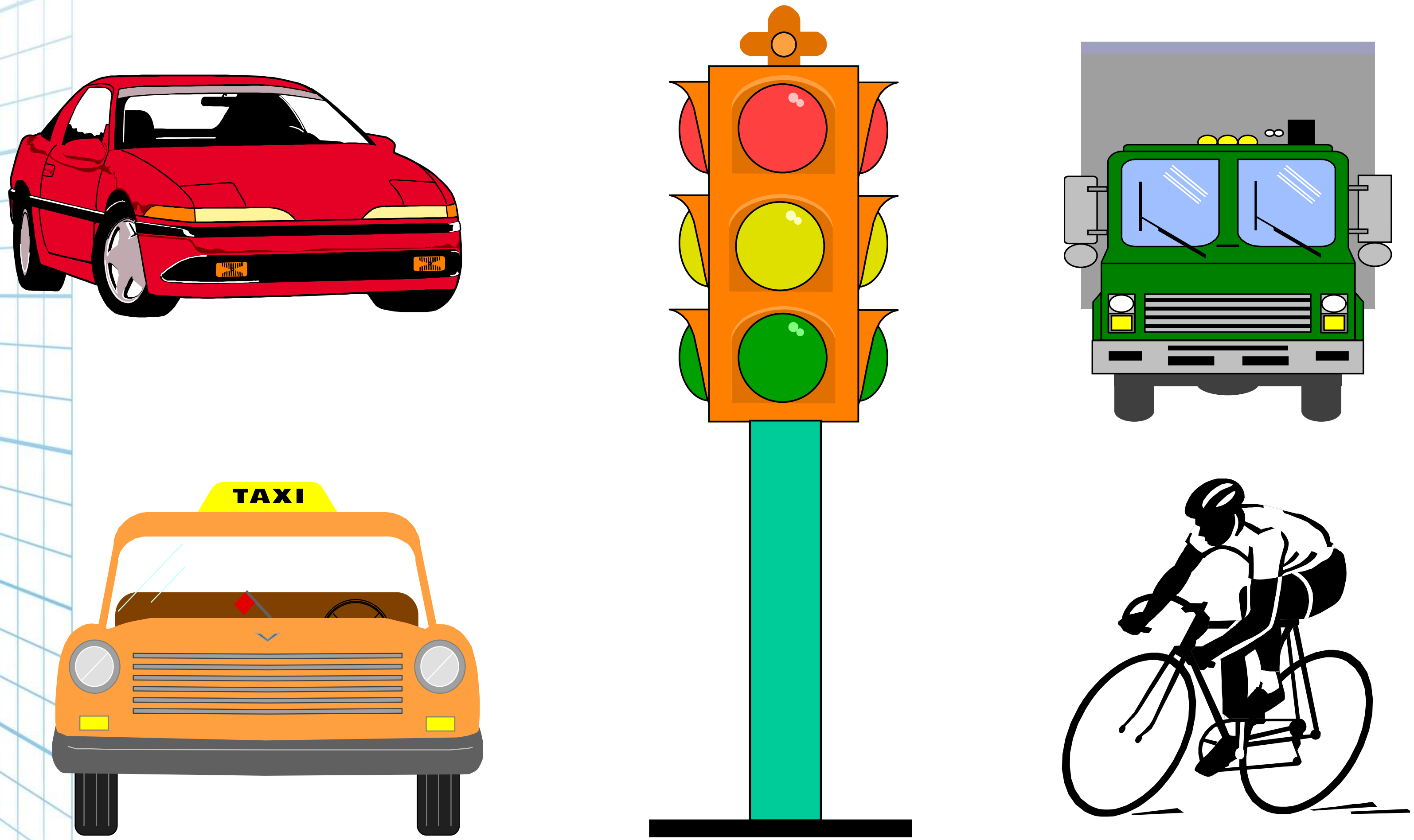
2. Open-loop Control Systems

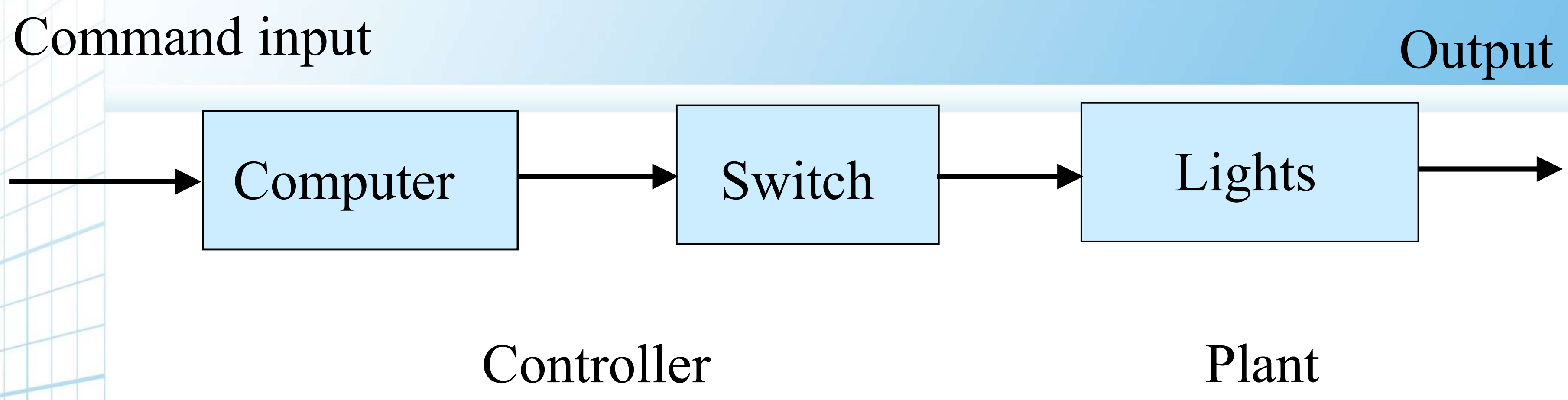
Those systems in which the output has no effect on the control action are called *open-loop control systems*. In other words, in an open-loop control system, the output is neither measured nor fed back for comparison with the input.

(1) To control the plant directly without using feedback: Feedforward control



Example. Control of Traffic Lights. An open-loop control system: The traffic lights turn on (off) on a time basis.

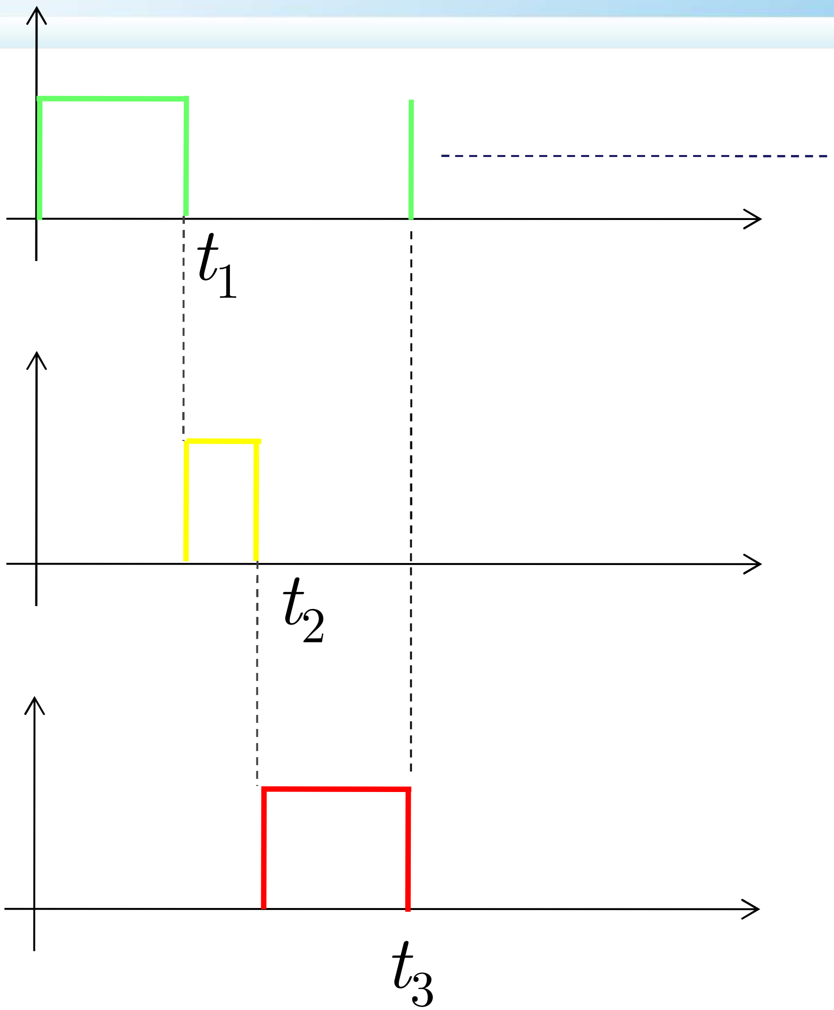




Controlled plant: Traffic lights

Controlled variable: The time interval on which the red, yellow and green lights turn on or turn off

Reference signal: Desired timing sequence generated by a computer *in advance*



The timing sequence is determined according to statistical data.

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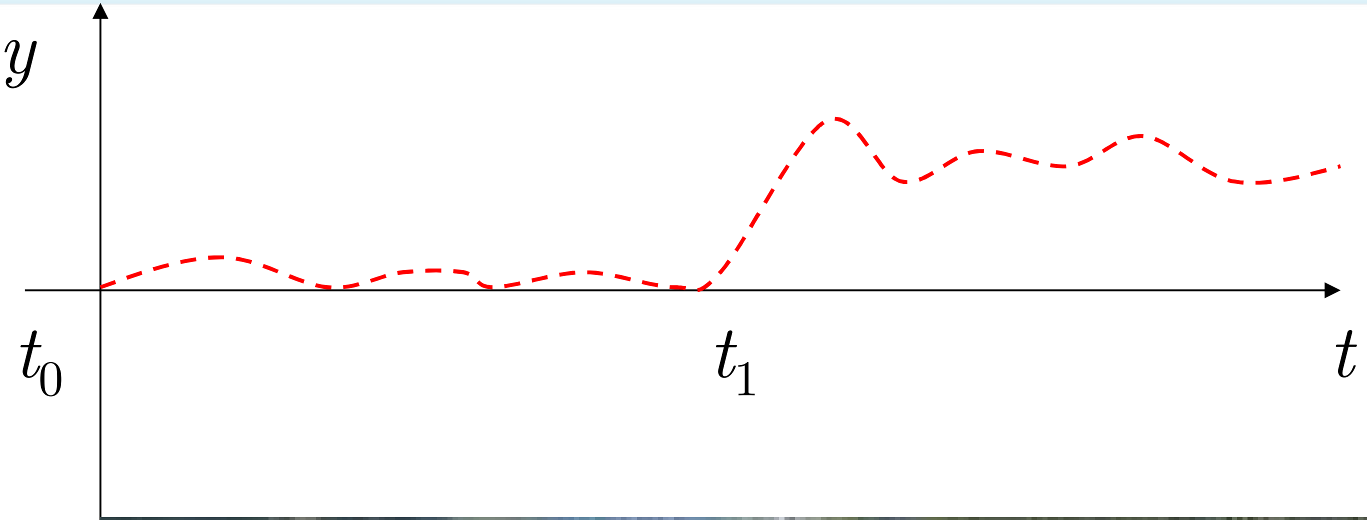
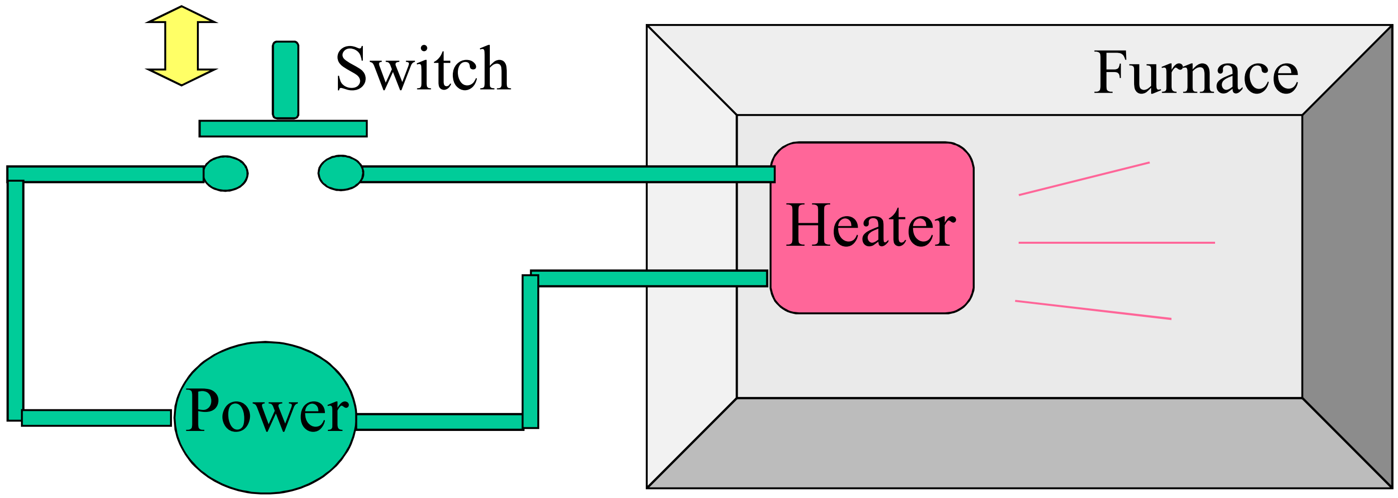
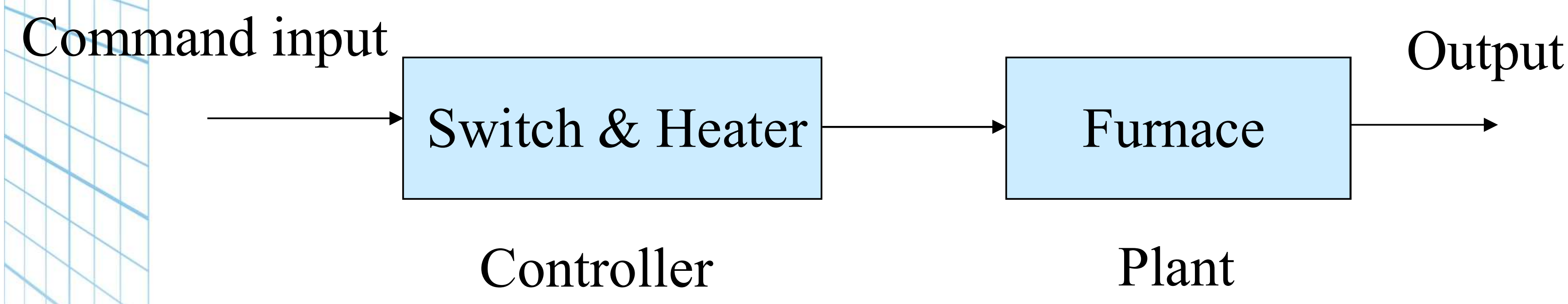
Traffic jam



Example. Furnace temperature control: Open-loop control method

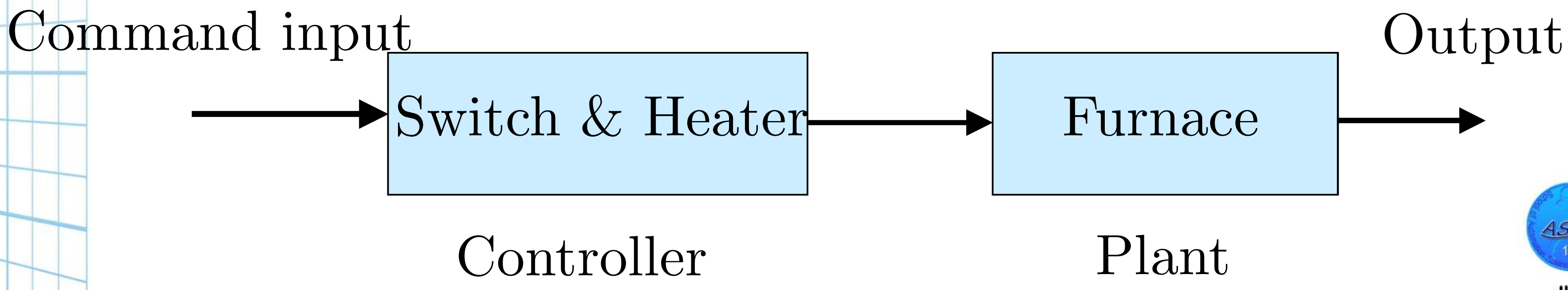


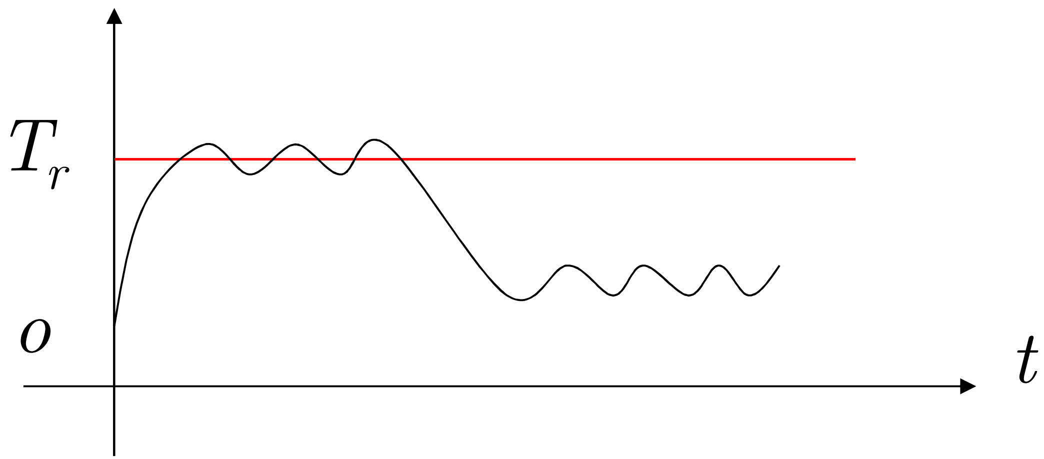


Controlled plant: Furnace

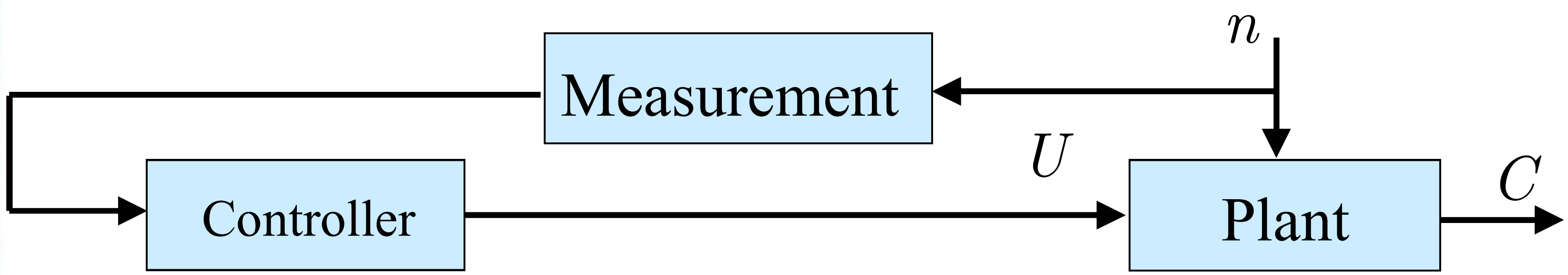
Controlled variable: Temperature of the furnace

Reference signal: Desired temperature (a timing sequence for the switch given in advance).





(2) To compensate for the disturbance without using feedback: Feedforward control

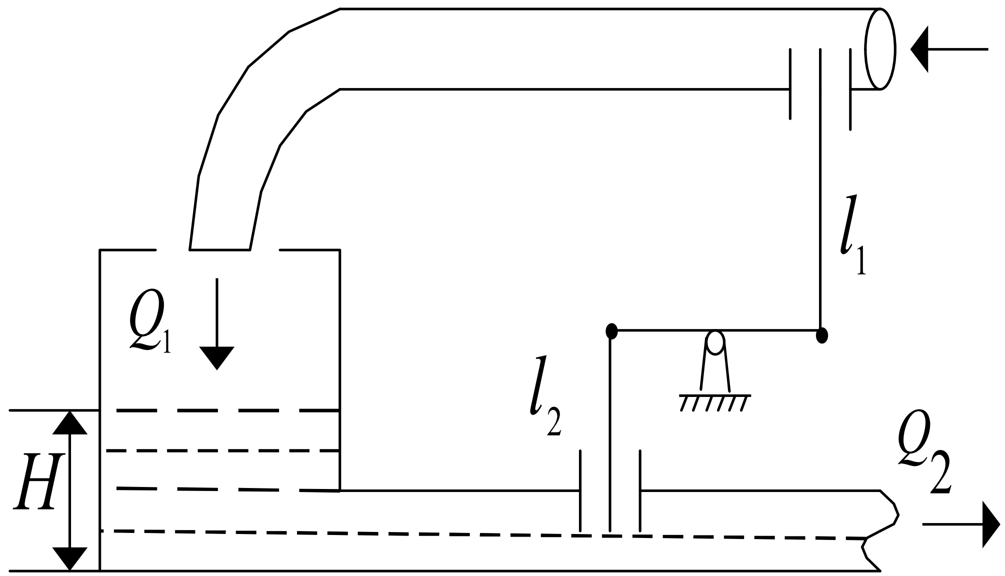


Example. Liquid-level control system

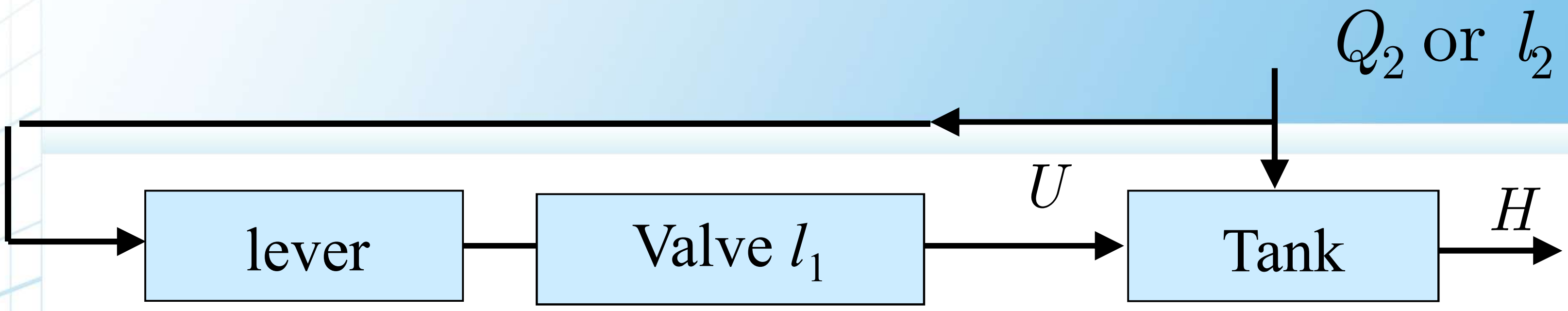
Controlled plant:
Water tank

Controlled variable:
Height of the liquid level, H.

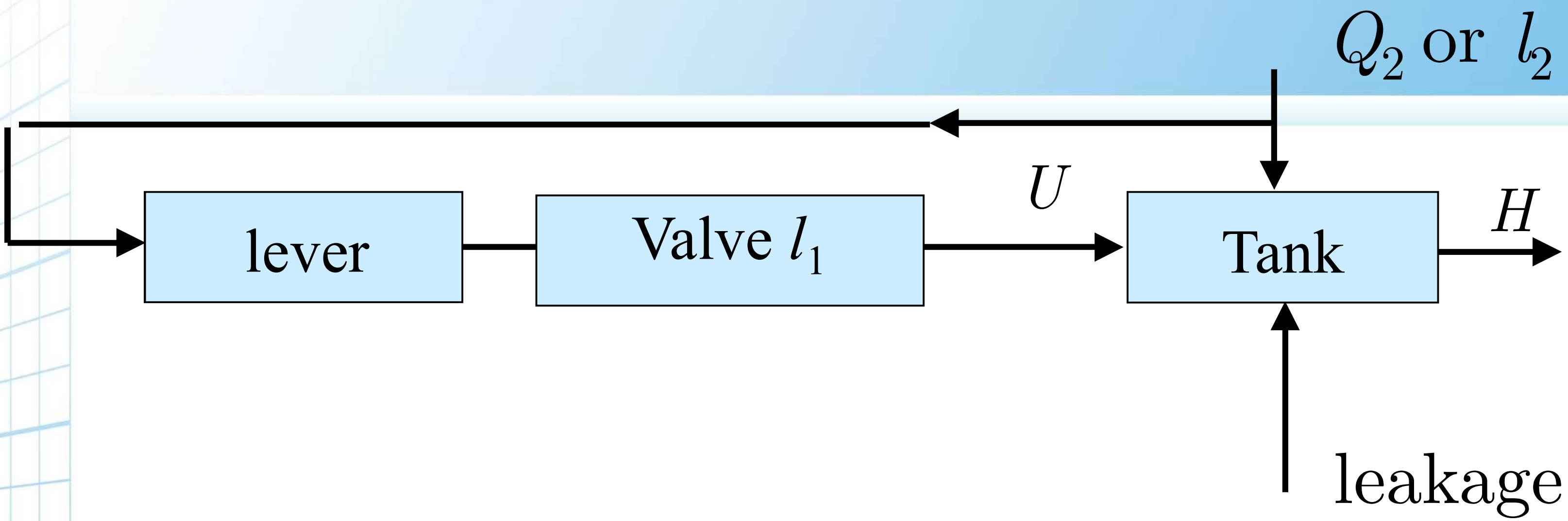
Reference signal:
Desired height of the liquid-level H_r.



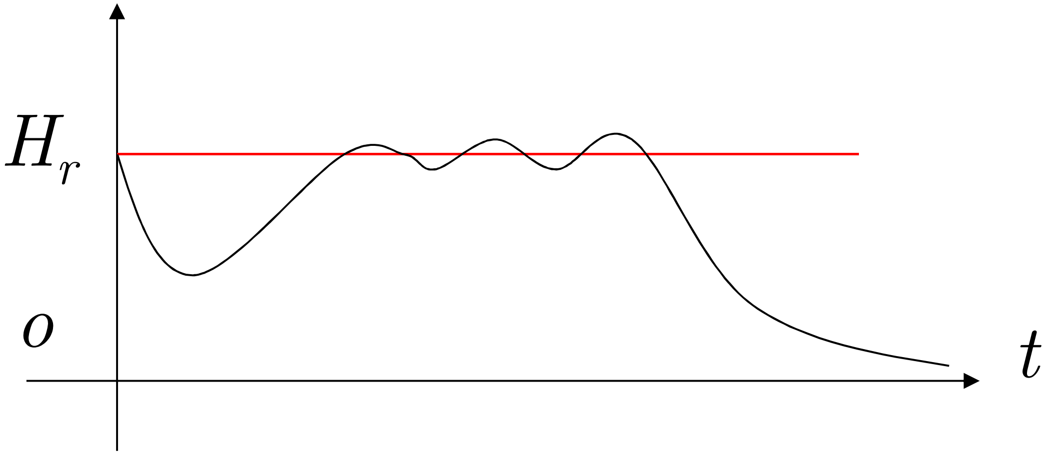
Control actions: If $Q_2\uparrow$=Valve $l_2\uparrow\rightarrow$lever$\rightarrow$Valve $l_1\downarrow$
$Q_1\uparrow\rightarrow$ $H\rightarrow H_r$.



This kind of control is still an open-loop control. For example, the system has no ability to counteract the leakage at the bottom of the tank.



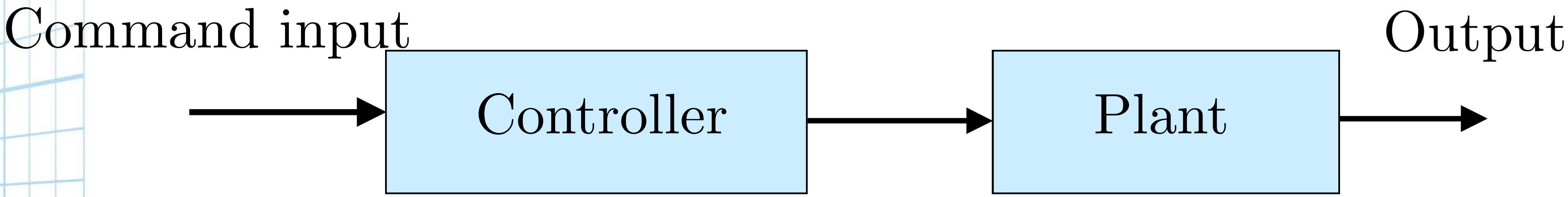
Q_2 or l_2
lever
Valve l_1
U
Tank
H
leakage



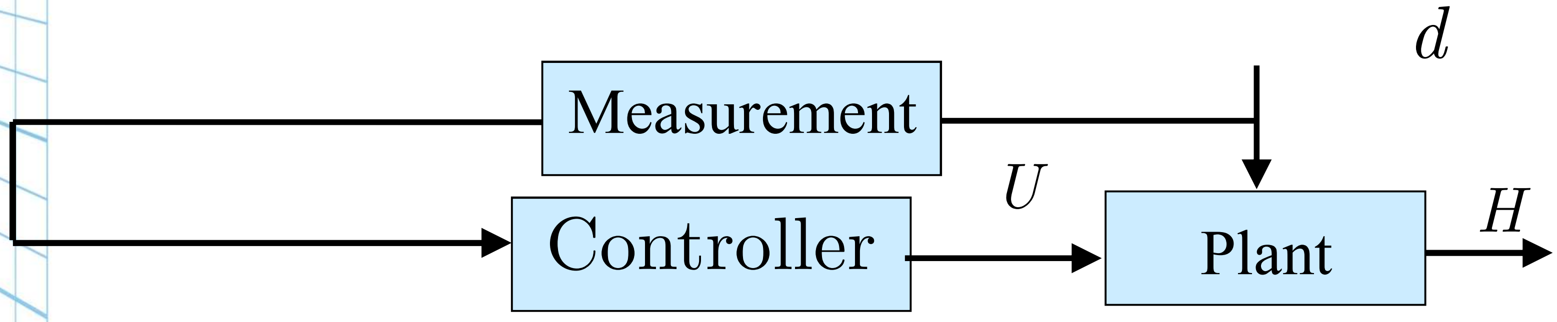
H_r
o
t

Two open loop control methods

1) To control the plant directly without using feedback



2) To compensate for the disturbance without using feedback



3. Closed-loop versus open-loop control systems

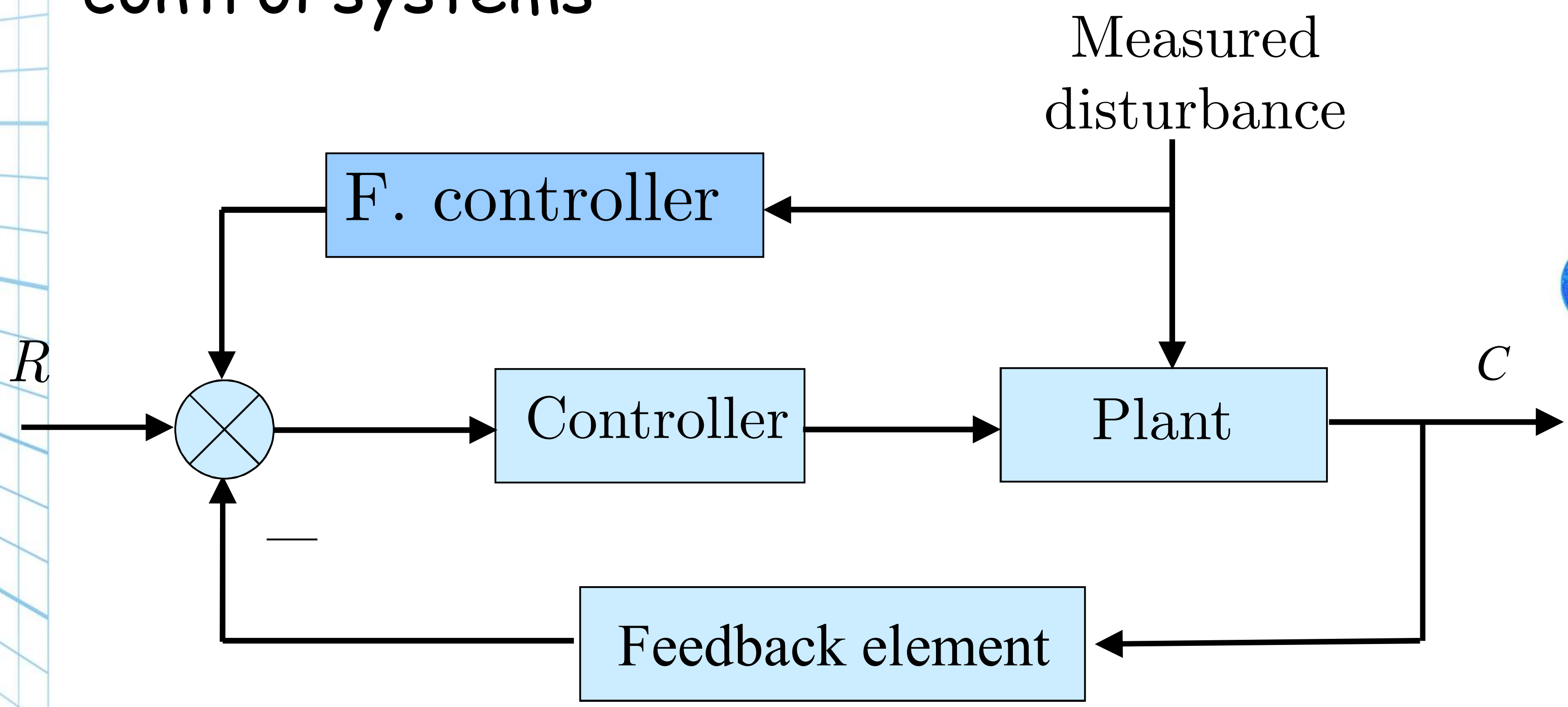
a) An advantage of the closed-loop control system is the fact that the use of feedback makes the system response relatively **insensitive** to external disturbances and internal variations in system parameters. It is thus possible to use relatively inaccurate and inexpensive components to obtain the accurate control of a given plant, whereas doing so is impossible in the open-loop case.

b) For systems in which the inputs are known ahead of time and in which there are no disturbances it is advisable to use open-loop control. The open-loop control system is simpler than a closed-loop system.

The main disadvantage of open-loop systems is the lack of ability to external disturbances and variations in system parameters.

c) A proper combination of open-loop and closed-loop controls is usually less expensive and will give satisfactory overall system performance.

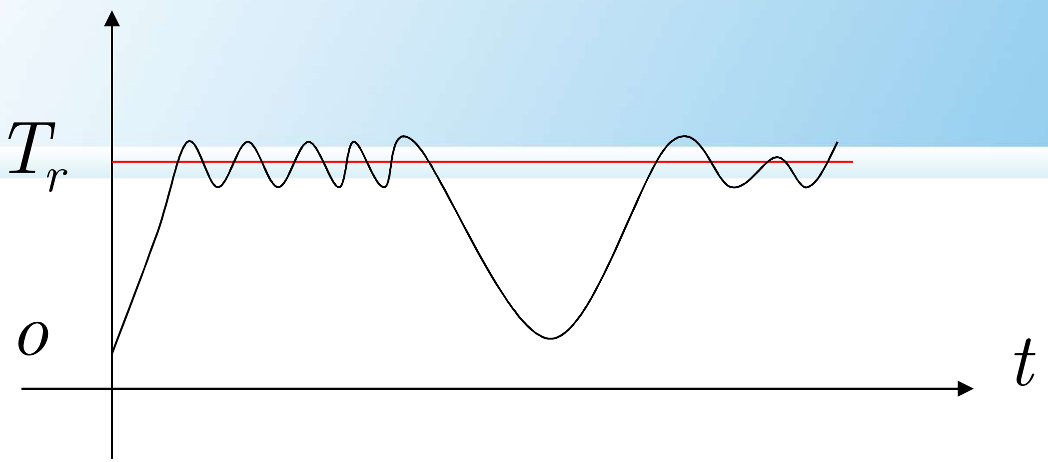
4. Combined feed-forward plus feedback control systems

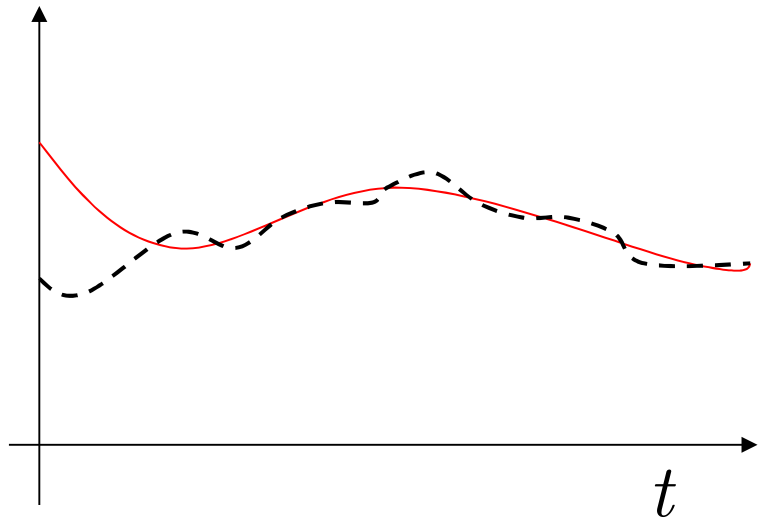


Combined feedforward plus feedback control can significantly improve performance over simple feedback control whenever there is a major disturbance that can be measured before it affects the plant output.

1-4 Design and compensation of control systems

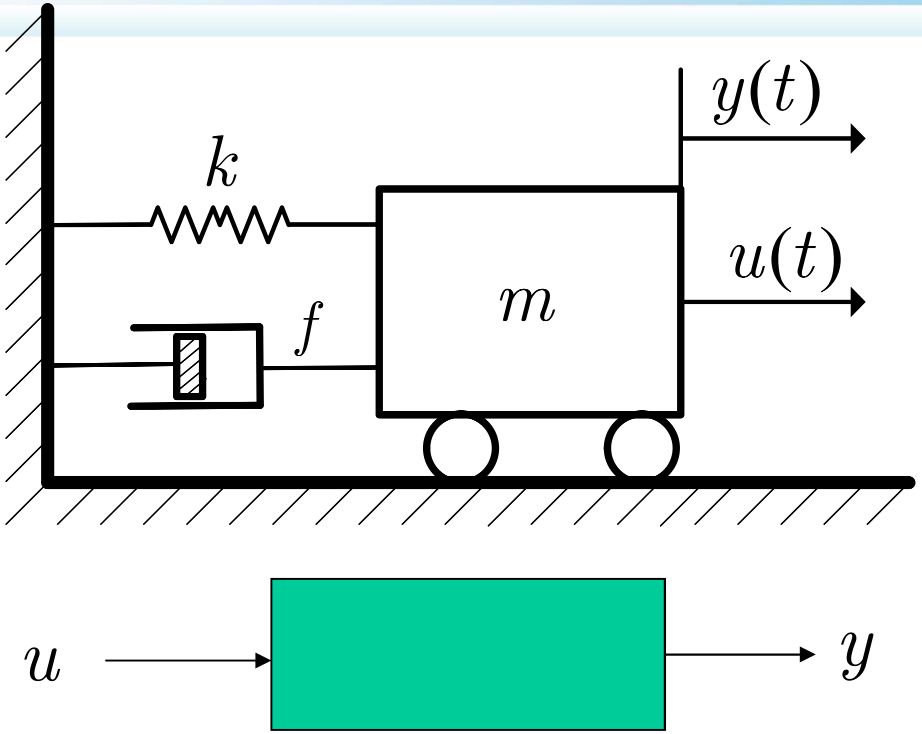
1. Mathematical models of systems





In studying a control system, one must model its dynamic characteristics so that the analysis and design of the system can be proceeded.

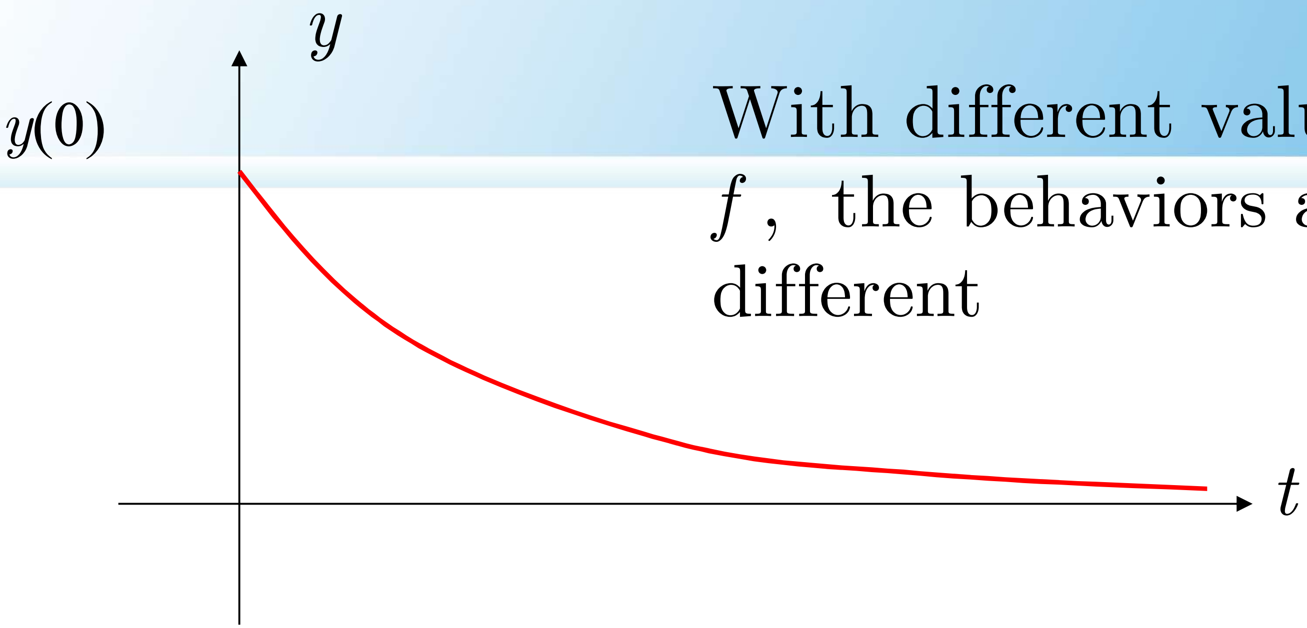
Example. Spring-mass-damper system



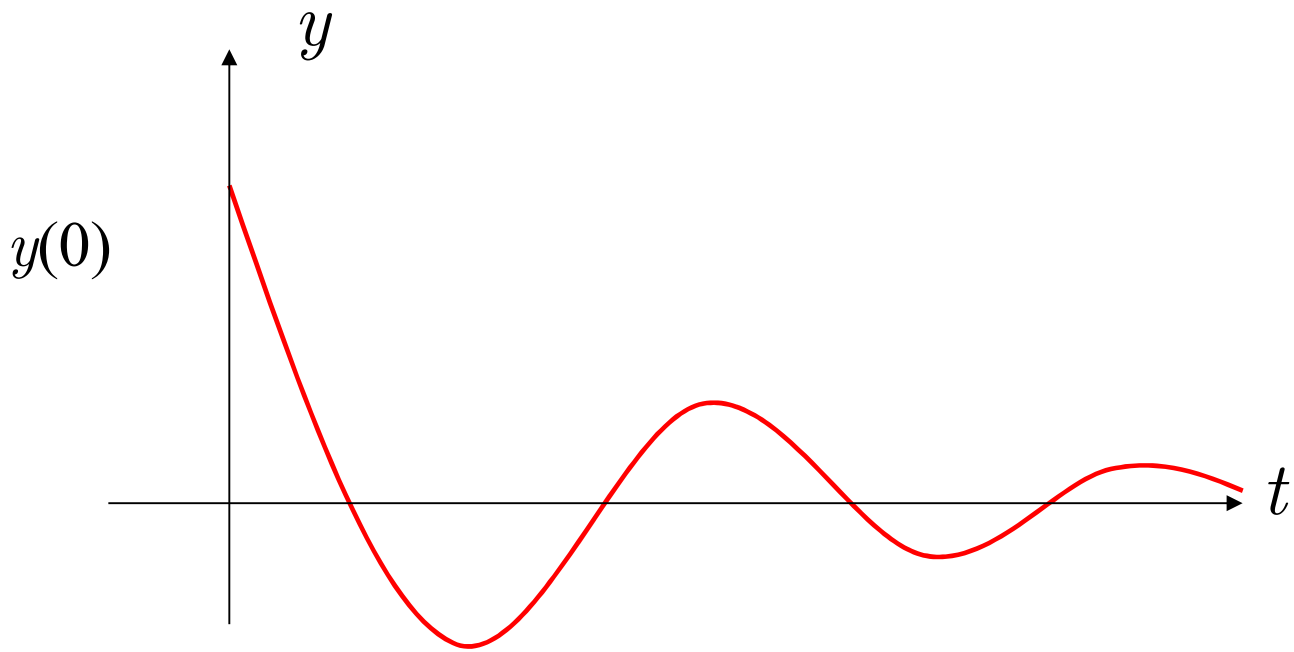
k : Spring constant

f : Damping coefficient

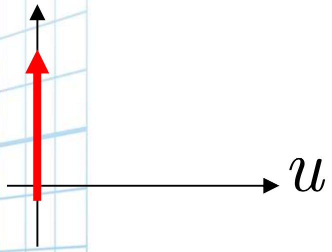
By using Newton's second law, the displacement $y(t)$ under the force, the input signal, $u(t)$, can be described by a second-order differential equation.

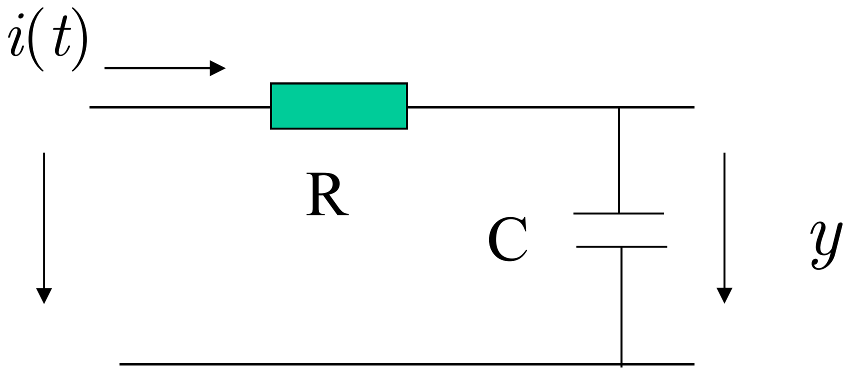


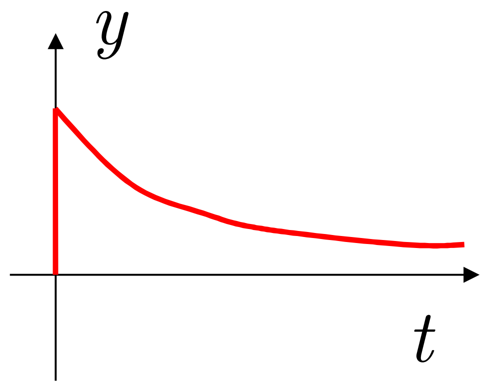
With different values of f, the behaviors are different



Example. R-C Network: A resistor–capacitor circuit

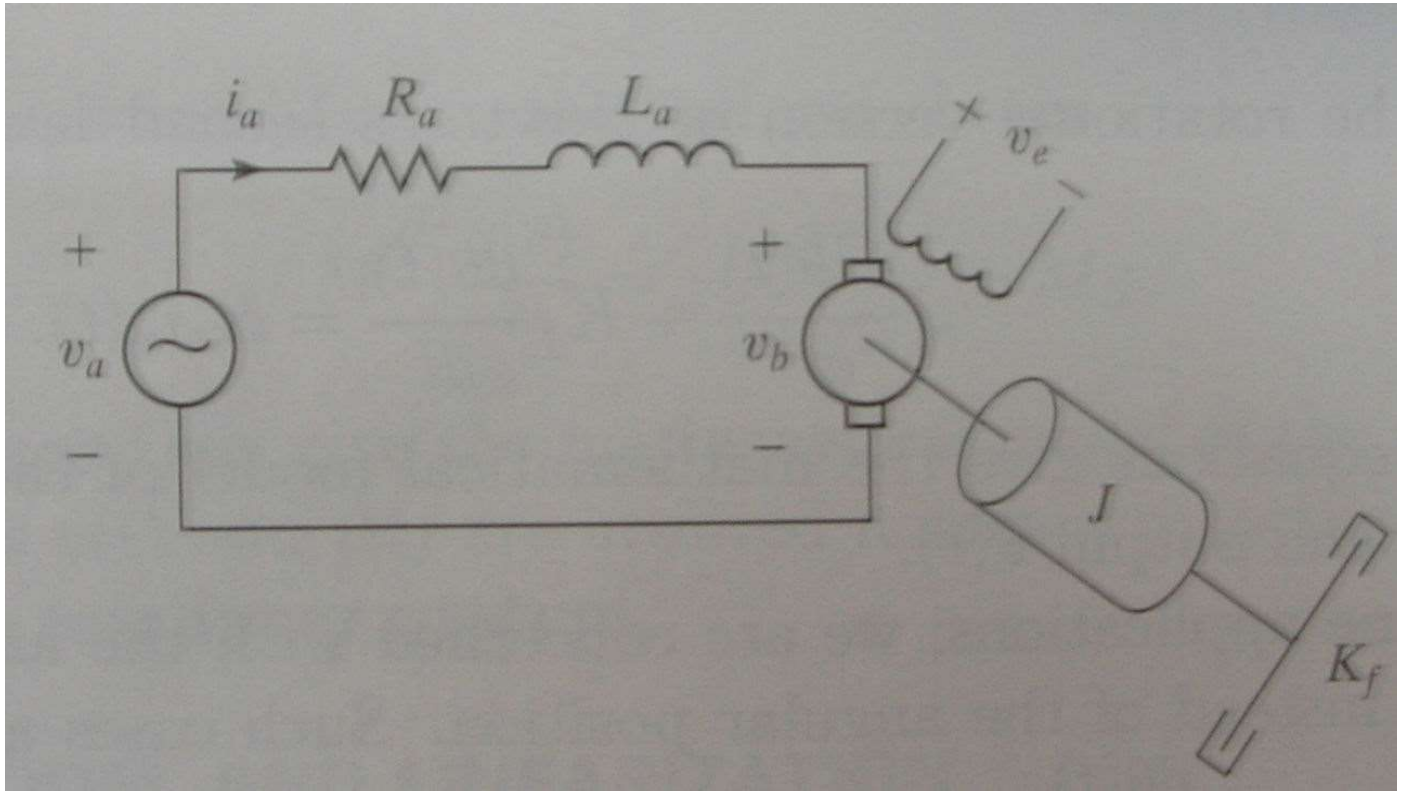


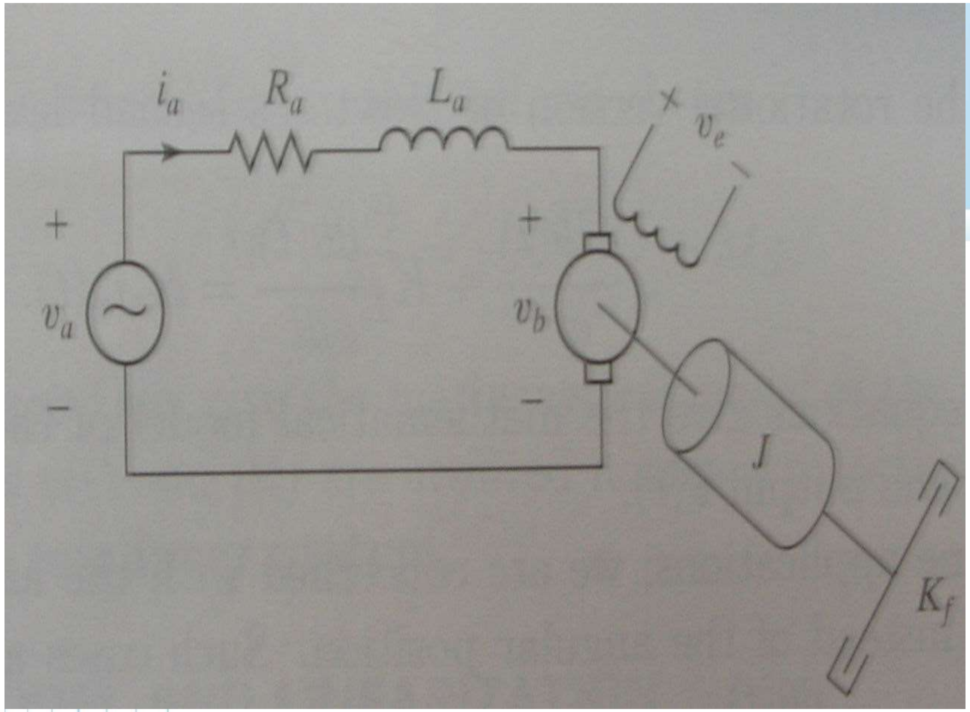




It can be checked that the system is describable by a first-order differential equation.

Example. DC motor. The description of some control systems may be complicated.
For example, the mathematical model of an armature-controlled DC motor system is more complicated than the above two examples.





R_a : armature resistance

L_a : armature inductance

J : moment of inertia of the load

K_f : friction coefficient

K_t : torque constant

K_b: back electro-motive force constant

$V_a(t)$: armature voltage

$V_b(t)$: back electro-motive force (back emf)

$\tau_m(t)$: motor torque

$\theta(t)$: angular position of the motor shaft

$\omega(t)$: angular velocity of the motor shaft

$i_a(t)$:armature current

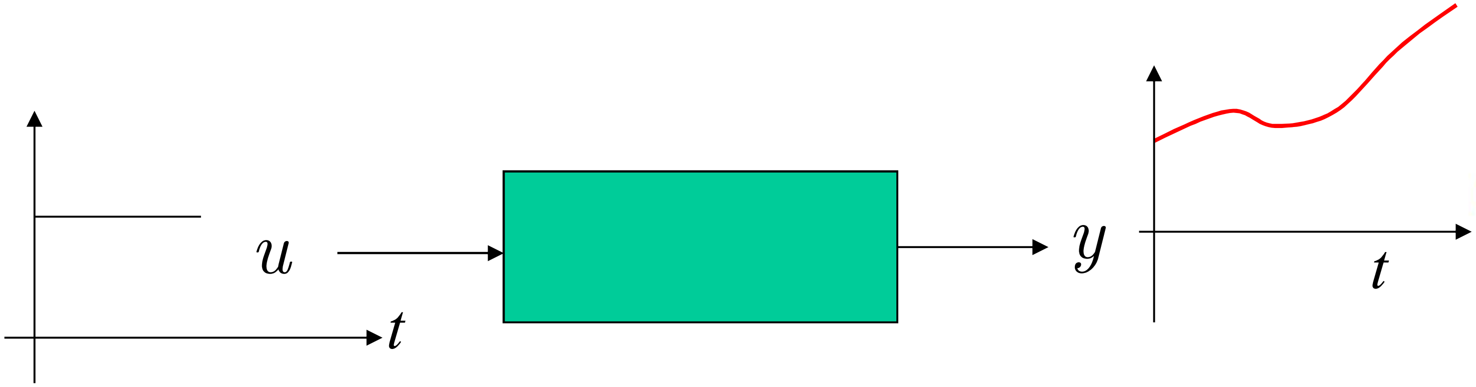
Summary

- We use quantitative mathematical models of physical systems to design and analyze control systems. The dynamic behavior is generally described by ordinary differential equations.
- The physical systems range over a wide field, including mechanical, hydraulic, and electrical systems.

2. Performance specifications

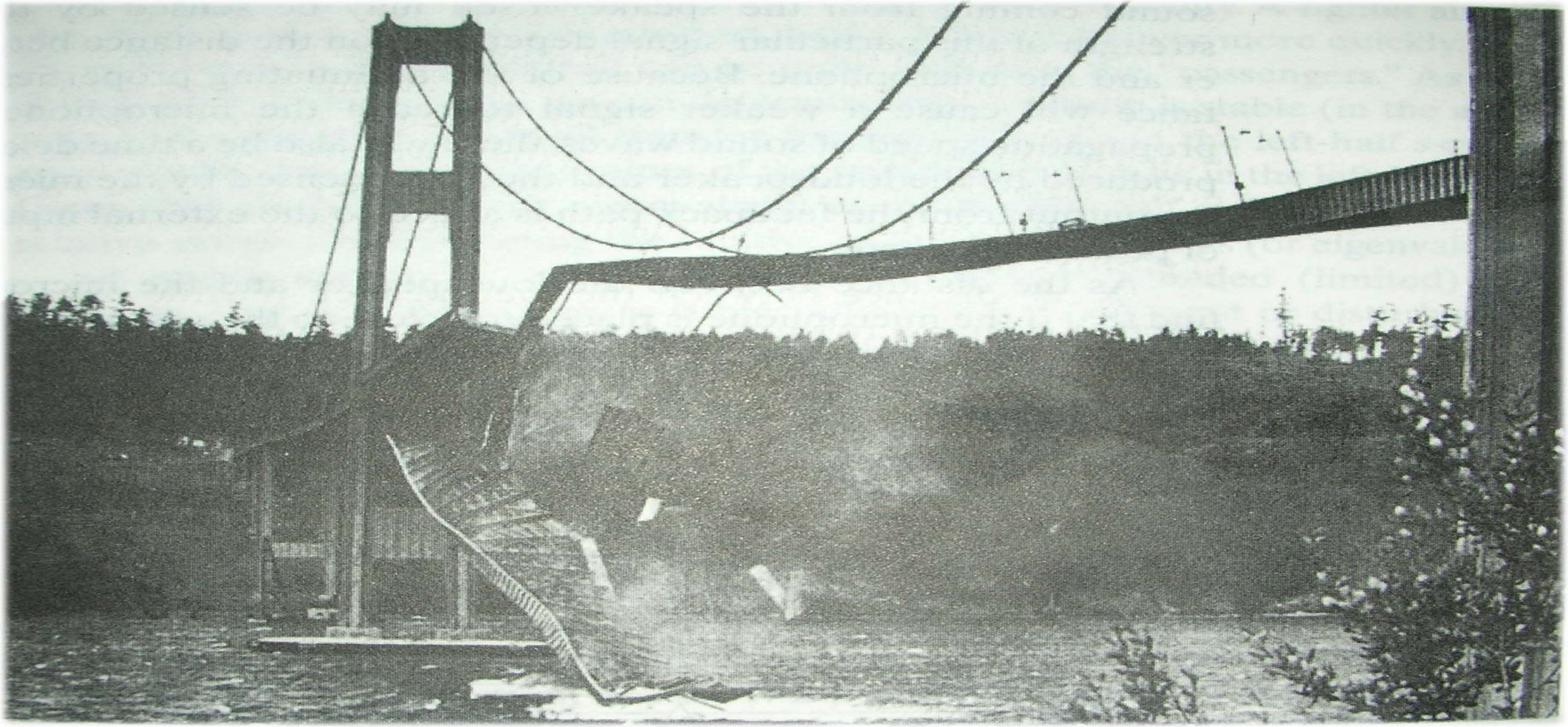
(a). Stability

A control system must be stable. A stable system is a dynamic system with a bounded response to a bounded input.



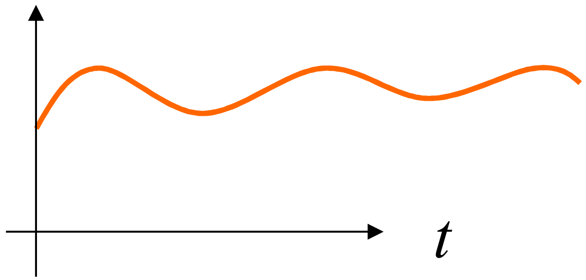
An unstable system

The famous Tacoma Narrows Bridge before it collapsed. The bridge was found to oscillate whenever the wind blew.

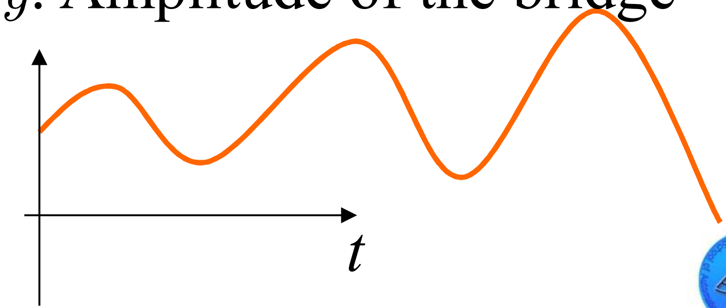


On November 7, 1940, a wind produced an oscillation that grew in amplitude until the bridge broke apart. The above picture shows the catastrophic failure.

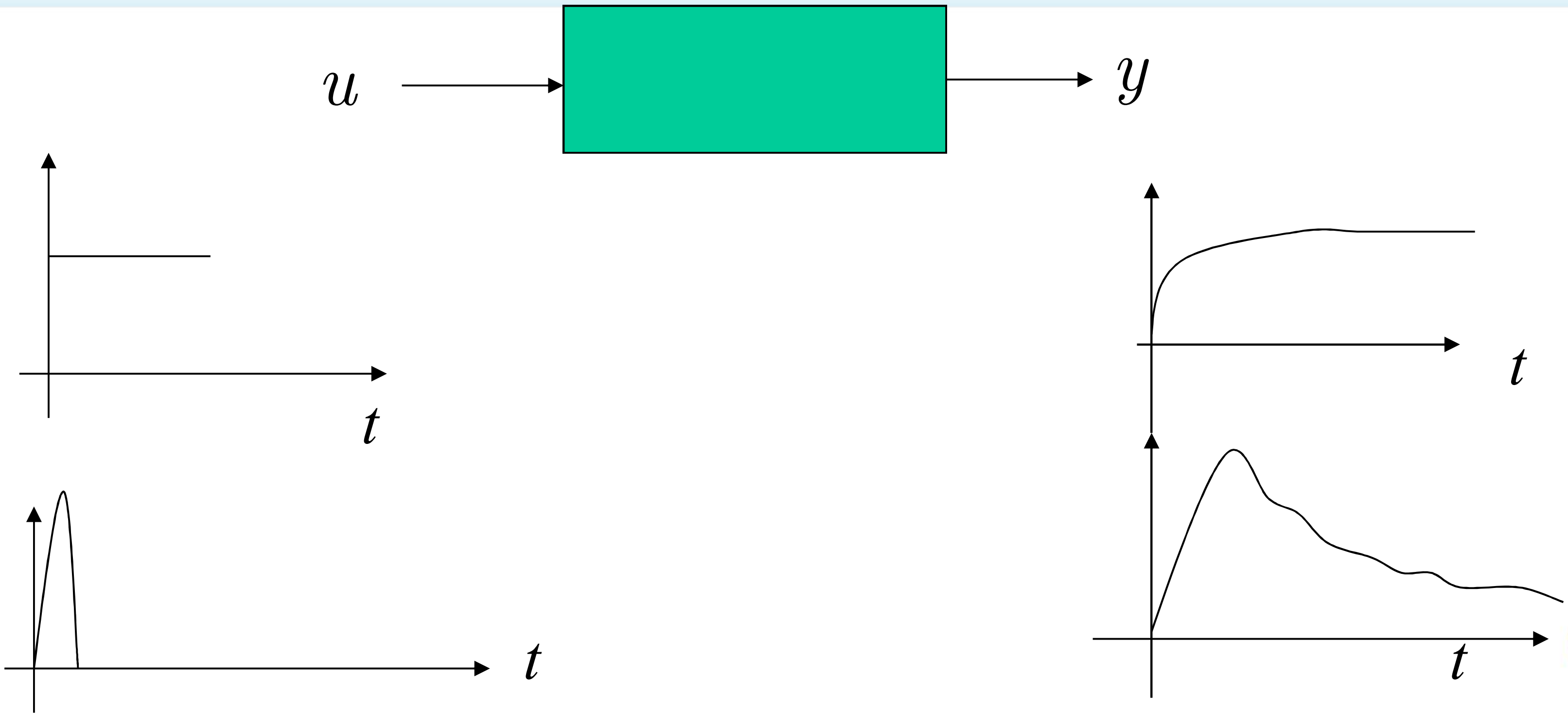
u: Wind energy



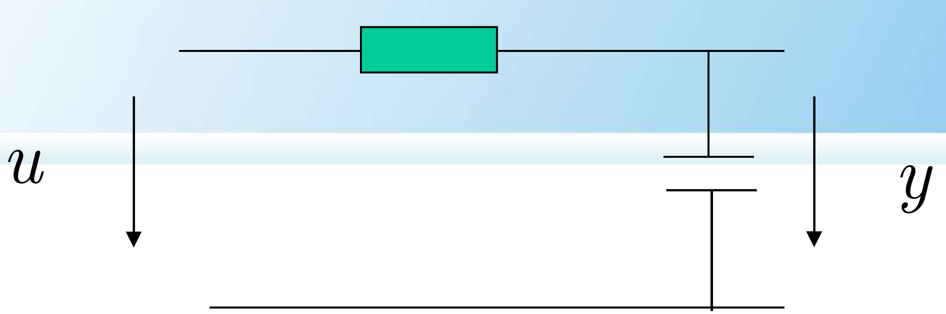
y: Amplitude of the bridge

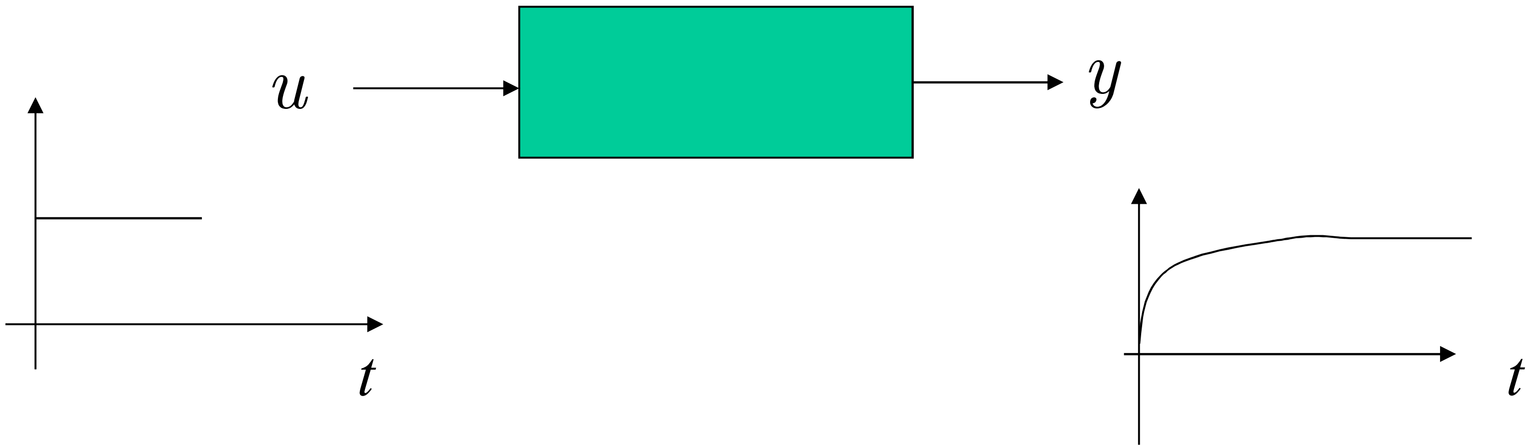


An unstable system

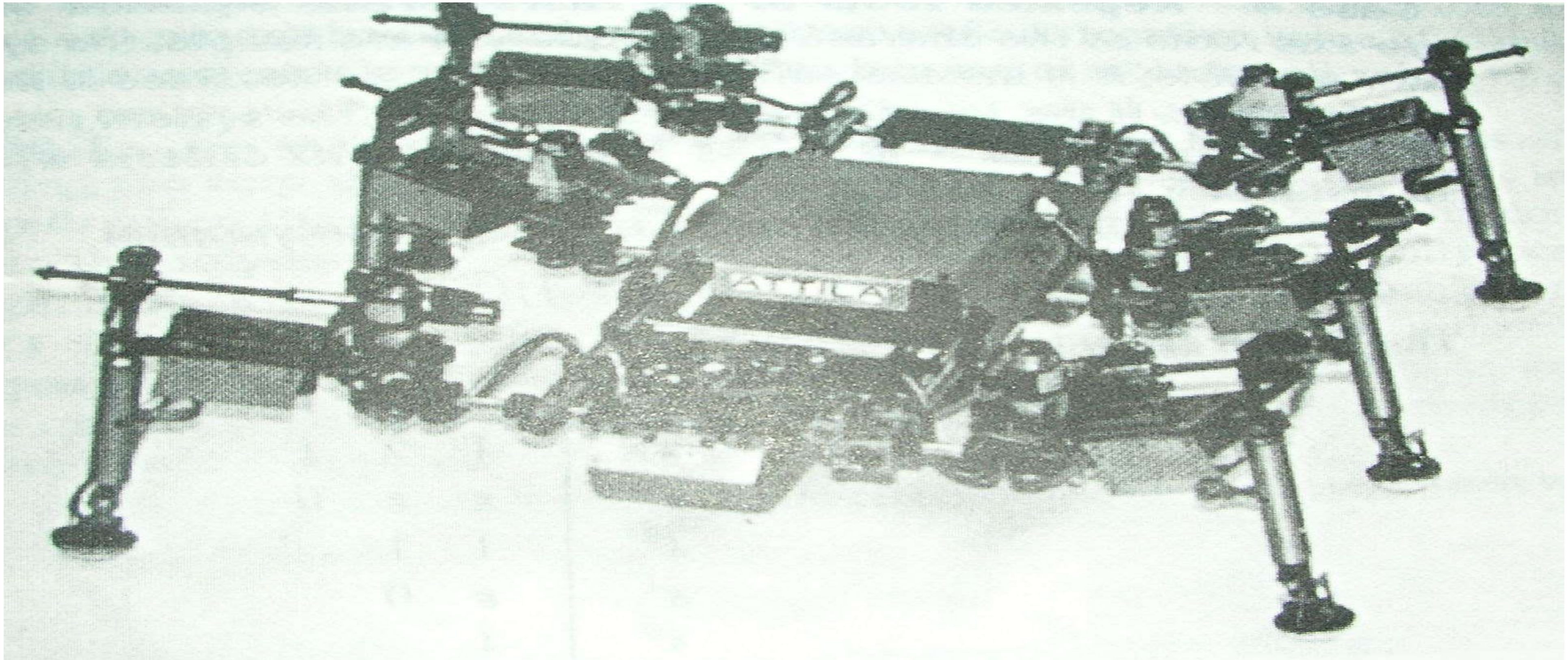


A stable system



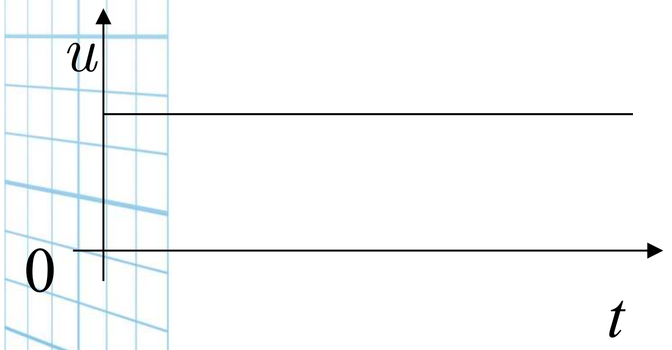


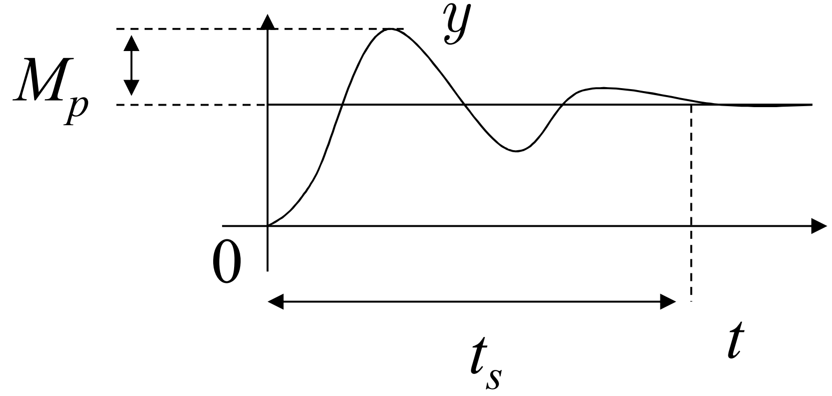
R-C network is a stable system



The robot is a six-legged micro robot system using highly flexible legs with high-gain controllers that may become unstable and oscillate. Therefore, more control effort is needed for the robot to work well.

(b). Transient response

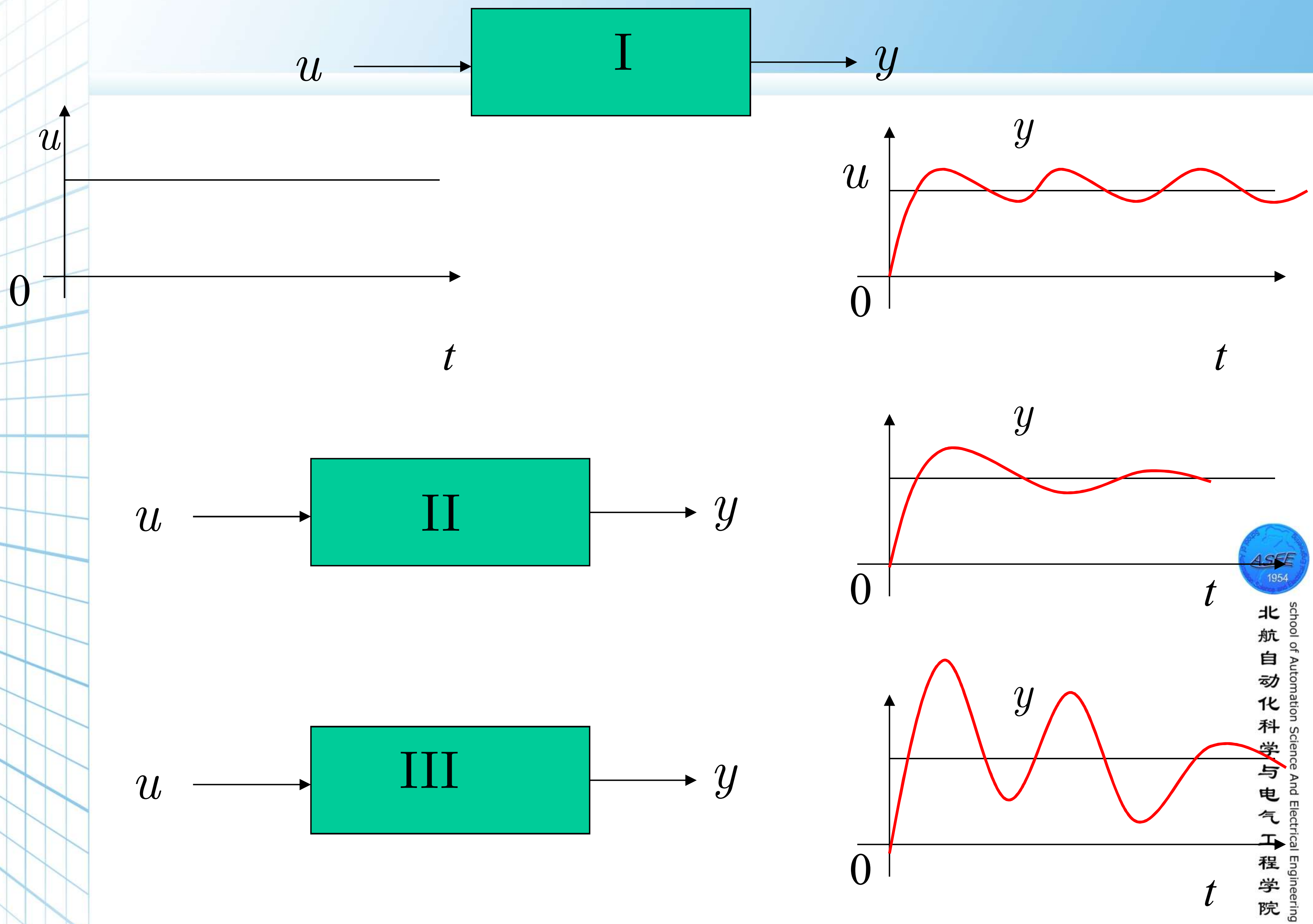




The transient response of a practical control system often exhibits damped oscillations before reaching steady state.

Requirements:

It is desirable that the transient response **be sufficiently fast and be sufficiently damped**.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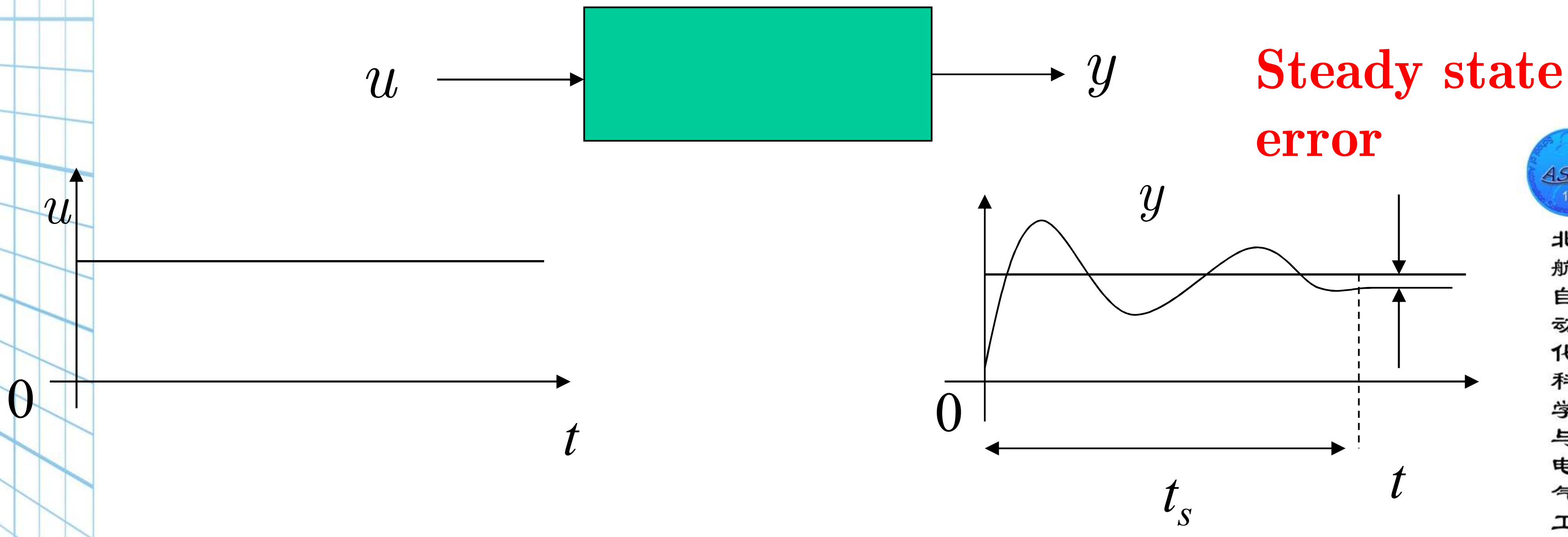
(c). Steady state error

- Steady state errors in a control system can be attributed to many factors

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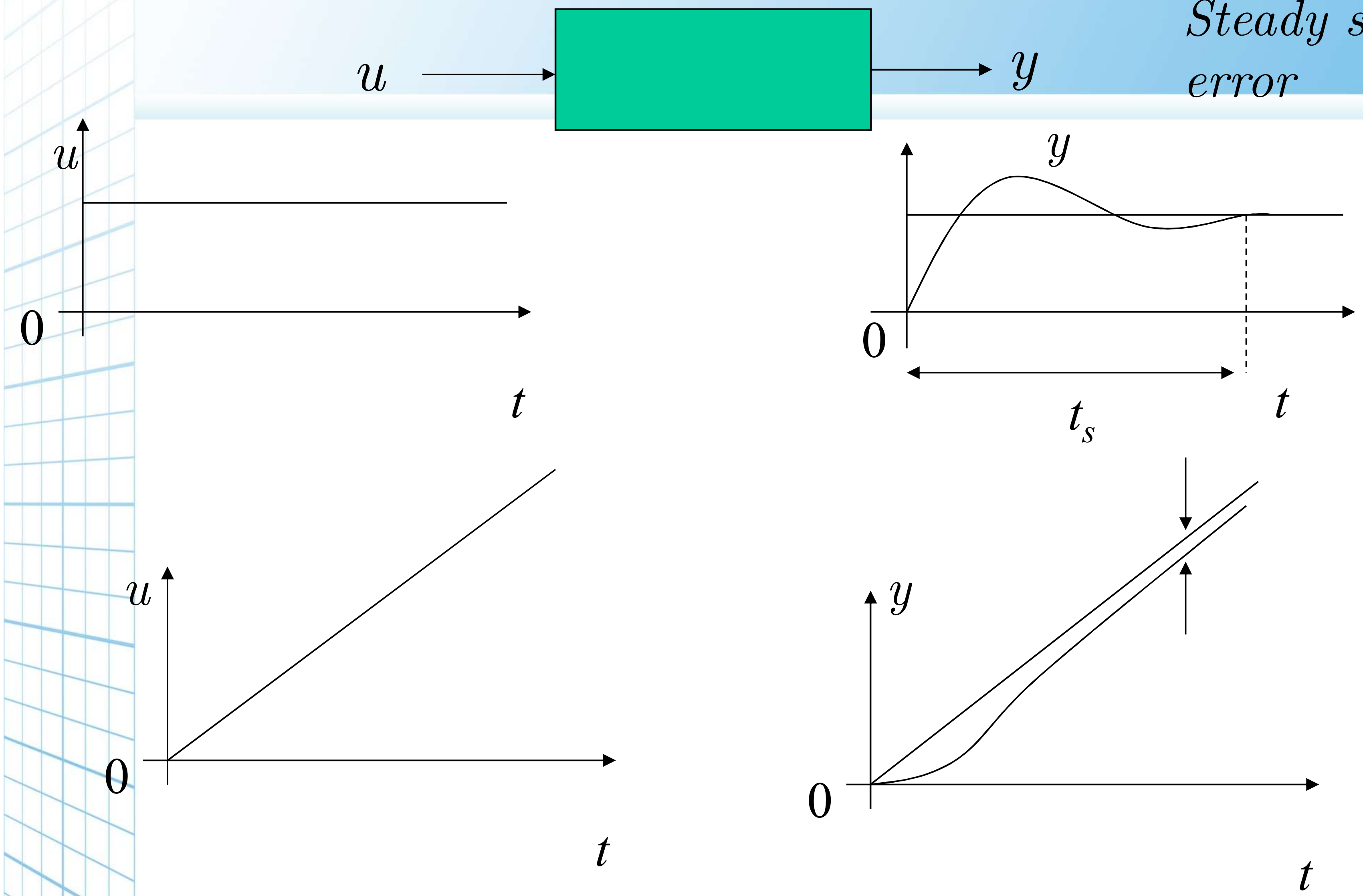
Steady state error



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- Changes in the reference input will cause unavoidable errors during transient periods and may also cause steady state errors.

Requirement:

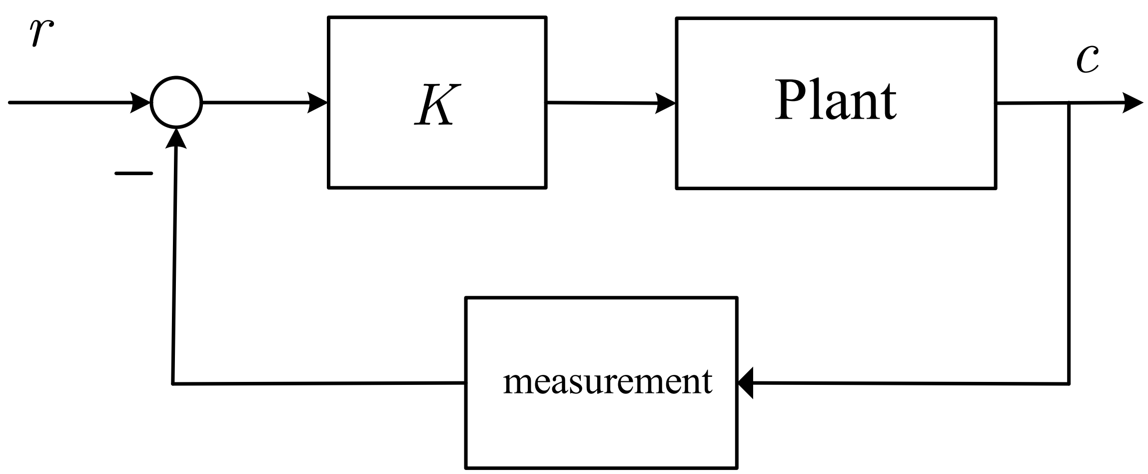
- It is desirable that the steady state error be **sufficiently small**.

Summary of performance specifications

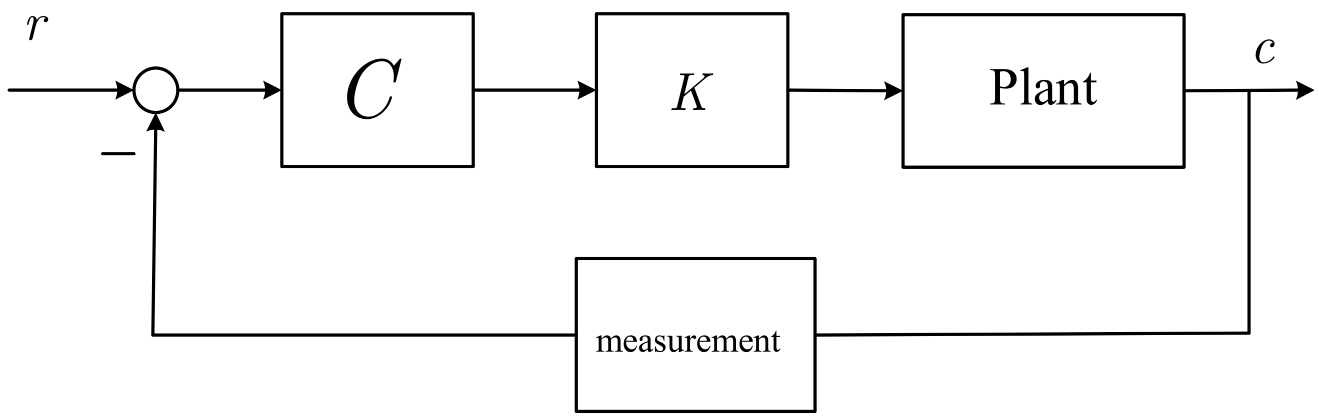
A desired control system should be stable with sufficiently fast transient response and sufficiently small steady-state error.

3. System compensation

The compensation is necessary if a control system does not satisfy the given performance specifications. For example:



If the adjustment of K still does not provide sufficient alteration of the system behavior to meet the given specifications, a compensator is necessary.



- PID
- Lead compensator
- Lag compensator
- ….

Review: Chapter 1

- What is a control system?
- What is an automatic control system? What is a closed-loop system? What is an open-loop system?
- How to describe a system?
- What are the basic requirements for a control system?