CHEE 351 · CHAPTER 1

Introduction to Process Control

What process dynamics and control mean, why we need them, and how feedback and feedforward strategies differ, built around a stirred-tank blending example.

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Learning objectives

01 Distinguish steady-state from dynamic (transient) process behavior

02 Identify controlled, manipulated and disturbance variables in a process

03 Derive a steady-state design equation and simple control laws for a blending system

04 Compare feedback, feedforward and combined control strategies

05 Describe the hierarchy of process control activities

06 Outline the major steps in developing a control system

01

Process dynamics

How processes behave when they are not at steady state.

What is process dynamics?

Steady state

Process variables do not change with time.

But on what time scale? A noisy measurement fluctuates even when the process is effectively steady.

Unsteady state

Process variables change with time: transient or dynamic behavior.

Process dynamics is the study of this unsteady-state behavior.

Many of the chemical engineering courses emphasizes steady-state or equilibrium situations:

- thermodynamics
- transport
- unit operations and
- reactor design

Yet, this is not the case usually !

Transients in continuous processes

Start-up and shutdown

Every continuous plant passes through large transients when it starts and stops.

Grade changes

Switching to a new product specification moves the whole plant to a new operating point.

Major disturbances

For example, a refinery operating during stormy or hurricane conditions.

Equipment or instrument failure

A pump trips, a valve sticks or a sensor fails.

Batch processes are inherently dynamic

A batch process never reaches steady state: it is **unsteady by design**.

In a batch reactor, composition changes with time as the reaction proceeds. Other variables, such as temperature, may be held constant by the control system.

Batch reactor

Charge reactants

React: composition changes

Hold T constant by control

Discharge product

02

Process control

What gets measured, what gets manipulated, and what we are trying to achieve.

Process control at industrial scale

1,000–5,000

process variables typically measured in a large continuous plant, such as an oil refinery, ethylene plant or pulp mill

seconds–minutes

typical sampling interval for process variables: flow, temperature, pressure, level

shift to weekly

typical sampling interval for quality variables, from once per 8-hour shift to weekly

Most of the measured variables in such plants are also controlled.

How is control implemented?

We implement process control by **manipulating process variables**, usually flow rates.

Manipulated flow	Typical purpose
Feed rate	Throughput, composition
Cooling or heating rate	Temperature
Product flow rate	Level, inventory

Batch plants

Smaller than continuous plants in most industries, but still with large numbers of measured variables.

Exception: microelectronics, with 200–300 processing steps.

Why do we need process control?

01 Safety

02 Environmental protection

03 Equipment protection

04 Smooth operation and production rate

05 Product quality

06 Profit optimization

07 Monitoring and diagnosis

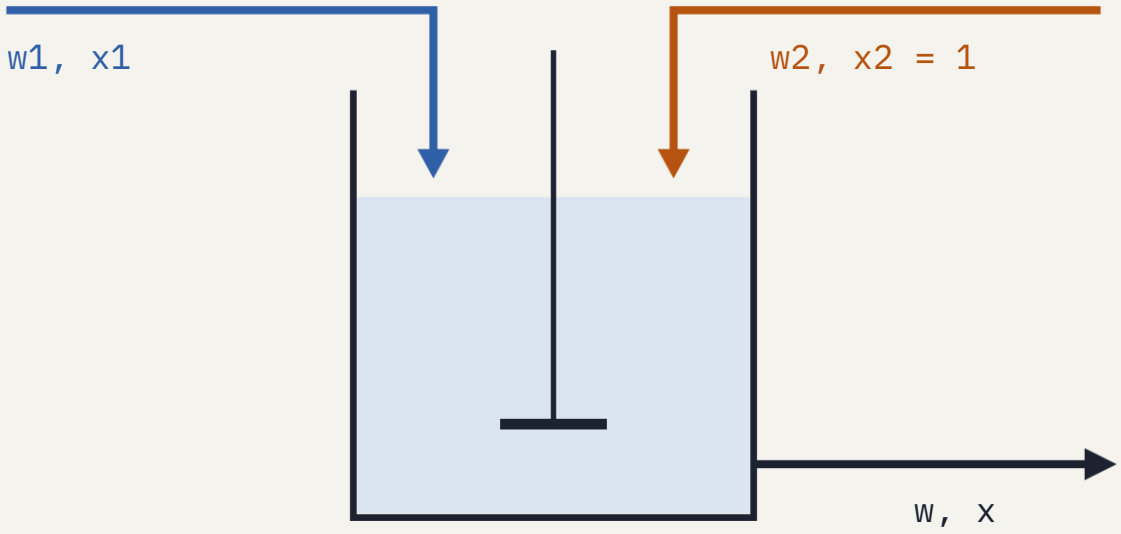
The first three are non-negotiable; the rest determine how well the plant performs.

03

Illustrative example: a blending system

One stirred tank, two inlet streams and one control objective.

The stirred-tank blending system



Two streams containing component A are mixed in a stirred tank.

Symbol	Meaning
w1, w2, w	mass flow rates
x1, x2, x	mass fractions of A

Stream 2 is pure A, so x2 = 1.

Assumptions, objective and terminology

Assumptions

01 w1 is constant

02 x2 = 1: stream 2 is pure A

03 Perfect mixing in the tank

CONTROL OBJECTIVE

Keep x at its set point xsp despite variations in x1(t), by adjusting w2.

Variable type	Here
Controlled (output)	x
Manipulated (input)	w2
Disturbance (load)	x1

Design question: what w2 gives x = xsp?

At steady state, with overbars marking nominal design values:

$$\text{Overall: } 0 = \bar{w}1 + \bar{w}2 - \bar{w} \quad (1\text{-}1)$$
$$\text{Component: } 0 = \bar{w}1\bar{x}1 + \bar{w}2\bar{x}2 - \bar{w}\bar{x} \quad (1\text{-}2)$$

Set $\bar{x} = xsp$ and $\bar{x}2 = 1$, then solve for $\bar{w}2$:

$$\bar{w}2 = \bar{w}1\ (xsp - \bar{x}1)/(1 - xsp) \quad (1\text{-}3)$$

The control question

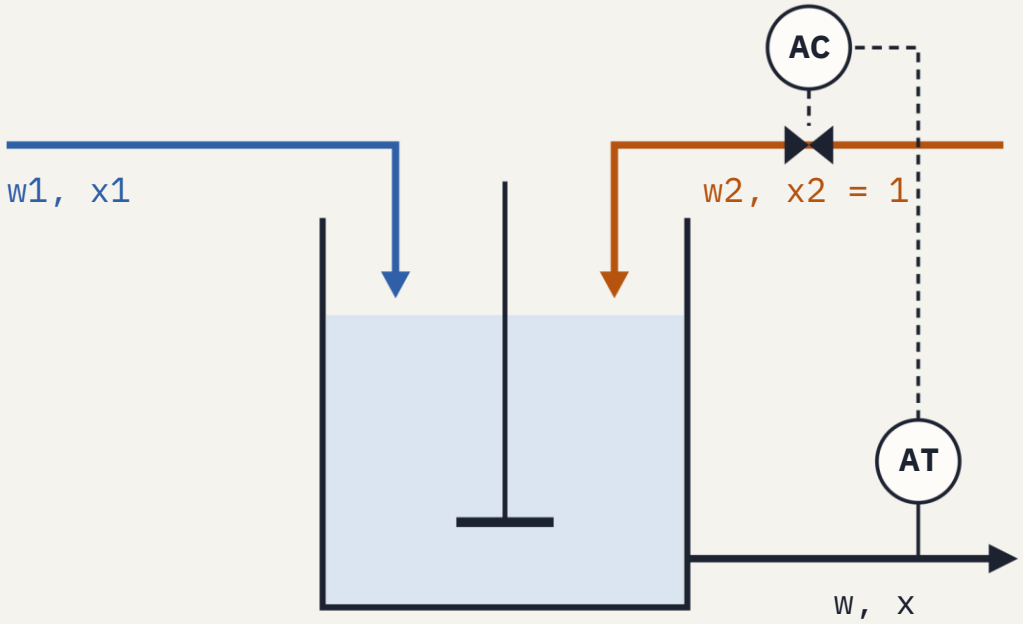
Suppose the inlet composition x1 changes with time. How do we keep x at or near xsp?

Example: if x1 rises above $\bar{x}1$ while w2 stays at $\bar{w}2$, then x rises above xsp.

Intuition

If x is too high, reduce w2. If x is too low, increase w2.

Method 1: measure x, adjust w2



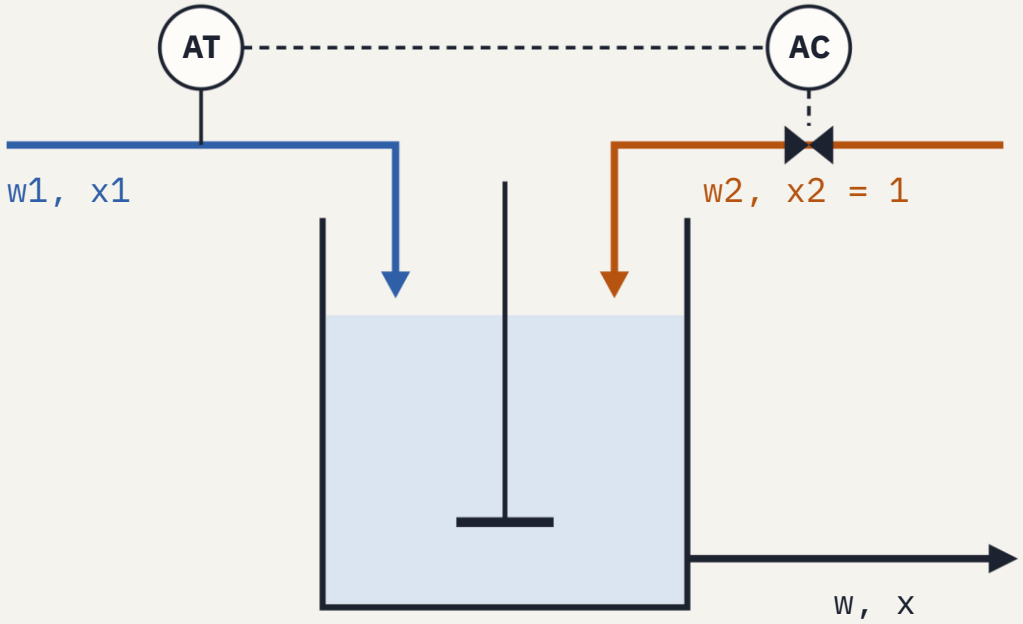
Feedback control. An analyzer (AT) measures x; the controller (AC) adjusts the valve on stream 2.

$$w2(t) = \bar{w}2 + Kc[xsp - x(t)] \quad (1\text{-}4)$$

Kc is the controller gain. The change in w2 is proportional to the deviation from the set point: **proportional control**.

Manual control: an operator makes the adjustments. Automatic control: the controller does.

Method 2: measure x1, adjust w2



Feedforward control. Measure the disturbance x1 and compute w2 before x is upset.

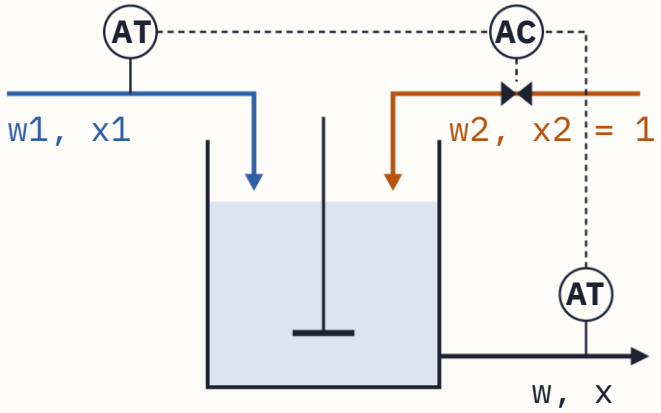
$$w2(t) = \bar{w}1\,[xsp - x1(t)]/(1 - xsp) \quad (1\text{-}5)$$

Obtained by replacing $\bar{x}1$ and $\bar{w}2$ in design equation 1-3 with x1(t) and w2(t).

Because Eq. 1-3 holds only at steady state, its effectiveness during transients is not guaranteed.

Methods 3 and 4

Method 3: measure x1 and x, adjust w2



Combines Methods 1 and 2: feedforward acts on the measured disturbance, and feedback corrects whatever remains.

Method 4: use a larger tank

A larger tank has more capacitance, so fluctuations in x1 are damped out before they reach the outlet.

Drawback: increased capital cost. This is a design change rather than a control strategy.

Classification of control strategies

Method	Measured variable	Manipulated variable	Category
1	x	w2	Feedback (FB)
2	x1	w2	Feedforward (FF)
3	x1 and x	w2	FF / FB
4	—	—	Design change

Table 1.1. The category is set by **what is measured**: the controlled variable for feedback, a disturbance for feedforward.

Feedback versus feedforward

Feedback

Measures the controlled variable

+ Corrective action regardless of the source of the disturbance
+ Reduces sensitivity to disturbances and to changes in the process
– No action until the disturbance has already upset the process
– Can give very oscillatory responses, or even instability

Feedforward

Measures a disturbance variable

+ Corrects for the disturbance before it upsets the process
– The disturbance must be measurable
– No corrective action for unmeasured disturbances

The hierarchy of process control activities

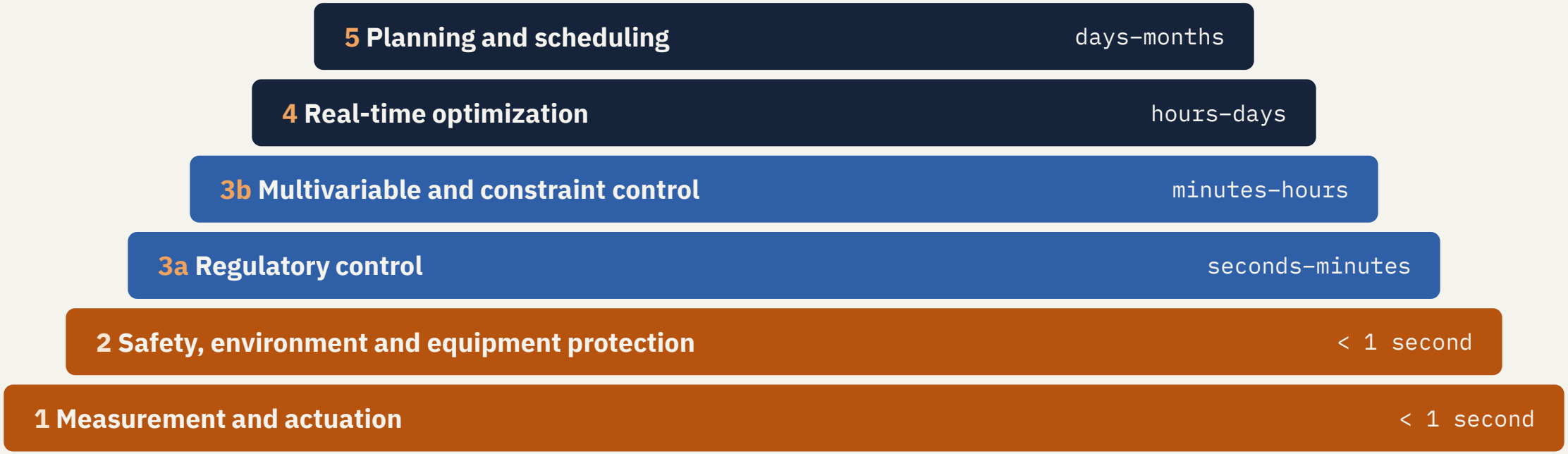


Figure 1.7. Lower levels act faster and sit closer to the process.

What happens at each level

Level	Activity	Examples
1	Measurement and actuation	Sensors, transmitters, control valves
2	Safety and protection	Alarms, interlocks, emergency shutdown
3a	Regulatory control	PID loops on flow, level, temperature, pressure
3b	Multivariable and constraint control	Model predictive control
4	Real-time optimization	Economically optimal set points
5	Planning and scheduling	Production targets, raw materials, shipments

Major steps in control system development

01 Formulate control objectives

02 Develop a process model from physical and chemical principles or plant data

03 Devise a control strategy

04 Select control hardware and software

05 Install the control system

06 Adjust the controller settings

Inputs along the way

Management objectives

Physical and chemical principles

Plant data, if available

Computer simulation

Key takeaways

01 Process dynamics is the study of transient behavior; control keeps processes near desired conditions despite it.

02 Every control problem has controlled, manipulated and disturbance variables.

03 Feedback measures the controlled variable and corrects any upset, but only after it occurs.

04 Feedforward measures a disturbance and acts first, but only for measured disturbances and with a good model.

05 Control activities form a hierarchy, from sub-second measurement to month-long planning.

Practice questions

01 For the blending system, what happens to x if w1 increases and w2 is held constant?

02 Rewrite the feedback law (1-4) for a case where w2 must increase when x rises. What sign must Kc have?

03 Why might the feedforward law (1-5) perform poorly during a rapid change in x1?

04 Identify the controlled, manipulated and disturbance variables for a shower with hot and cold water valves.

05 Give one example of a plant situation for each level of the control hierarchy.