Master in Control Engineering

Process Automation
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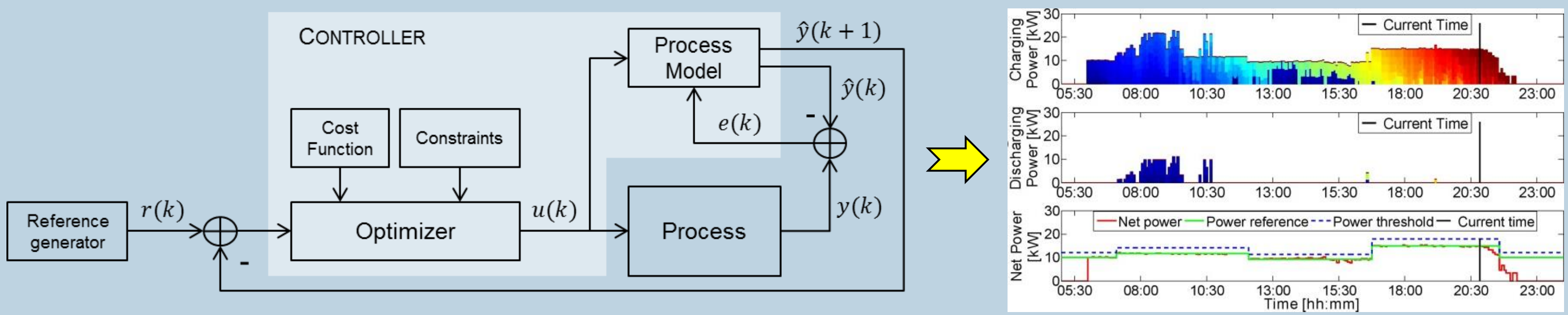
Master in Control Engineering

Process Automation

3. Introduction to Process Control

Slides based on:
D.E. Seborg et al., *Process Dynamics and Control (3rd ed.)*, 2009, Ch. 1, pp. 1-11



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Outline

- Introduction to Process Control
  - Examples of process control problems
    - Continuous processes
    - Batch processes
  - Process control strategies and design
  - Control of a distillation column
- Summary

Examples of process control problems

- What is a process?
  - PROCESS

    Conversion of raw materials to products using chemical and/or physical operations

- Continuous vs. batch production
  - CONTINUOUS PRODUCTION

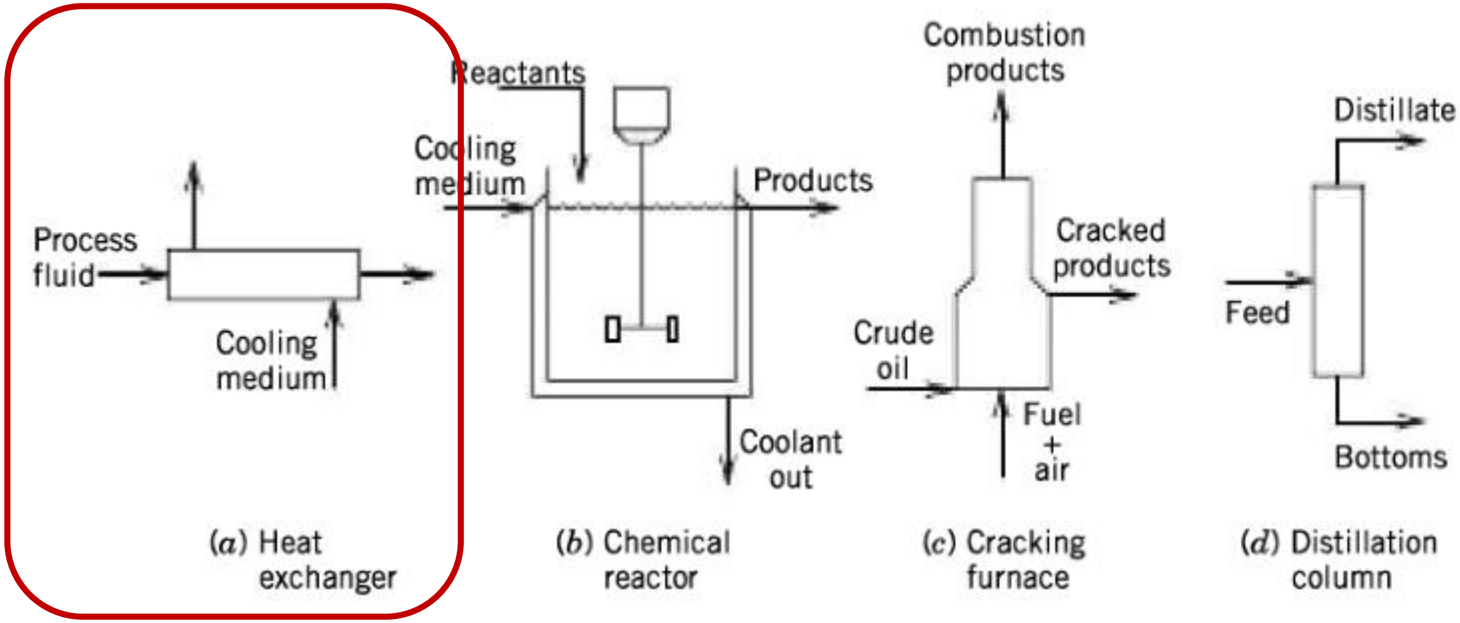
    Flow production method used to manufacture, produce, or process materials without interruption
    The materials (e.g., dry bulk or fluids) that are being processed are continuously in motion and undergo chemical reactions or mechanical or heat treatment

  - BATCH PRODUCTION

    Technique used in manufacturing, in which the object in question is created stage-by-stage over a series of workstations, and different batches of products are made

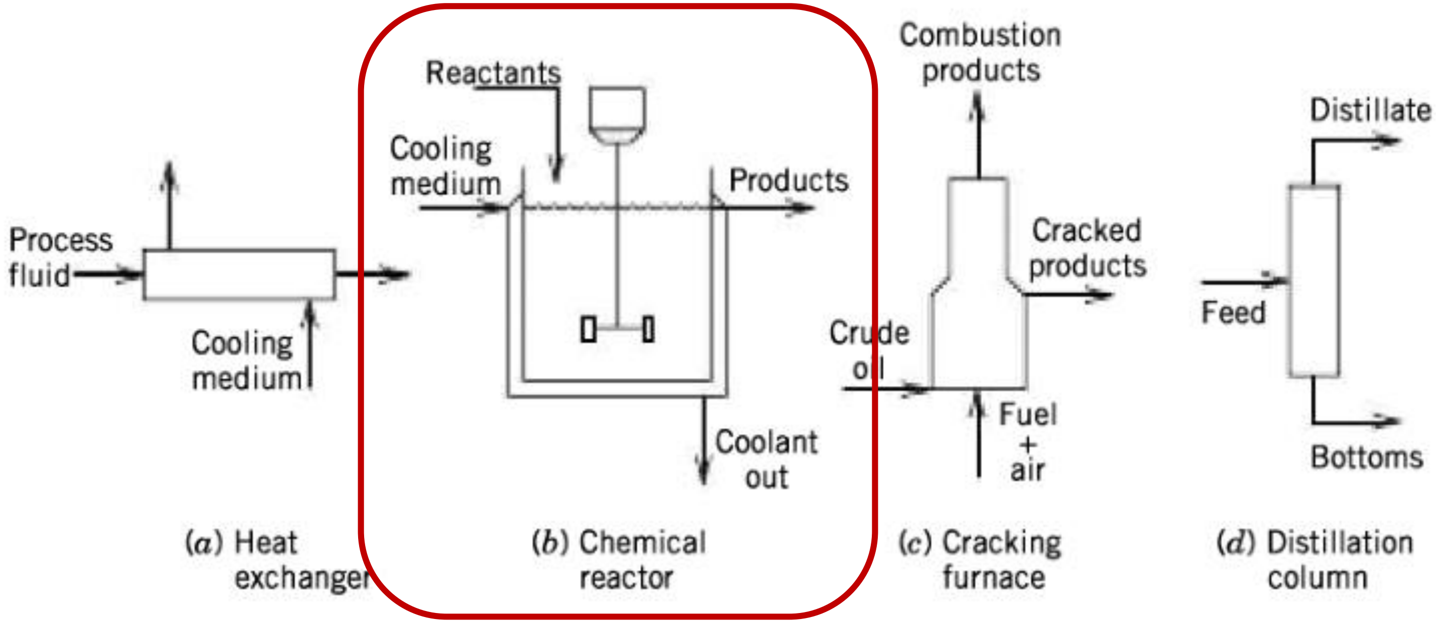
Examples of process control problems

- Continuous processes
  - (a) Tubular heat exchanger
    - A process fluid on the tube side is cooled by cooling water on the outer side (controlled variable)
    - The exit temperature of the process fluid is controlled by manipulating the flow rate of the cooling water (control variable or manipulated variable)
    - The inlet temperature variations affect the heat exchanger operation (disturbance variable)



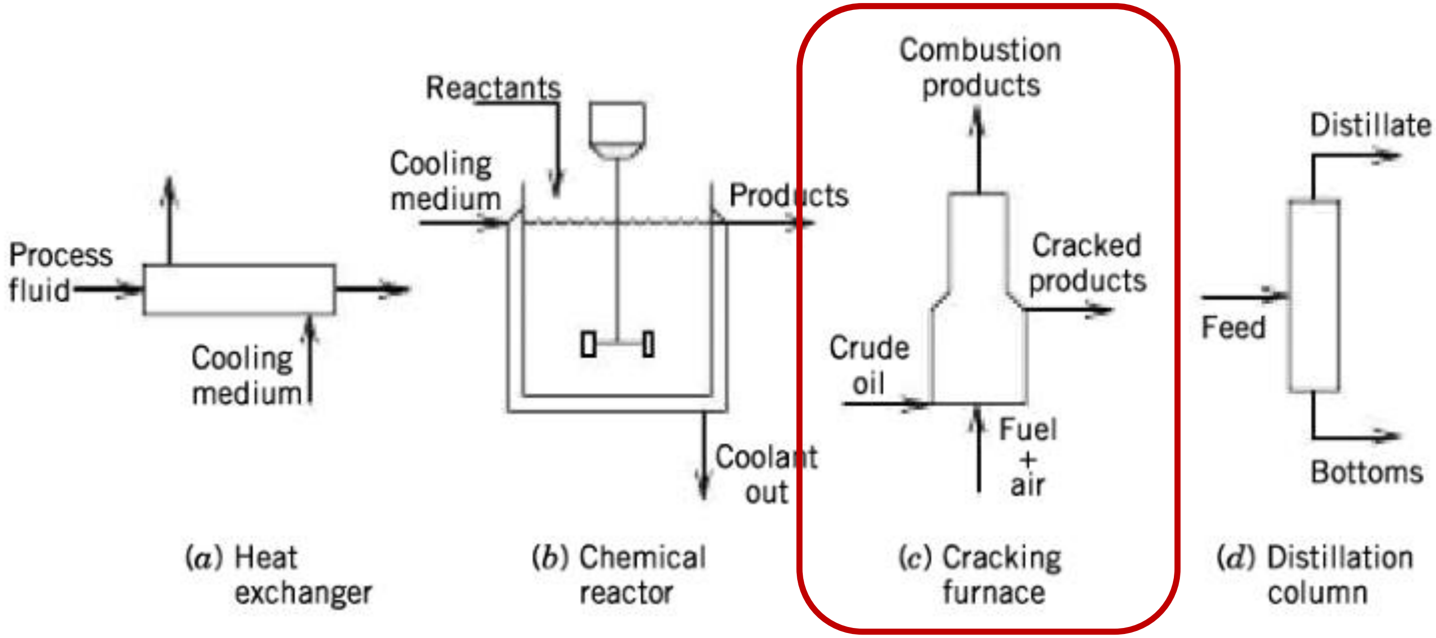
Examples of process control problems

- Continuous processes
  - (b) Continuous tank reactor
    - Highly exothermic reaction
    - Control the reactor temperature (controlled variable) by manipulating the flow rate of coolant in a jacket or cooling coil
    - Composition, flow rate and and temperature (feed conditions) are manipulated variables or disturbance variables.



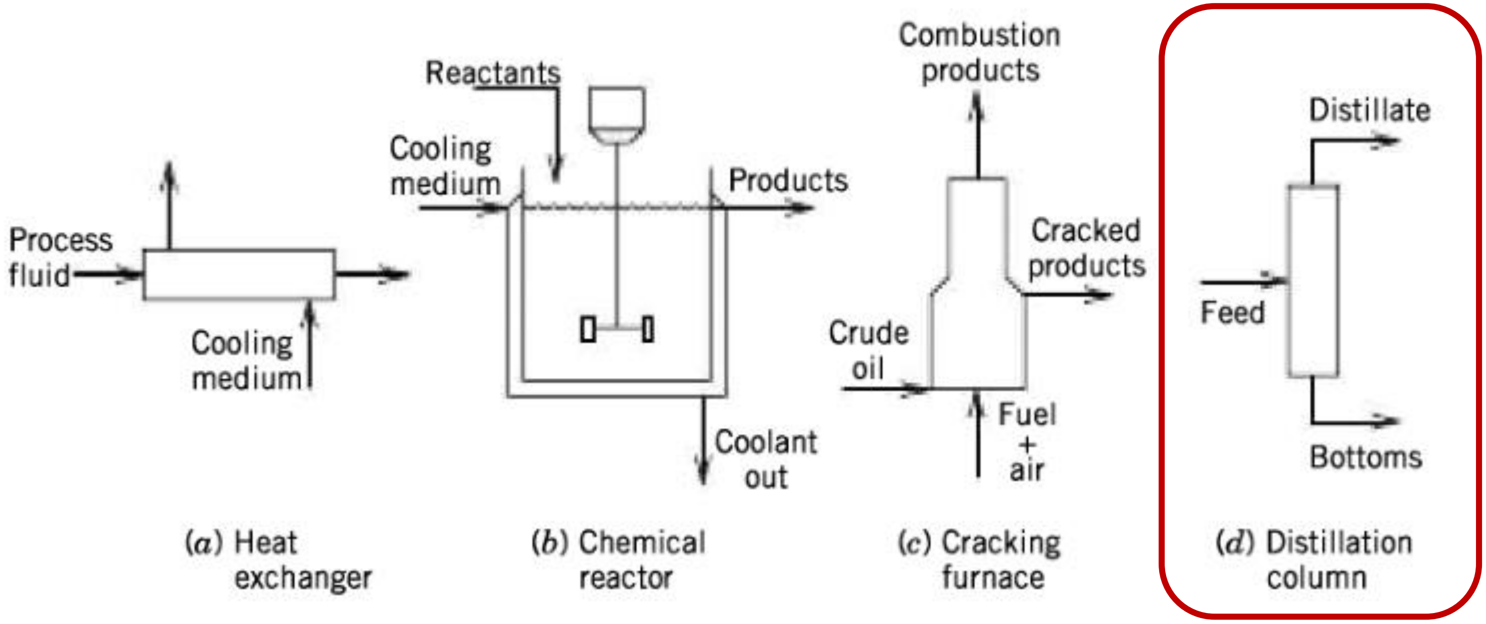
Examples of process control problems

- Continuous processes
  - (c) Thermal cracking furnace
    - Crude oil is broken down ("cracked") into a number of lighter petroleum fractions by the heat transferred from a burning fuel/air mixture (control objective)
    - The fuel flow rate controls the furnace temperature (manipulated variable)
    - The fuel/air ratio controls the amount of excess air in the fuel gas (manipulated variable)
    - The crude oil composition and the heating quality of the fuel are disturbance variables



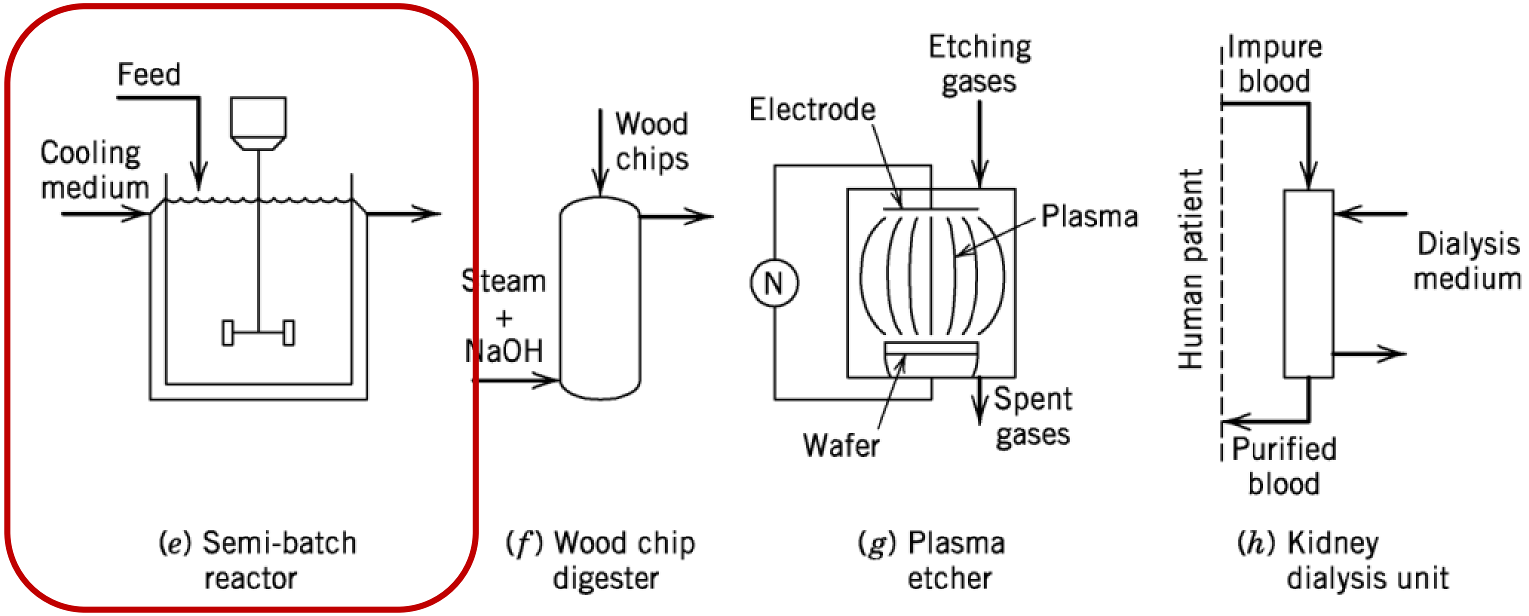
Examples of process control problems

- Continuous processes
  - (d) Multicomponent distillation column
    - Different control objectives
      - Control the distillate composition by adjusting the reflux flow rate or the distillate flow rate
      - Control the tray temperature near the top of the column if the composition cannot be measured on-line
    - The feed conditions are disturbance variables.



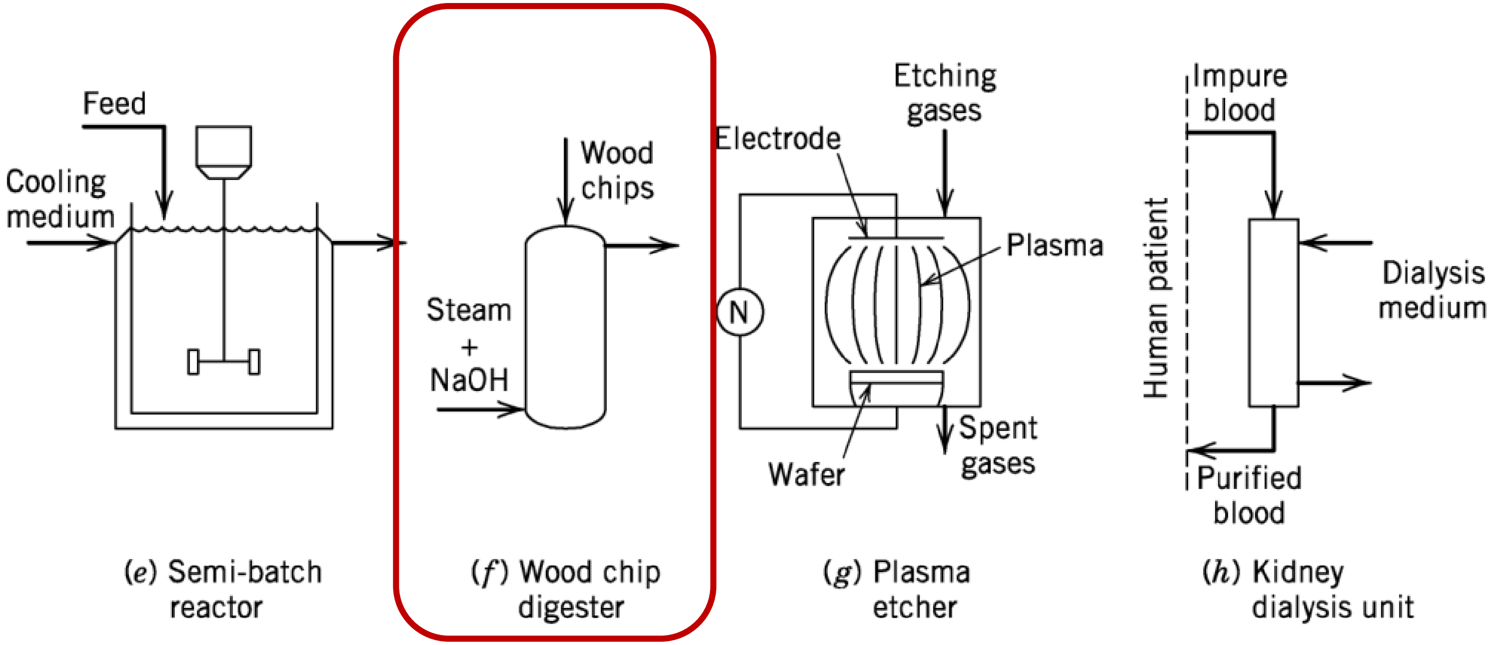
Examples of process control problems

- Batch and semi/batch processes
  - (e) Batch or semi-batch reactor
    - E.g., used in specialty chemical plants, polymerization plants, pharmaceutical facilities,
    - An initial charge of reactants is brought up to reaction conditions, and the reactions are allowed to proceed for a specified period of time or until a specified conversion is obtained
    - The reactor temperature is controlled by manipulating a coolant flow rate
    - The end-point (final) concentration of the batch can be controlled by adjusting the temperature, the flow of reactants, the cycle time



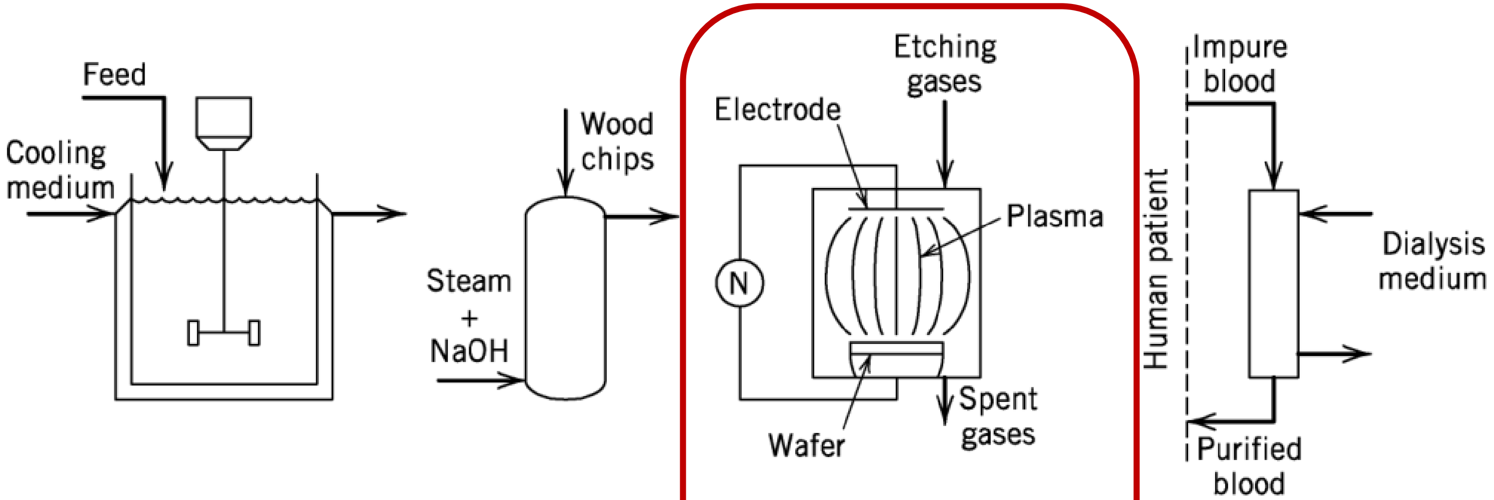
Examples of process control problems

- Batch and semi/batch processes
  - (f) Batch digester in a pulp mill
    - Both continuous and semi-batch digesters are used in paper manufacturing to break down wood chips in order to extract the cellulosic fibers
    - The end point of the chemical reaction is indicated by measuring of lignin content (measured variable)
    - Manipuated variables are digester temperature, pressure, cycle time



Examples of process control problems

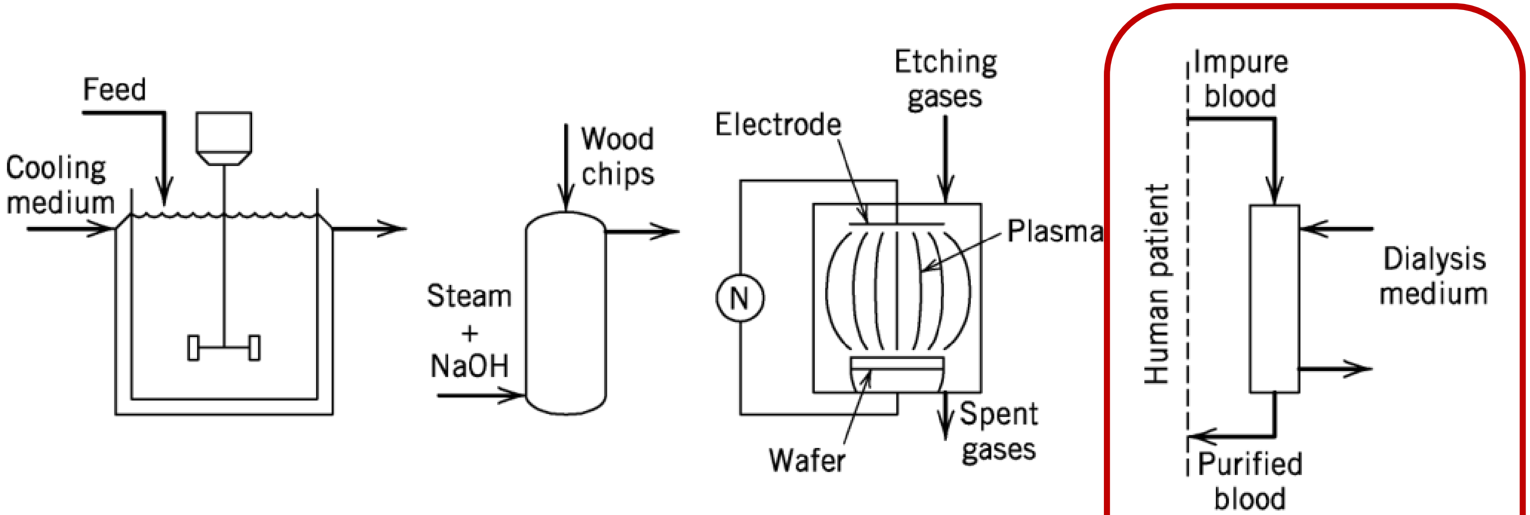
- Batch and semi/batch processes
  - (g) Plasma etcher in semiconductor processing
    - A single wafer containing hundreds of printed circuits is subject to a mixture of etching gases under conditions suitable to establish and maintain a plasma
    - The unwanted material on a layer of a microelectronics circuit is selectively removed by chemical reactions
    - Controlled variables are temperature, pressure, flow rates of etching gases to the reactor
    - Manipulated variables are electrical heaters and control valves.



(e) Semi-batch reactor
(f) Wood chip digester
(g) Plasma etcher
(h) Kidney dialysis unit

Examples of process control problems

- Batch and semi/batch processes
  - (h) Kidney dialysis unit
    - Medical equipment used to remove waste products from the blood of human patients whose own kidneys are failing or have failed
    - The blood flow rate is maintained by a pump
    - Ambient conditions (e.g., temperature in the unit), are controlled by adjusting a flow rate
    - The dialysis is continued long enough to reduce waste concentrations to acceptable levels



(*e*) Semi-batch reactor

(*f*) Wood chip digester

(*g*) Plasma etcher

(*h*) Kidney dialysis unit

Process control strategies

- Method 1: feedback control strategy
  - The controlled variables are measured, and that the measurement is used to adjust the manipulated variables
  - The disturbance variable is not measured
  - Advantages
    - Corrective action occurs regardless of the source of the disturbance
      - It reacts to the *effect* of the disturbance, and not on the *cause* of it
    - The sensitivity of the controlled variable to unmeasured disturbances and process changes is limited
  - Disadvantages
    - No corrective action is taken until after the disturbance has upset the process
      - E.g., until after the controlled variable deviates from the set point

Process control strategies

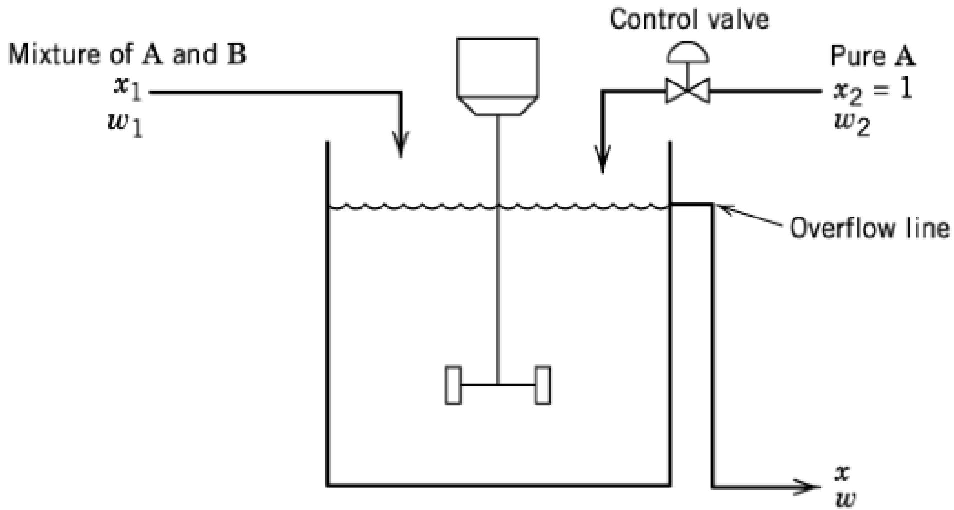
- Method 2: feedforward control strategy
  - The disturbance variable is measured
  - The controlled variable is not measured
  - Advantage:
    - Corrective actions are taken before the controlled variable deviates from the set point
      - Ideally, the corrective action will cancel the effects of the disturbance on the controlled variable
  - Disadvantages
    - The disturbance variables must be measured (or accurately estimated)
      - Uneconomical to try to measure all potential disturbances in industrial applications
    - No corrective action is taken for unmeasured disturbances
    - A process model is required

Process control strategies

- Method 3: combined feedforward-feedback control system
  - Feedback control provides corrective action for unmeasured disturbances
  - Feedforward control reacts to eliminate measured disturbances before the controlled variable is upset
  - Normally used in industrial applications
- Method 4: process design change
  - E.g., over dimensioning
  - Not a proper control strategy

Example: blending process control

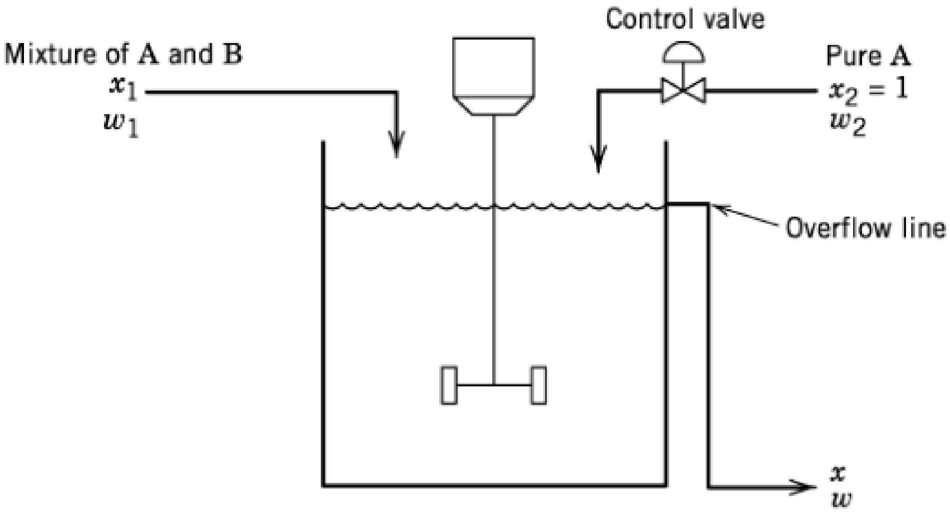
Continuous, stirred-tank blending system



- Blending operations are commonly used to ensure that final products meet customer specifications
- Control objective
  - Blend the two inlet streams to produce an outlet stream with desired composition
- Stream 1
  - A mixture of two chemical species, A and B, with constant total mass flow rate w_1
  - Mass fraction of A x_1 varies with time
- Stream 2
  - Mass flow rate w_2 can be manipulated using a control valve
  - Pure A $(x_2 = 1)$

Example: blending process control

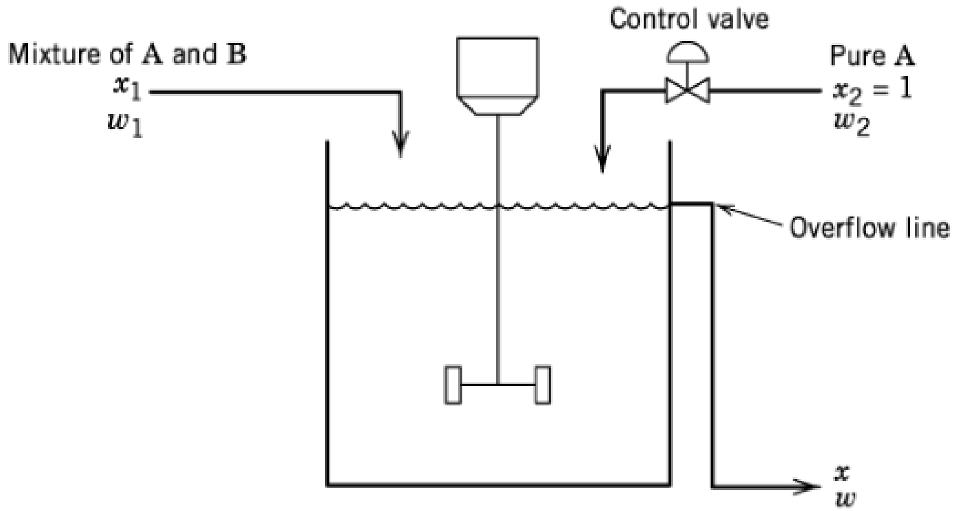
Continuous, stirred-tank blending system



- Design question
  - Given the nominal values $\bar{x}_1$, $\bar{x}_2$ and $\overline{w}_1$ of x_1, x_2 and w_1, respectively, what nominal flow rate $\overline{w}_2$ is required to produce the desired outlet concentration x_{sp}?

Example: blending process control

Continuous, stirred-tank blending system



– Balance equations

$$\begin{cases} w_1(t) + w_2(t) = w(t) \\ w_1 x_1(t) + w_2(t) x_2 = w(t) x(t) \end{cases}$$

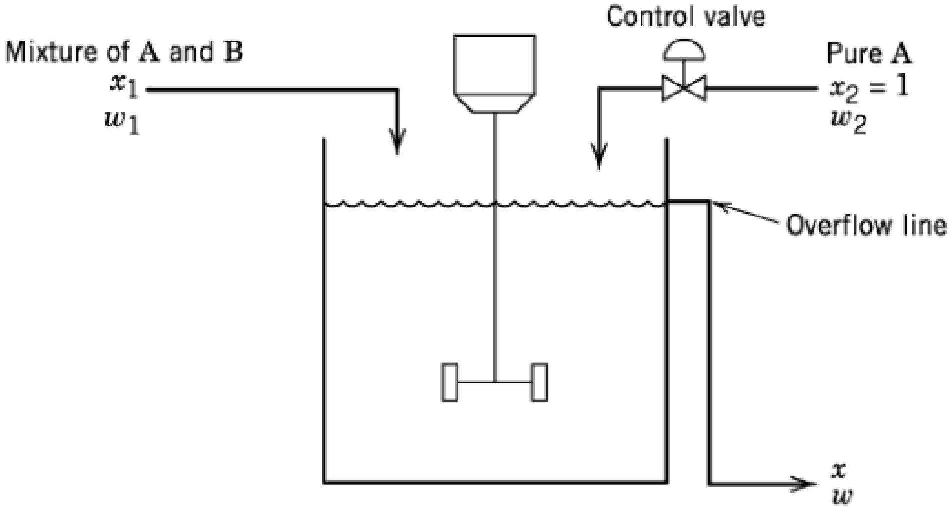
- Design (dimensioning)
  - At the steady-state we want that $\bar{x} = x_{SP}$
    - Steady-state (*nominal*) value of w_2 retrieved from the balance equations at the steady-state

$$\bar{w}_1 \bar{x}_1 + \bar{w}_2 \bar{x}_2 = (\bar{w}_1 + \bar{w}_2)\bar{x} \Rightarrow \bar{w}_2 = \bar{w}_1 \frac{\bar{x} - \bar{x}_1}{\bar{x}_2 - \bar{x}} = \bar{w}_1 \frac{x_{SP} - \bar{x}_1}{1 - x_{SP}}$$

    - But $x_1(t)$ varies with time!

Example: blending process control

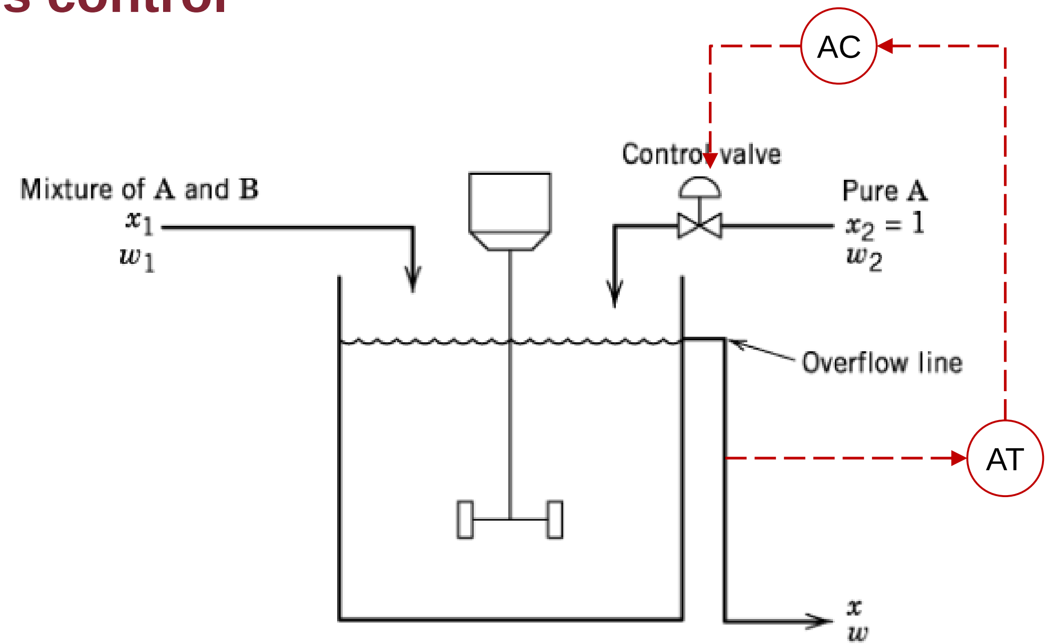
Continuous, stirred-tank blending system



- Control question
  - Suppose that inlet concentration x_1 varies with time, ensure that the outlet composition x remains at or near its desired value x_{sp}?
  - Required equipment (depending on the control strategy)
    - Analyzer and transmitter, which generates a milliampere (mA)-level signal corresponding to the tank exit concentration
    - Controller functionalities
      - Convert the actual set-point into an equivalent internal signal
      - Calculate the output according to the control law
    - Control valve (controller)
      - The controller output is a DC current signal that is sent to the control valve to adjust the valve stem position, which in turn affects flow rate $w_2(t)$.

Example: blending process control

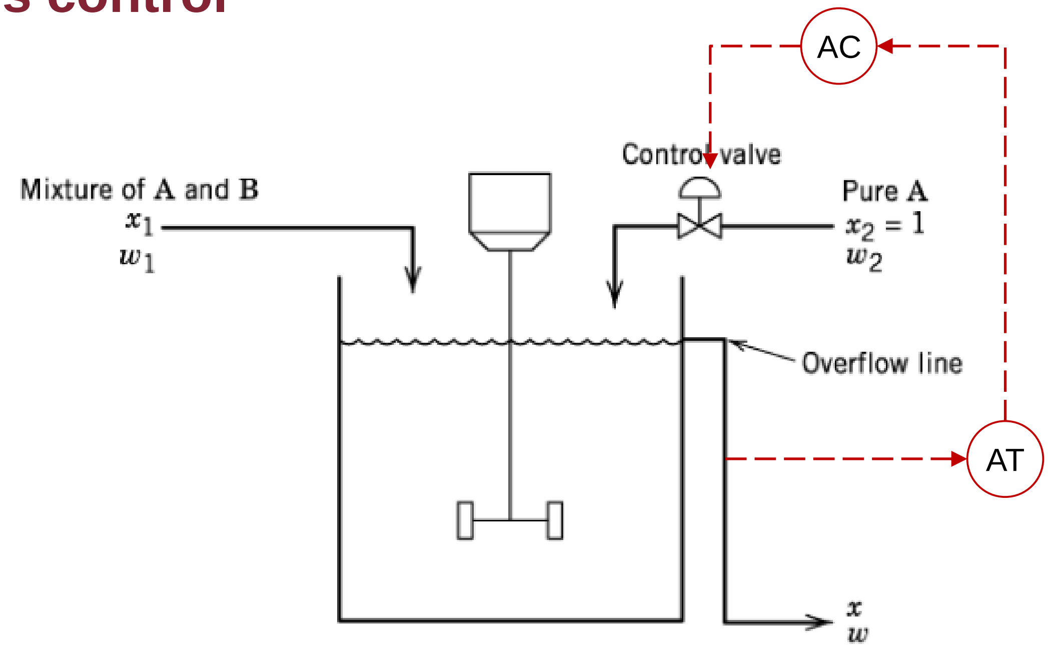
Continuous, stirred-tank
blending system



- Method 1
  - Feedback control
    - Measure $x(t)$ to regulate $w_2(t)$
      - $x(t)$ *measaured variable*
      - $w_2(t)$ *manipulated variable*
    - Required equipment (depending on the control strategy)
      - AT – Analyzer and transmitter, which generates a milliampere (mA)-level signal corresponding to the tank exit concentration
      - AC – Composition controller

Example: blending process control

Continuous, stirred-tank blending system

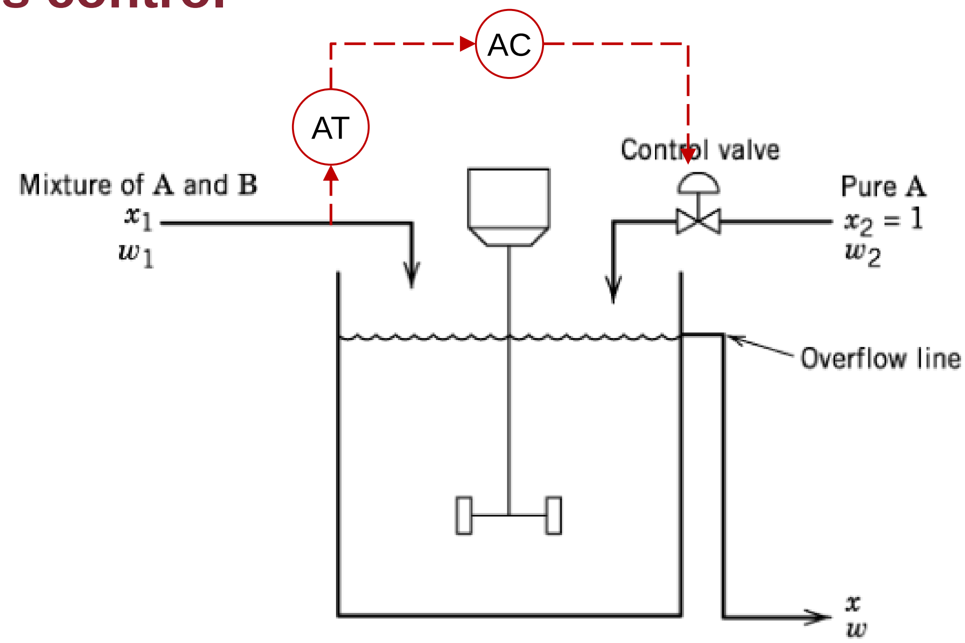


- Method 1
  - Proportional control law
    - Empirical principles
      - «increase (decrease) the flow of pure A if the outlet concentration of A decreases (increases)»
      - «enforce large (small) variations of the flow of pure A if there is a large (small) variation of the outlet concentration of A from its steady state

$$w_2(t) - \bar{w}_2 = -K_c \cdot (x(t) - x_{SP}) \Rightarrow \Delta w_2(t) = -K_c \Delta x(t)$$

Example: blending process control

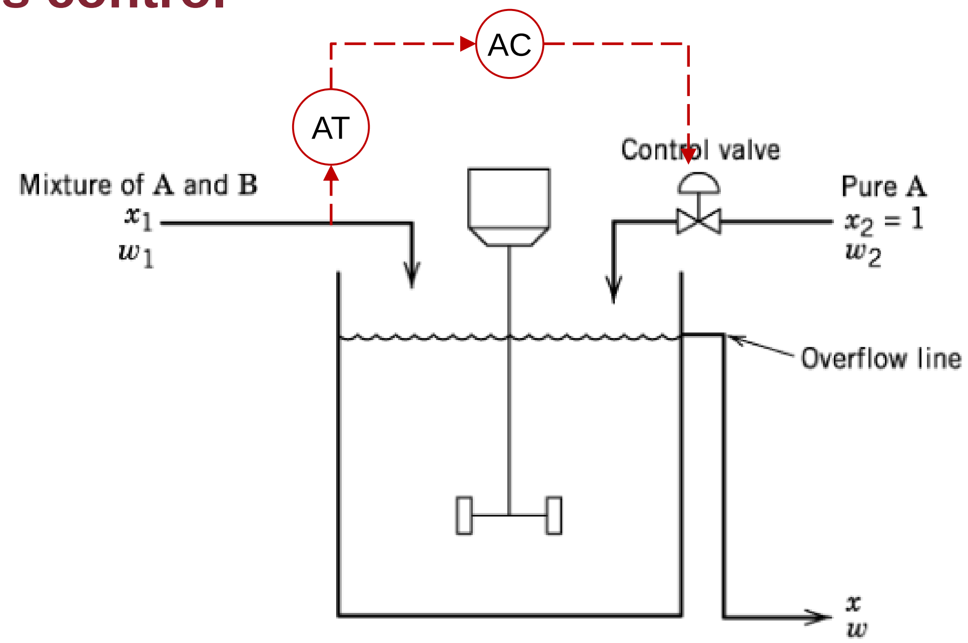
Continuous, stirred-tank blending system



- Method 2
  - Feedforward control
    - Measure $x_1(t)$ to regulate $w_2(t)$
      - $x_1(t)$ *measaured disturbance*
      - $w_2(t)$ *manipulated variable*
    - Required equipment (depending on the control strategy)
      - AT – Analyzer and transmitter, which generates a milliampere (mA)-level signal corresponding to the tank exit concentration
      - AC – Composition controller

Example: blending process control

Continuous, stirred-tank blending system

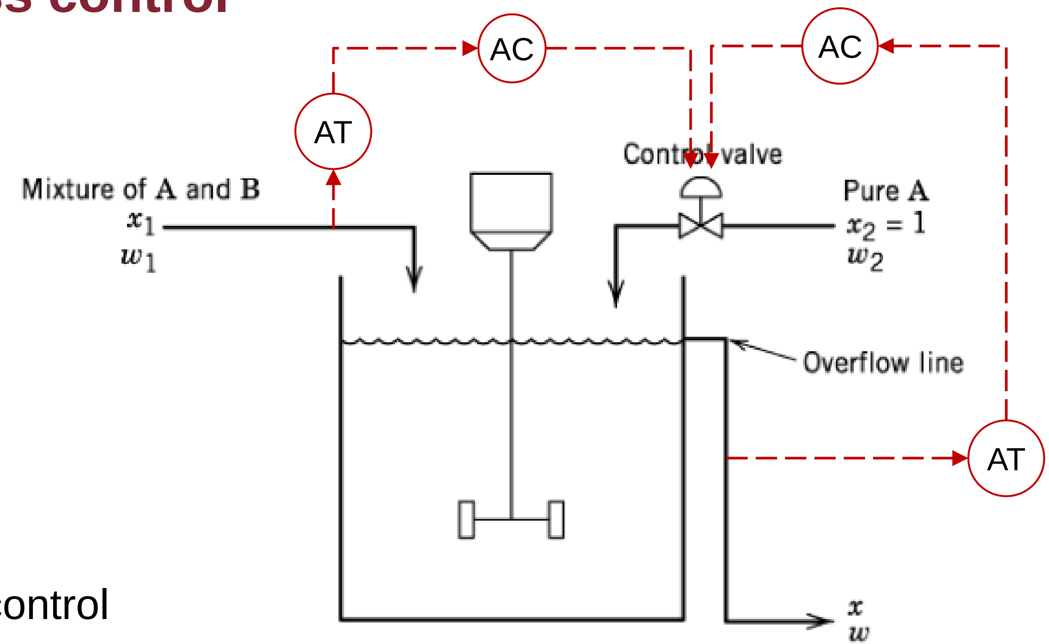


- Method 2
  - Feedforward control
    - Empirical principle
      - «If the inlet concentration of A grows, the outlet concentration grows as well, and therefore the flow of pure A must be reduced»
        - » …but we need to start from steady-stae values $x(t) = x_{SP}$, $w_1(t) = \bar{w}_1$!!
      - From the balance equations we know that: $w_2(t) = \bar{w}_1 \frac{x_{SP} - x_1(t)}{1 - x_{SP}}$
      - At the steady state we know that: $\bar{w}_2 = \bar{w}_1 \frac{x_{SP} - \bar{x}_1}{1 - x_{SP}}$

$$w_2(t) - \bar{w}_2 = -\bar{w}_1 \frac{x_1(t) - \bar{x}_1}{1 - x_{SP}} \Rightarrow \Delta w_2(t) = -\bar{w}_1 \frac{\Delta x_1(t)}{1 - x_{SP}} \Rightarrow \Delta w_2(t) = -K_{ff} \cdot \Delta x_1(t)$$

Example: blending process control

Continuous, stirred-tank
blending system



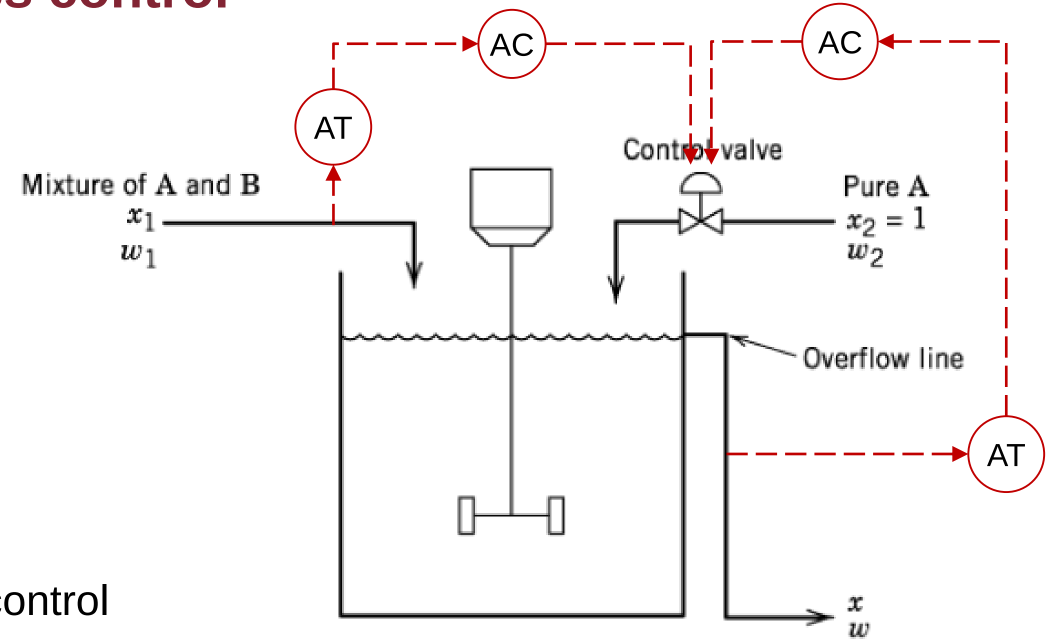
- Method 3
  - Feedback + feedforward control
    - $x(t)$ *measaured variable*
    - $x_1(t)$ *measaured disturbance*
    - $w_2(t)$ *manipulated variable*
      » The superposition principle must hold (linear systems)!
  - Required equipment (depending on the control strategy)

AT – 2 pieces of analyzer and transmitter, which generates a milliampere (mA)-level signal corresponding to the tank exit concentration

AC – 2 pieces of composition controller

Example: blending process control

Continuous, stirred-tank blending system



- Method 3
  - Feedback + feedforward control

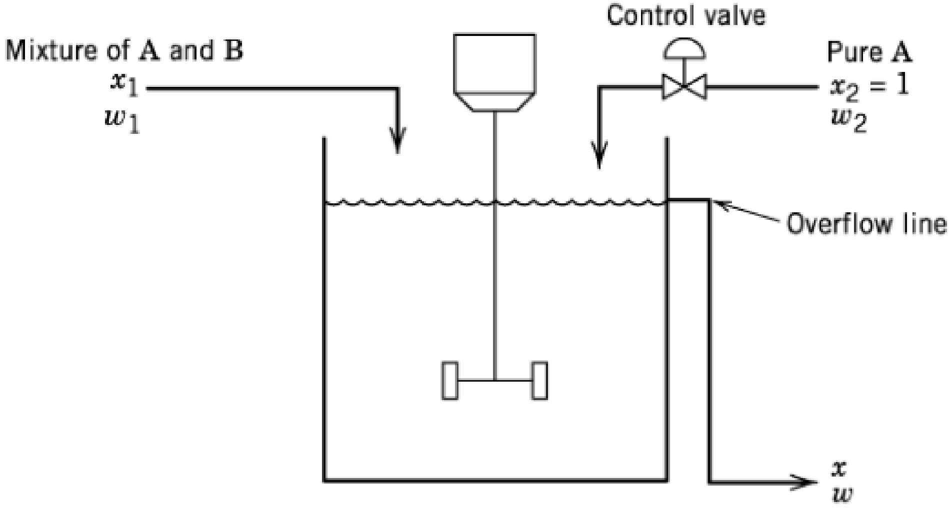
$$\Delta w_2(t) = -K_c \cdot \Delta x(t) - K_{ff} \cdot \Delta x_1(t)$$

The first component has the task of steering $x(t) \rightarrow x_{SP}$

The second component reacts to the disturbance

Example: blending process control

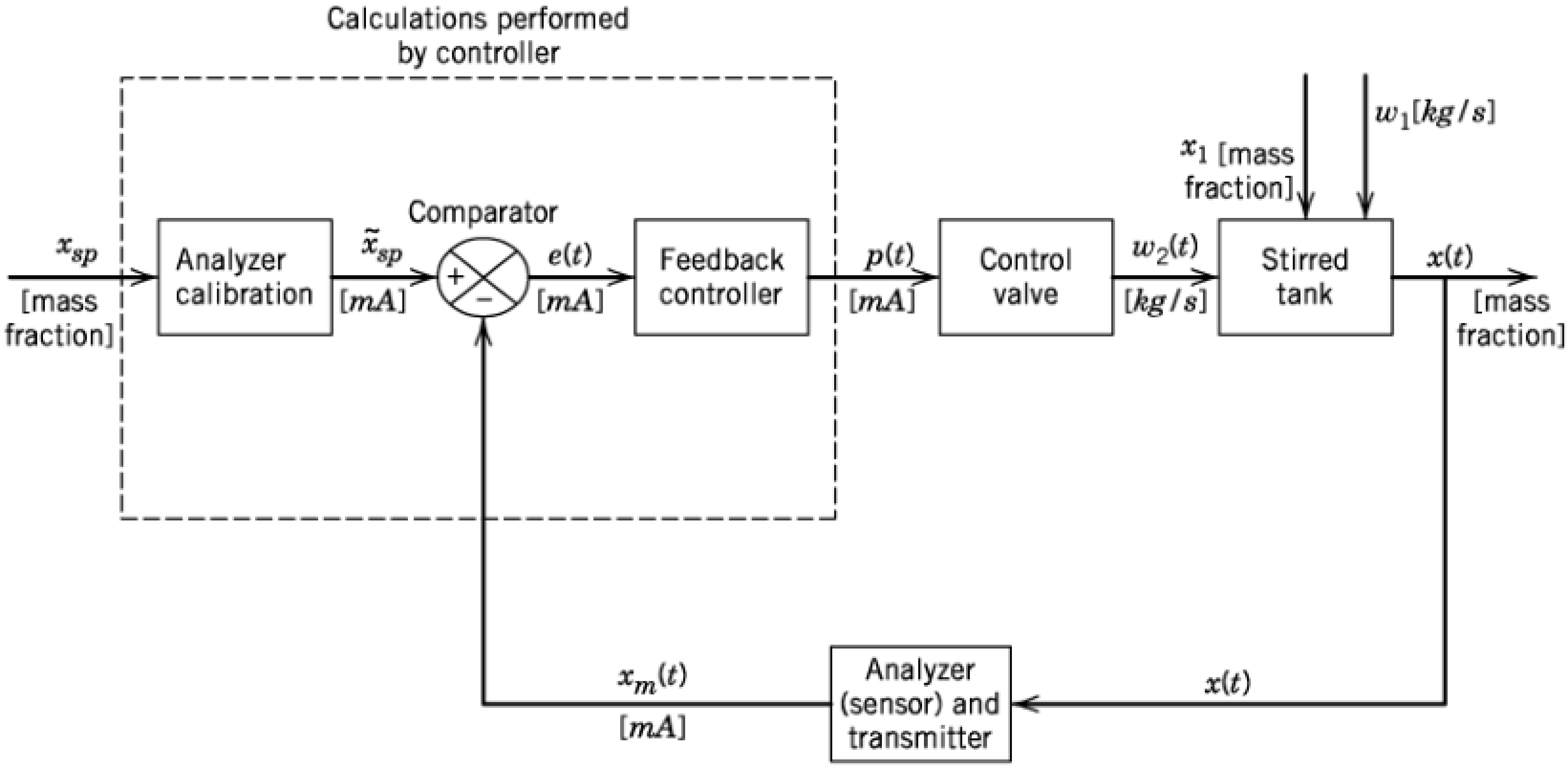
Continuous, stirred-tank blending system



- Method 4
  - Overdimensioning
    - Use a larger tank to render the variations of $x_1(t)$ “small”

Example: blending process control

- Control diagram (feedback controller)
  - For the actual control we need models of all the components
    - Equations describing the behaviour af the 'boxes'
    - Models let us compute the control laws (e.g., the values of K_c and K_{ff})



Summary

- Introduction to Process Control
- Examples of process control problems referred to continuous processes and batch processes
- Basics of process control strategies and design
- Examples of control strategies applied to a distillation column