Master in Control Engineering

Process Automation
2020-2021

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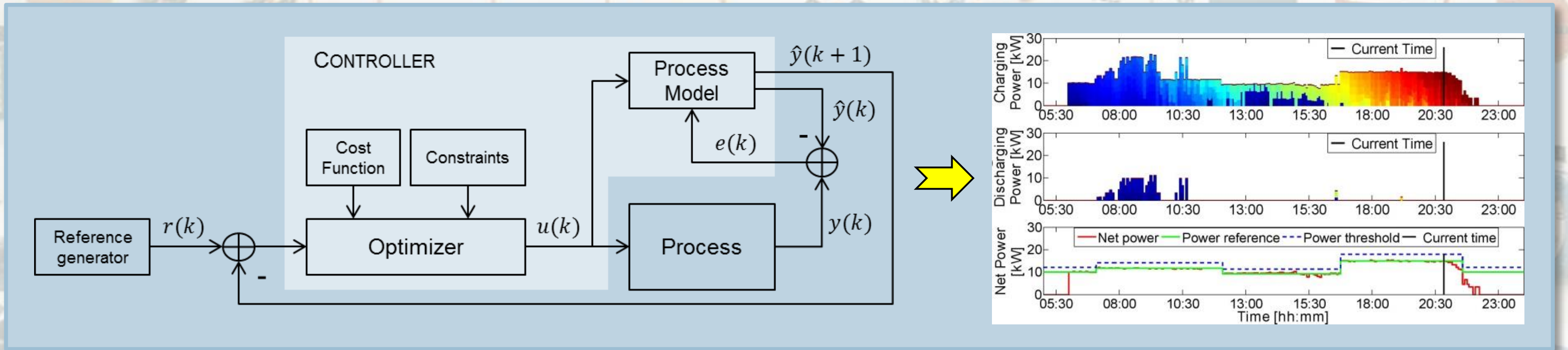
Master in Control Engineering

Process Automation

2. Process Control Overview

Slides based on:
T. F. Edgar, J. Hahn, “Process Automation”, in *Handbook of Automation*, 2009, pp. 529-543



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Outline

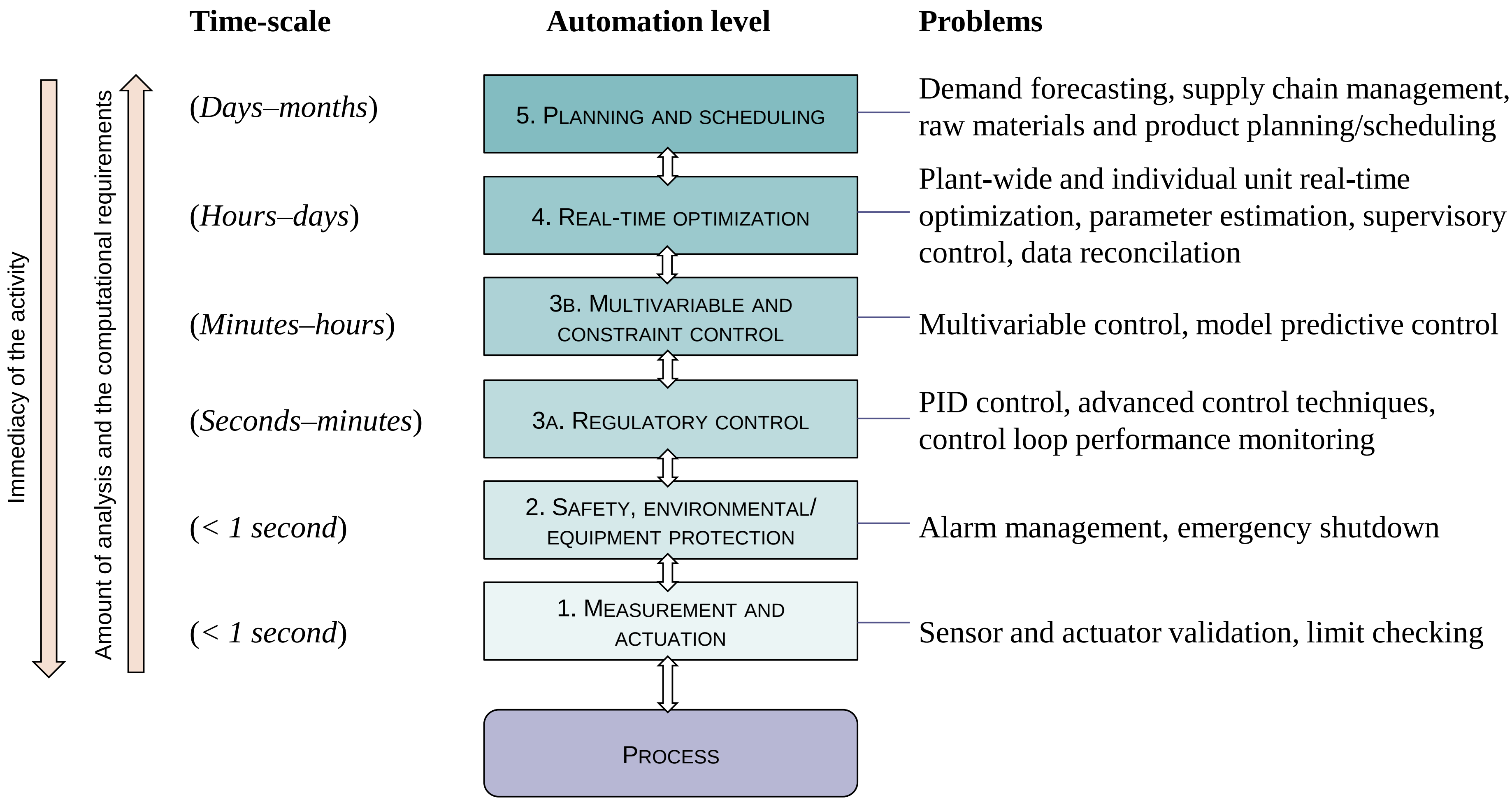
- Process Control Overview
  - Introduction
    - Objectives
    - Levels of Process Control
  - Process Dynamics and Mathematical Models
  - Regulatory Control
  - Control System Design
  - Multivariable Control
  - Model Predictive Control
  - Batch Process Automation
  - Automation and Process Safety
- Summary

Introduction

- Process automation
  - Objectives
    - Maximize production while maintaining a desired level of product quality and safety
    - Making the process more economical
  - Process control systems examples
    - Facilities for the production of chemicals
    - Facilities for the production of pulp and paper
    - Facilities for the production of metals
    - Facilities for the production of food
    - Pharmaceuticals
    - ….
  - Methods of production is different vary from plant to plant, but the *principles of automatic control* are generic and can be seamlessly applied

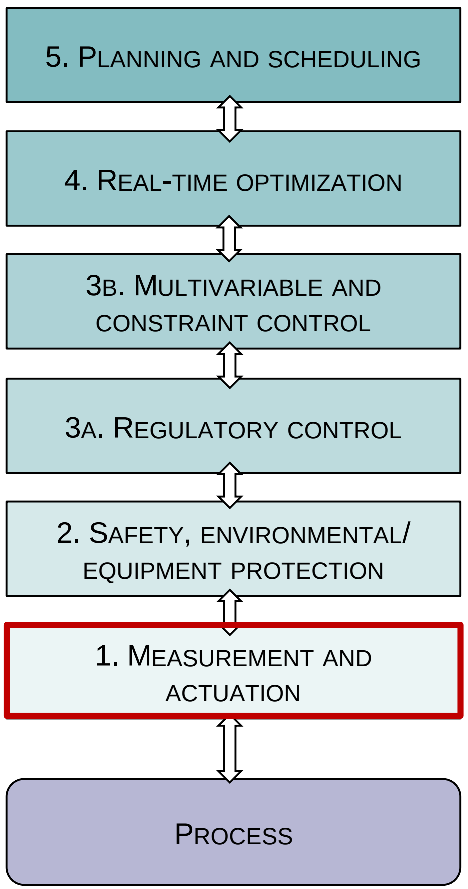
Introduction

- Levels of process control



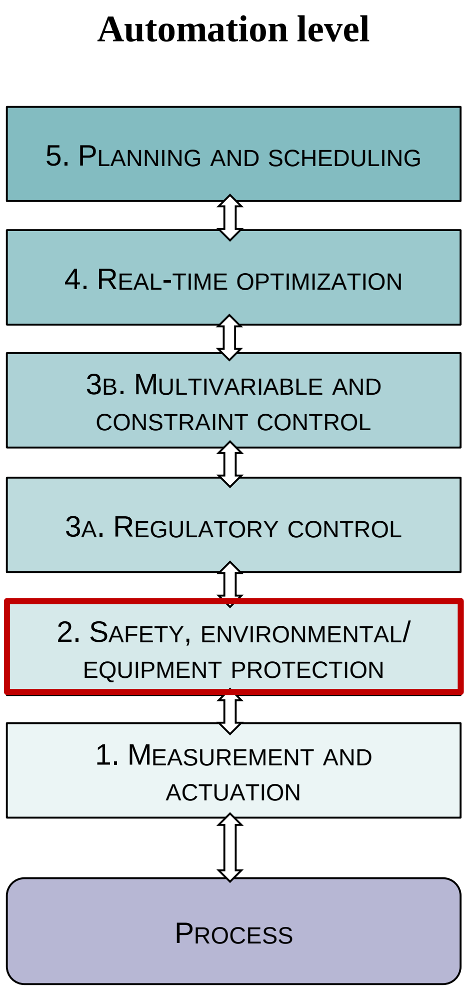
Introduction

Automation level



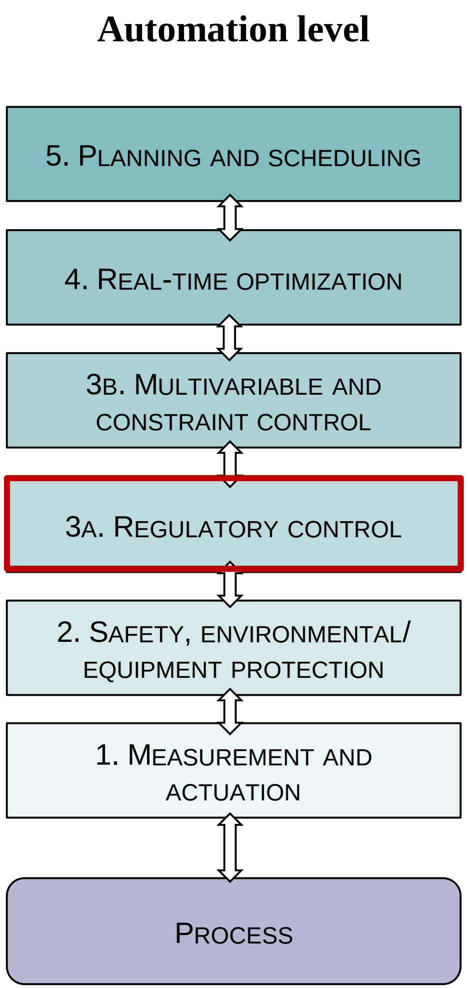
- Level 1: Measurement and Actuation
  - Interface between the plant (process) and the control system
    - Measurement devices (sensors and transmitters) measure the *process variables*
    - Actuation devices (e.g., control valves) are enforced the calculated *control actions*

Introduction



- Level 2: Safety and Environmental/Equipment Protection
  - Ensuring that the process is operating safely and satisfies environmental regulations
    - Process safety relies on the principle of multiple protection layers that involve equipment and/or human actions
      - Process control functions (e.g., alarm management during abnormal situations)
        - » Safety instrumented systems for emergency shutdowns
        - » Safety equipment (including sensors and control valves) operates independently of the regular instrumentation used for regulatory control in level 3a
        - » Sensor validation techniques to check that the sensors are working properly

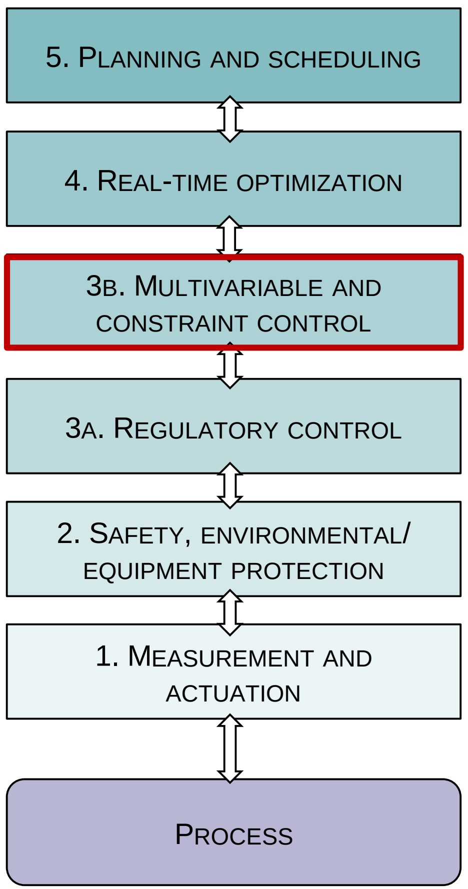
Introduction



- Level 3a: Regulatory Control
  - Successful operation of a process requirements
    - Key process variables (e.g., flow rates, temperatures, pressures) must be operated at, or close to, their *set points*
    - Regulatory control is achieved by applying (usually) standard *feedback control* techniques

Introduction

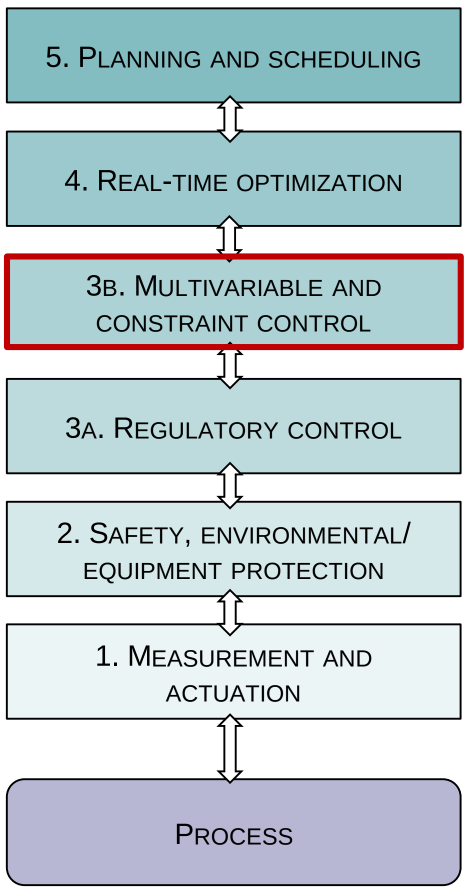
Automation level



- Level 3b: Multivariable and Constraint Control
  - Process control characteristics
    - Significant interactions among key process variables
    - Inequality constraints exist for manipulated and controlled variables
      - Upper and lower limits due to
        - » equipment constraints
          - » e.g., each manipulated flow rate has an upper limit determined by the pump and control valve characteristics
        - » operational constraints
          - » e.g., a reactor temperature may have an upper limit to avoid undesired side reactions or catalyst degradation, and a lower limit to ensure that the reaction proceeds

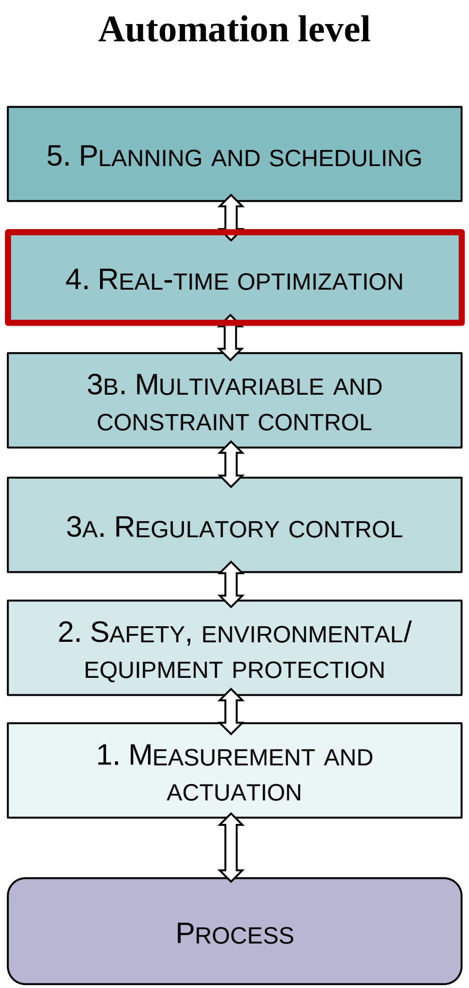
Introduction

Automation level



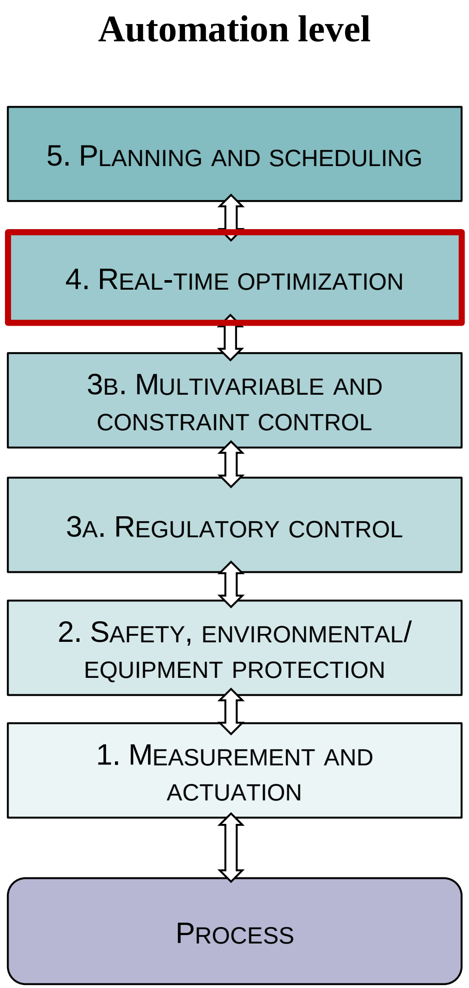
- Level 3b: Multivariable and Constraint Control (cont'd)
  - Advanced control techniques required
    - Objective for advanced process control operate a process close to a limiting constraint
      - the set point should be within a *small* tolerance from the constraint value
        - » a process disturbance could force the controlled variable beyond the limit
    - Multivariable control, constraint control
      - e.g., model predictive control (MPC)

Introduction



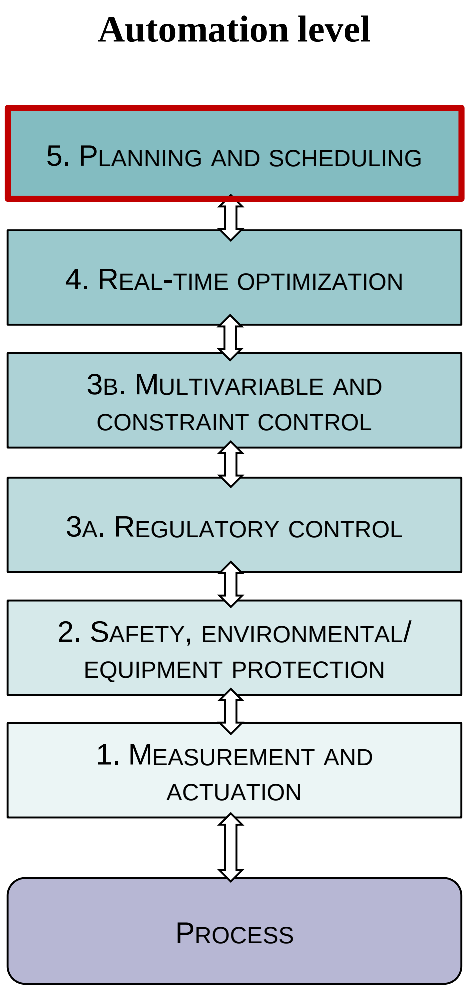
- Level 4: Real-Time Optimization
  - Optimum operating conditions for a plant are determined at the process design, but, during plant operations, they may change due to
    - changes in equipment performance/availability
    - process disturbances
    - economic conditions
    - …

Introduction



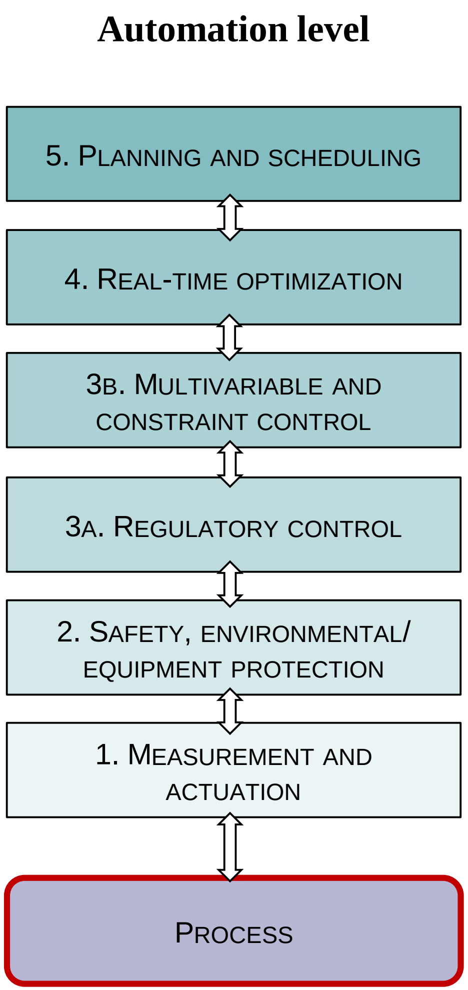
- Level 4: Real-Time Optimization (cont'd)
  - Optimum operating conditions are re-calculated on a regular basis
    - Optimum conditions are implemented as *set points* for controlled variables.
    - Real-time optimization (RTO)
      - Calculations are based on a steady-state model of the plant and economic data (costs, product values)
      - Calculations can be performed for a single process unit and/or on a plant-wide basis.
  - Data analysis to check the process model accuracy in current conditions
    - Data reconciliation techniques
    - Process model updated using parameter estimation techniques and recent plant data

Introduction



- Level 5: Planning and Scheduling
  - Planning and scheduling operations for the entire plant
    - In continuous processes, production rates of all products and intermediates must be planned based on
      - equipment constraints
      - storage capacity
      - sales projections
      - operation of other plants
      - …
    - Intermittent operation of batch processes
      - the production control problem becomes a batch scheduling problem based on similar considerations

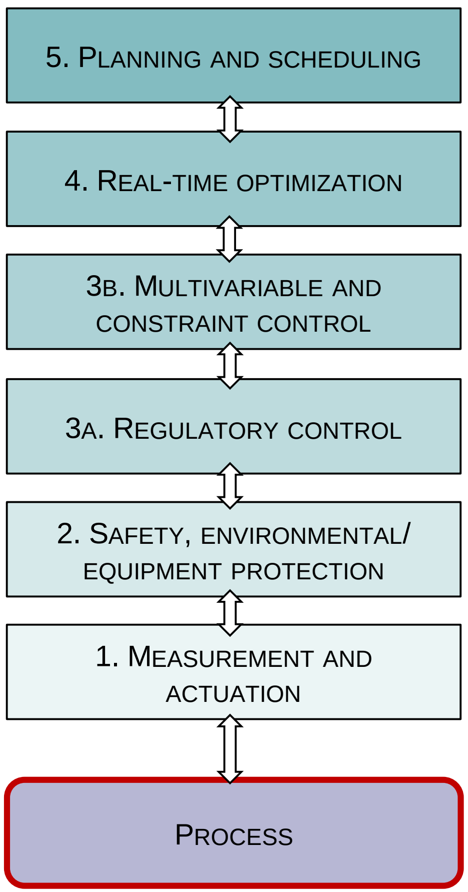
Process Dynamics and Mathematical Models



- Development of dynamic models
  - Controller design and tuning is usually performed by using a mathematical representation (*dynamic model*) of the process
    - Derived from first-principles knowledge about the system
    - Derived from past plant data
    - It can be solved for a variety of conditions
      - Changes in the input variables
      - Variations in the model parameters
      - Presence of disturbances
      - …

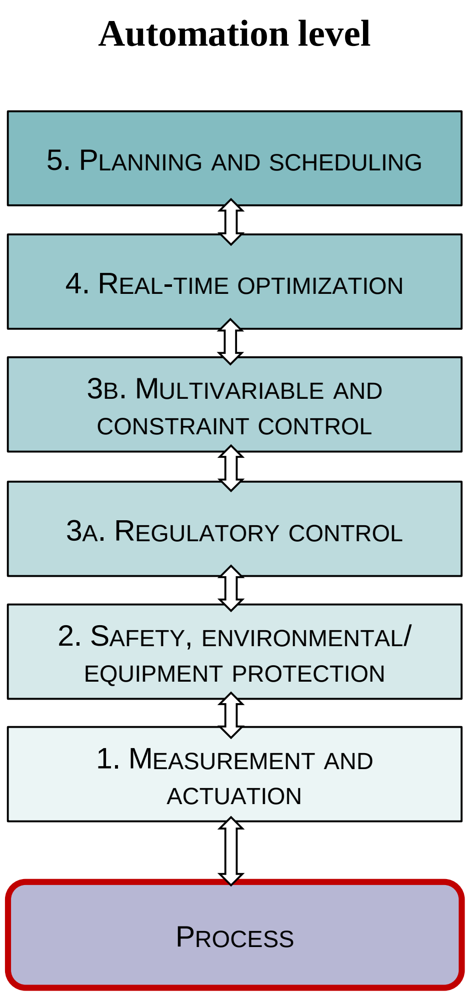
Process Dynamics and Mathematical Models

Automation level



- Development of dynamic models (cont'd)
  - Model-based dynamic simulators achieved a high degree of acceptance in process engineering and control studies
    - They allow to evaluate plant dynamics, real-time optimization, and alternative control configurations for an existing or a new plant
    - They can be used for operator training
  - Most processes can be accurately represented by a set of nonlinear differential equations

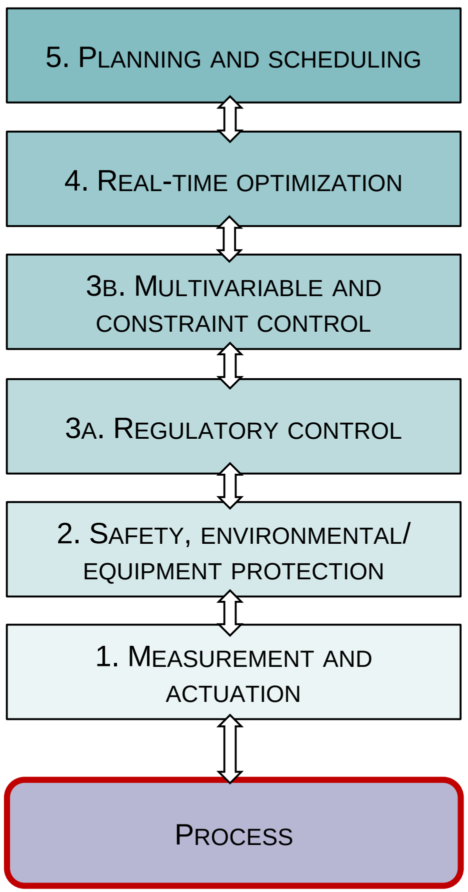
Process Dynamics and Mathematical Models



- Development of dynamic models (cont'd)
  - Linear model approximation
    - A process is usually operated within a certain neighborhood of its normal operating point (*steady state*), thus its model can be closely approximated by a linearized version
    - Advantages
      - Use of more convenient and compact methods for representing process dynamics
        - » e.g., Laplace transforms
    - <u>Identification</u> of model parameters in transfer functions
      - Step test on the process and collect the data along the trajectory until it reaches steady state
      - The parameters of the transfer function are estimated by using nonlinear regression

Process Dynamics and Mathematical Models

Automation level



- Development of dynamic models (cont'd)
  - Examples of process models
    - First Order Process (FOP)

$$F(s) = \frac{K}{\tau s + 1}, \tau > 0$$

    - Second Order Process (SOP)

$$F(s) = \frac{K(\tau_3 s + 1)}{(\tau_1 s + 1)(\tau_2 s + 1)}, \tau_1 > 0, \tau_2 > 0, \tau_3 > 0$$

    - Unstable First Order Process

$$F(s) = \frac{K}{-\tau s + 1}, \tau > 0$$

    - First Order Process with Time Delay (FOPTD)

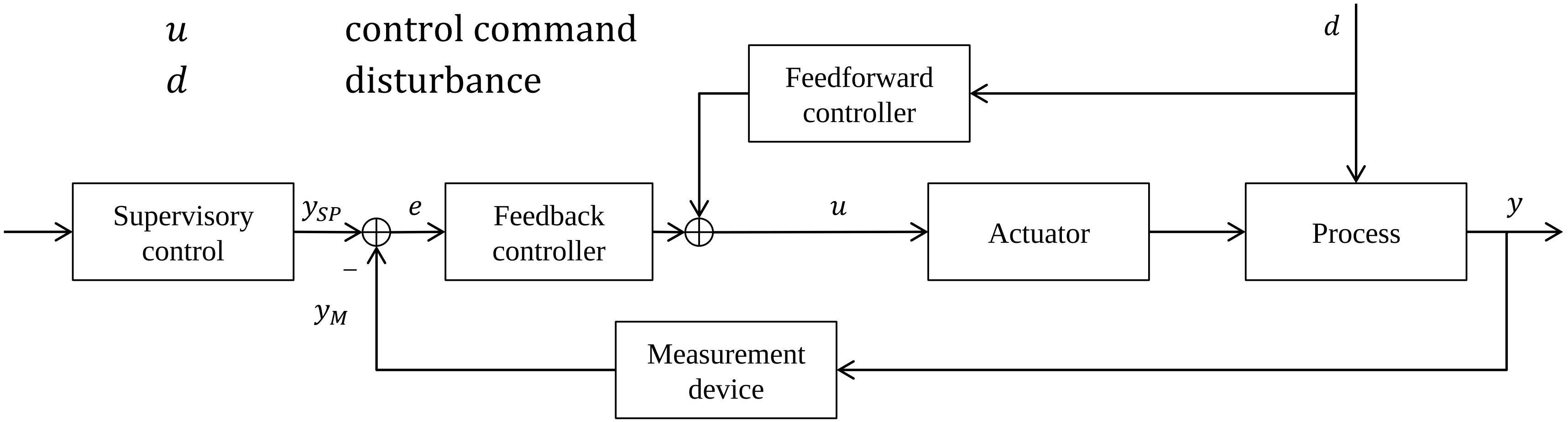
$$F(s) = \frac{K}{\tau s + 1} e^{-sT}, \tau > 0$$

    - The process parameters (gain K, time constants τ_i, time delay T) have to be determined for controller design or for simulation purposes

Regulatory Control

- Connected systems
  - Overall dynamic behavior described by combining the transfer functions for each component
  - Regulatory control deals with treatment of disturbances that enter the system
    - e.g., classic control system

y	controlled variable
y_{SP}	set-point for the controlled variable
y_M	measured variable
e	error between set-point and measured variable
u	control command
d	disturbance



Regulatory Control

- Sensors
  - Process measurement devices which sense the values of process variables
    - e.g., temperature, flow, pressure, level, composition, ...
  - Selection of the proper instrumentation for a particular application depends on
    - Type and nature of the fluid or solid
    - Process conditions
    - Range
    - Accuracy
    - Response time
    - Installed cost
    - Maintainability
    - Reliability
    - ...

Regulatory Control

- Control Valves
  - Material and energy flow rates are the most commonly selected manipulated variables for control schemes
  - Control valve performance is essential for achieving good control performance
    - Accuracy of control action

Regulatory Control

- Controllers
  - Proportional–integral (PI) controller is the most commonly employed feedback controller in the process industry

$$u(t) = K_C\left(e(t) + \frac{1}{\tau_I}\int_0^t e(t')dt'\right)$$

K_c: proportional constant

τ_I : integral time constant

- Integral action eliminates offset for constant load disturbances
  - it can potentially lead to the ”windup” problem in case of saturation of controller output

Regulatory Control

- Controllers
  - PID (D = derivative) controller

$$u(t) = K_C\left(e(t) + \frac{1}{\tau_I}\int_0^t e(t')dt' + \tau_D\frac{de(t)}{dt}\right)$$

τ_D : derivative time constant

- Better transient response, but it may amplify the noise of the process measurement
  - If the derivative of the error changes rapidly, the derivative action grows

Control System Design

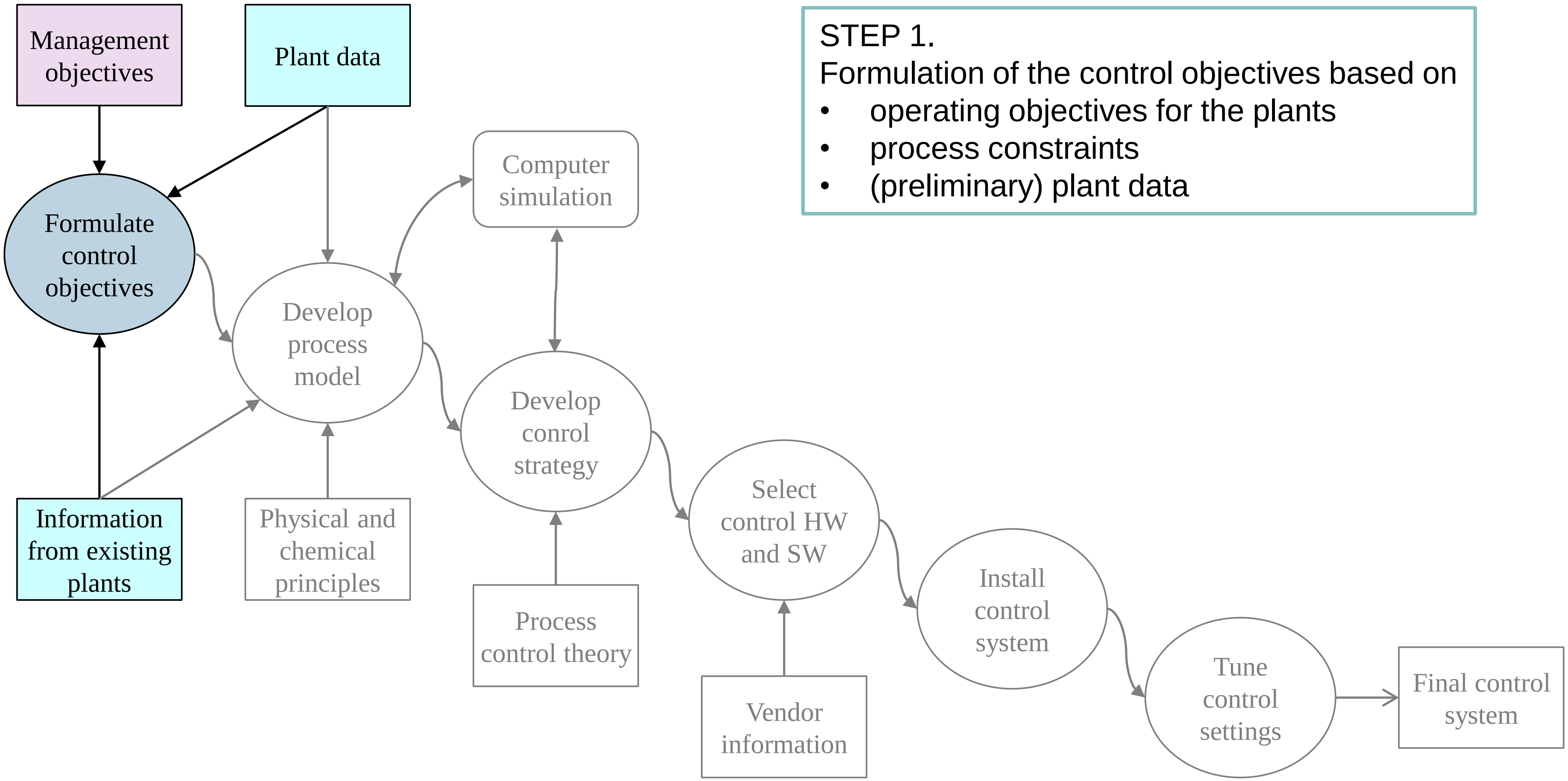
- Control system development
  - Outdated approach
    - The control system design is initiated after plant design is completed
      - Limitations, since the plant design determines the process dynamics of the plant
        - » The process may be uncontrollable, even though the design appears satisfactory from a steady-state point of view
    - Still used in case of plant revamping
  - Modern approach
    - Process dynamics and control issues early dealt with in the process design

Control System Design

- Approaches to control system design
  - *Traditional approach*
    - Control strategy and control system hardware selected based on knowledge of the process and operators' experience
    - After that the control system is installed in the plant, the controller settings (e.g., PID controller parameters) are adjusted (*controller tuning*)
  - *Model-based approach*
    - A dynamic model of the process is first developed
      - it can be used as the basis for model-based controller design methods
      - it can be incorporated directly in the control law (for example, internal model control and model predictive control)
      - It can be used in a computer simulation to evaluate alternative control strategies and to determine preliminary values of the controller settings
    - For complex processes, a process model is invaluable both for control system design and for an improved understanding of the process

Control System Design

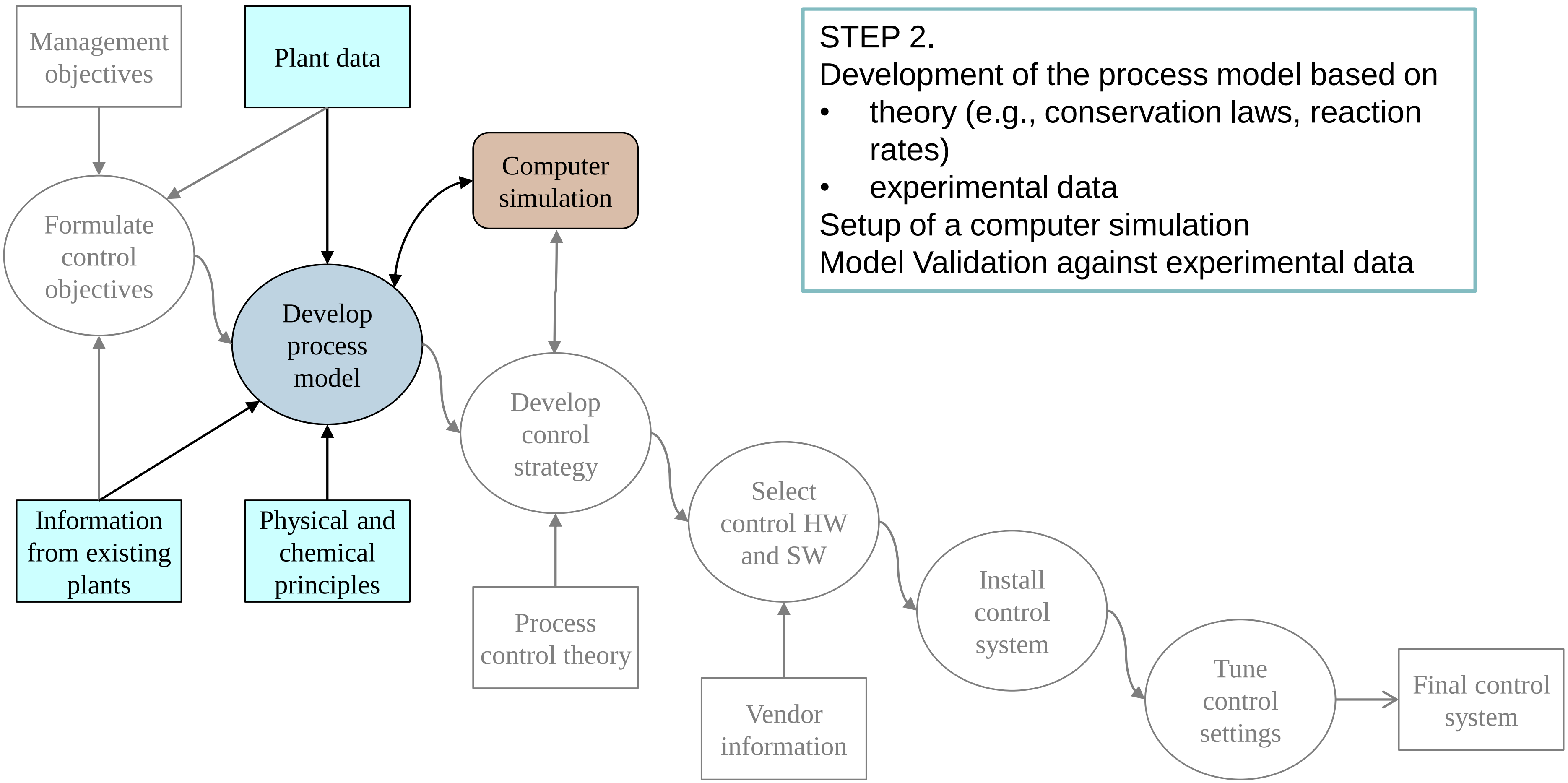
- Control system development under the model-based approach



STEP 1.
Formulation of the control objectives based on
- operating objectives for the plants
- process constraints
- (preliminary) plant data

Control System Design

- Control system development under the model-based approach

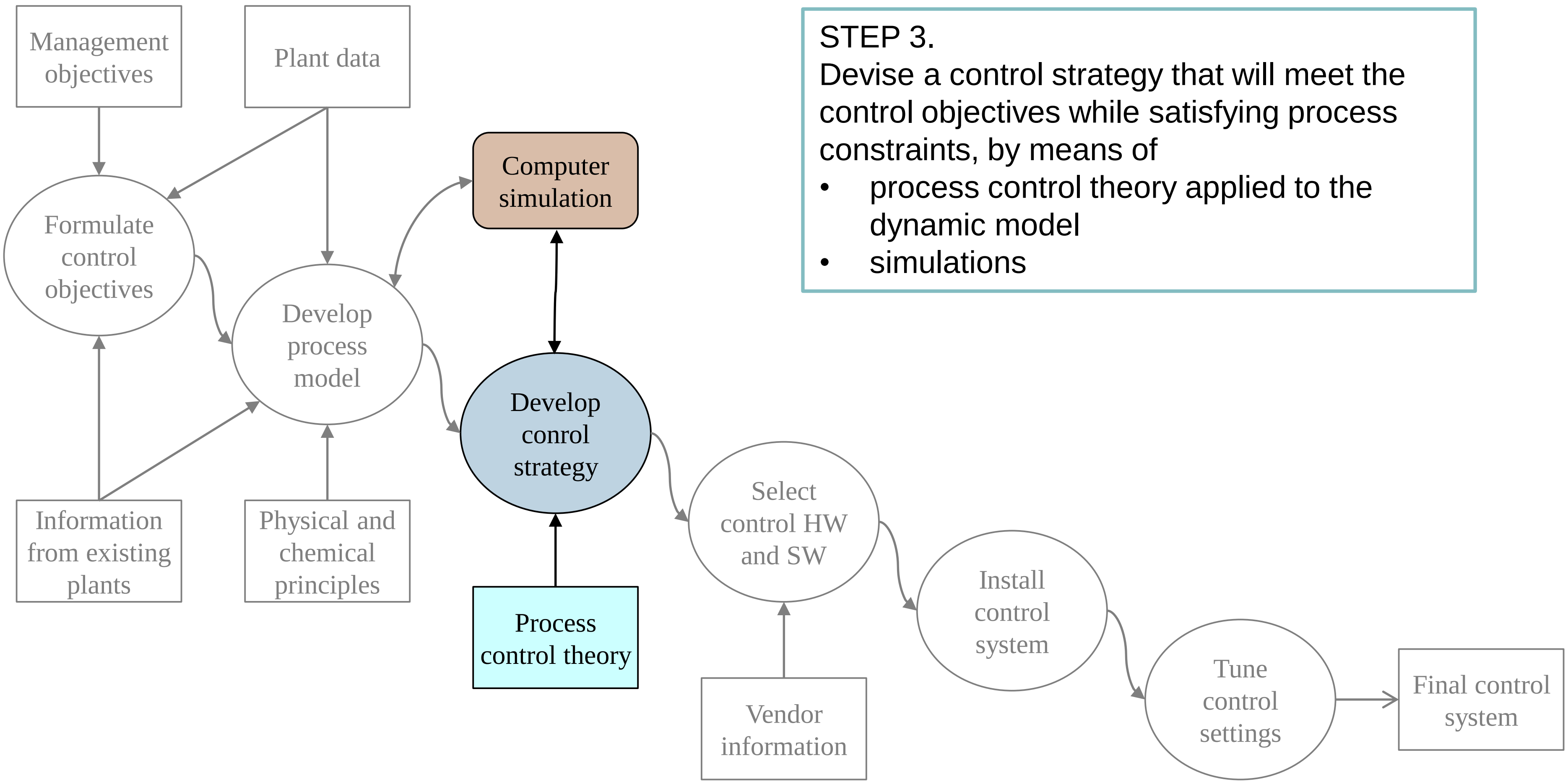


STEP 2.
Development of the process model based on
- theory (e.g., conservation laws, reaction rates)
- experimental data

Setup of a computer simulation
Model Validation against experimental data

Control System Design

- Control system development under the model-based approach

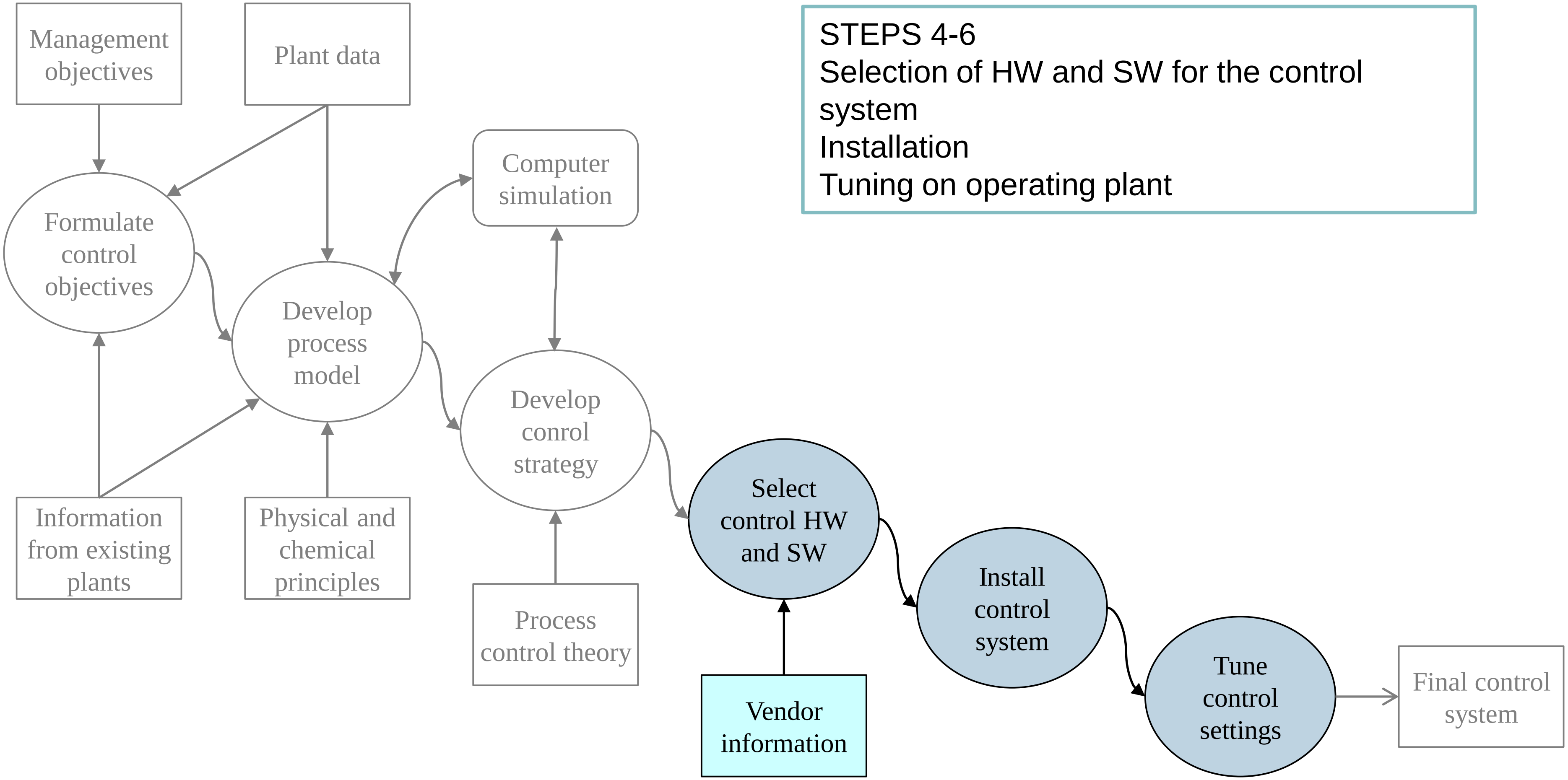


STEP 3.
Devise a control strategy that will meet the control objectives while satisfying process constraints, by means of

- process control theory applied to the dynamic model
- simulations

Control System Design

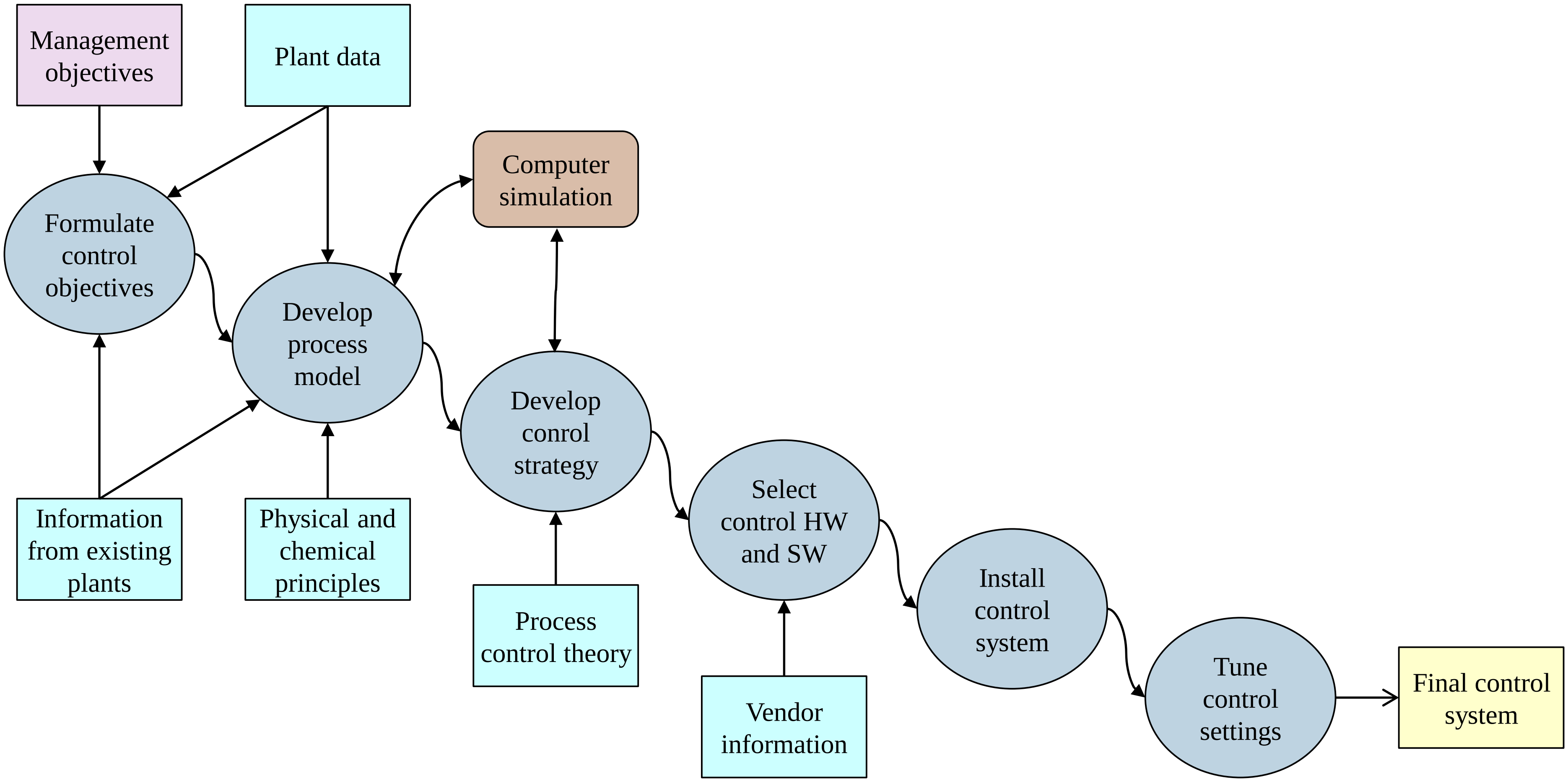
- Control system development under the model-based approach



STEPS 4-6
Selection of HW and SW for the control system
Installation
Tuning on operating plant

Control System Design

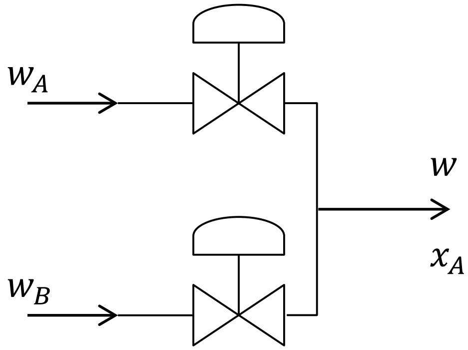
- Control system development under the model-based approach



Multivariable Control

- In most industrial processes, there are a number of variables that must be controlled, and a number of variables can be manipulated
  - Multiple-input multiple-output (MIMO) control problems

  - Example: inline blending system
    - Two streams containing species A and B have to be blended to produce a stream with mass flow rate w and composition x_A (mass fraction of A)
      - Adjusting the manipulated flow rates w_A and w_B affects both w and x_A.



Multivariable Control

- MIMO control problems are inherently more complex than single-input single-output (SISO) control problems
  - Process interactions occur between controlled and manipulated variables
    - For a control problem with n controlled variables and n manipulated variables, there are $n!$ possible multi-loop control configurations
    - PID control often inadequate
  - Model Predictive Control is the most practical methodology to handle MIMO processes

Model Predictive Control

- MPC principles
  - Process model captures the dynamic and static interactions between input, output, and disturbance variables
  - Constraints on inputs and outputs are considered in a systematic manner
  - Control calculations are coordinated with the calculation of optimum set points
  - Model predictions can provide early warnings of potential problems
  - The success of MPC depends on the accuracy of the process model
    - Inaccurate predictions can make things worse, instead of better!

Model Predictive Control

- MPC developed in the late1970s by two industrial research groups

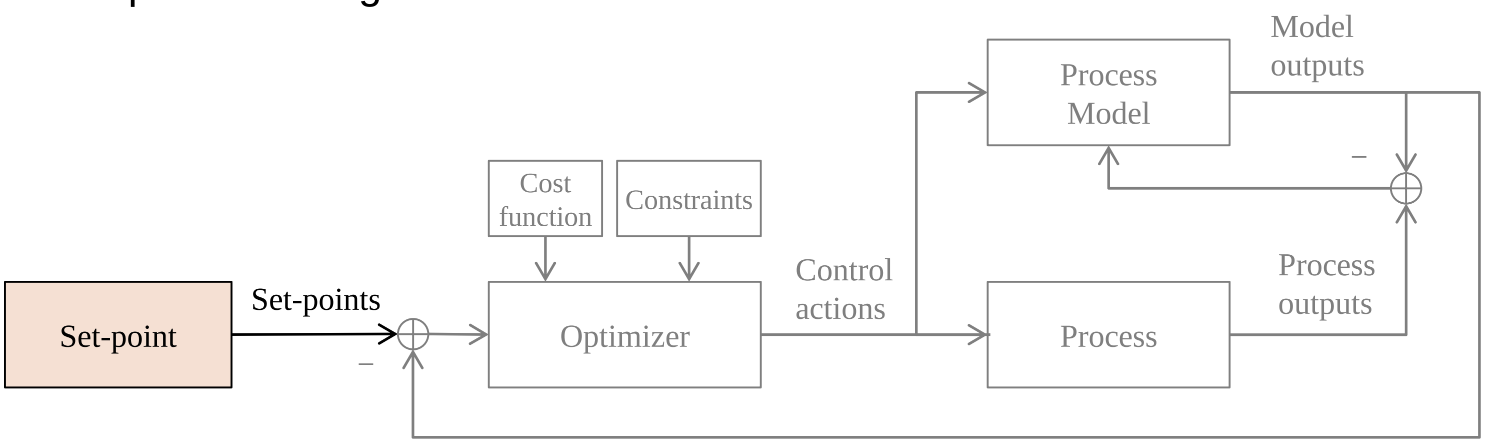
    J. Richalet, A. Rault, J.L. Testud, J. Papon, “Model predictive heuristic control: applications to industrial processes”, Automatica, n. 14, pp. 413-428, 1978.

    C.R. Cutler, B.L. Ramaker, “Dynamic matrix control – a computer control algorithm”, *Proc. Jt. Auto. Control Conf.*, paper WP5-B, San Francisco, 1980.

  - Major impact on industrial practice, initially in oil refineries and petrochemical plants
    - Multivariable control problems with inequality constraints
- Objectives
  - Drive some output variables to their optimal set points, while maintaining other outputs within specified ranges
  - Prevent violations of input and output constraints
  - Control as many process variables as possible when a sensor or actuator is not available

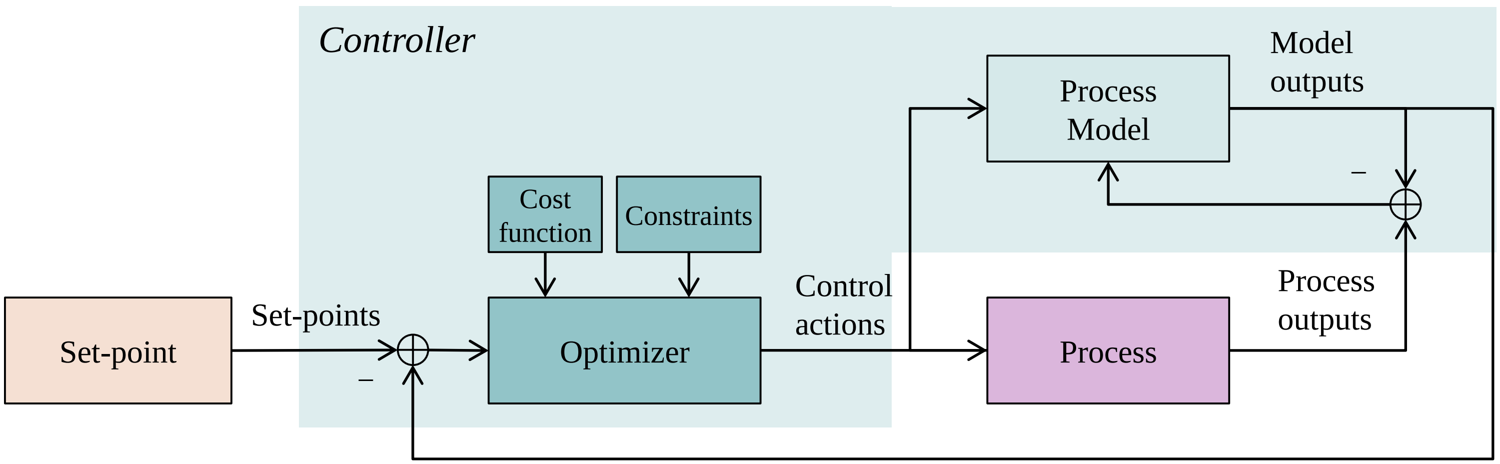
Model Predictive Control

- Set points (targets) are calculated from an economic optimization based on a steady-state model of the process
  - Optimization objectives: maximizing a profit function, minimizing a cost function, maximizing a production rate, ...
  - Set points are changed frequently due to variations of process conditions
    - e.g., constraint changes are due to variations in process conditions, equipment variations, instrumentation variations, economic data variations (prices, costs)
  - Each time the set points are re-calculated the control calculations are performed again



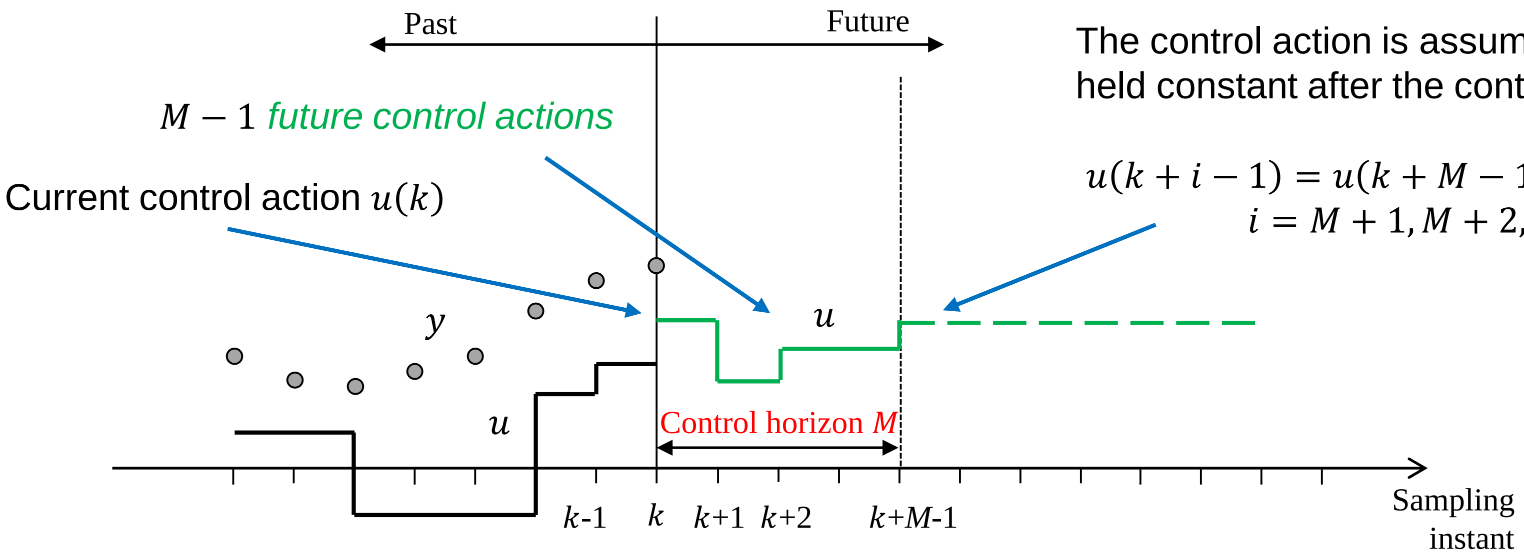
Model Predictive Control

– Control calculations are based on
  - Current measurements
  - Predictions of the future values of the outputs, computed using a dynamic model
    – Models can de based on physical laws or based on black-box approaches (neural networks)
      » e.g., linear empirical model (multivariable version of the step response models), transfer function models, state-space models, nonlinear dynamic models



Model Predictive Control

- Future control sequence
  - The objective of the MPC control calculations is to determine a sequence of control actions u so that the *predicted output* $\hat{y}$ moves to the set point in an *optimal manner*
  - At current sampling instant k, the MPC strategy calculates M control action values $\{u(k+i-1)\}_{i=1,\dots,M} = \{u(k), u(k+1), \dots, u(k+M)\}$
    - M is the number of control actions to compute (control horizon)

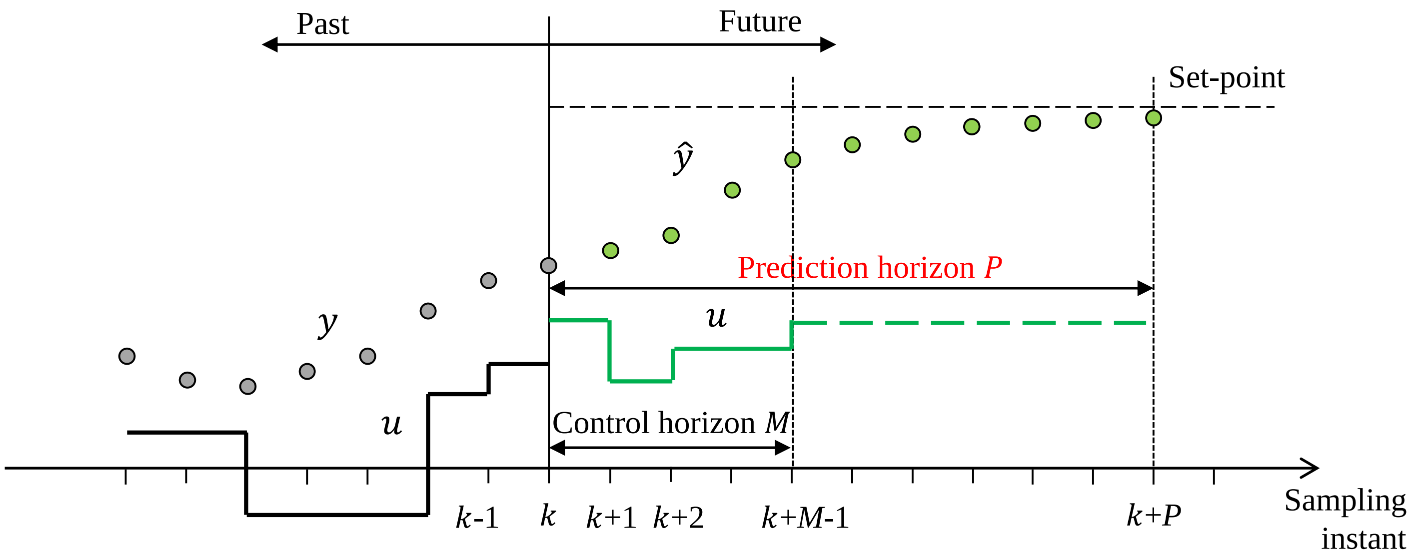


The control action is assumed to be held constant after the control horizon:

$$u(k+i-1) = u(k+M-1),\quad i = M+1, M+2, \dots$$

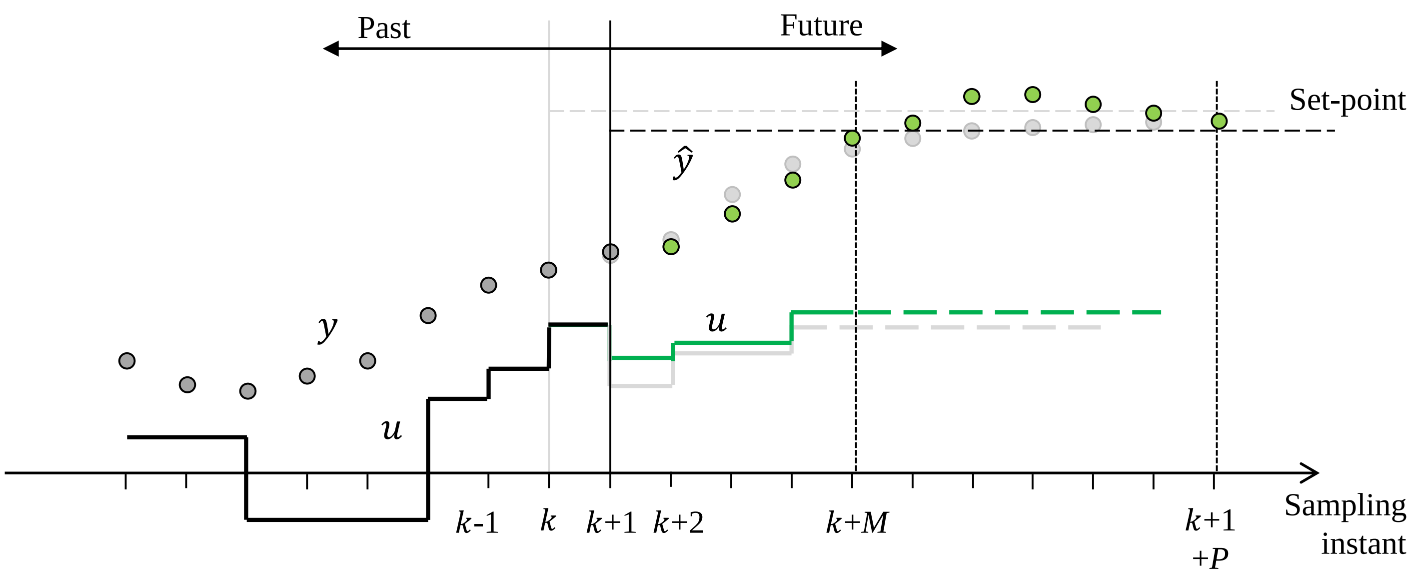
Model Predictive Control

- Output prediction
  - The inputs are calculated so that a set of P predicted outputs $\{\hat{y}\,(k\ +\ i)\}_{i\,=\,1,2,\dots\,,P}$ reaches the set point in an *optimal* manner
    - P is the number of predictions (prediction horizon)



Model Predictive Control

- *Receding horizon* approach
  - A sequence of M control moves is calculated at each sampling instant k
  - *Only the first move* $\color{red}{u(k+1)}$ *is actually implemented*
  - A new sequence is calculated at the next sampling instant $k+1$, after new measurements $y(k+1)$ become available



Model Predictive Control

- Characteristics of MPC applications
  - Inequality constraints on input variables
    - Input constraints occur as a result of physical limitations on plant equipment (pumps, control valves, heat exchangers, …)
      - e.g., a manipulated flow rate might have a lower limit of zero and an upper limit determined by the pump, control valve, and piping characteristics
  - Inequality constraints on state and output variables
    - Key component of the plant operating strategy
      - e.g., a distillation column control objective maximize the production rate while satisfying constraints on product quality and *avoiding undesirable operating regimes* such as flooding or weeping
  - Hard and soft constraints
    - A hard constraint cannot be violated at any time
    - A soft constraint can be violated, but the amount of violation is penalized by a modification of the cost function
      - Small soft constraint violations can be tolerated for short periods of time

Batch Process Automation

- Batch processing
  - "*Batch production is a 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*"
  - Alternative to continuous processing
    - A sequence of one or more steps is performed in a defined order, yielding a specific quantity of a finished product
      - Product quality specifications must be satisfied by each batch
    - The production amounts are usually smaller than for continuous processing
      - Large production runs are achieved by repeating the process steps on a predetermined schedule
      - Batch processing units are organized so that a range of products can be manufactured with a given set of process equipment (no dedicated equipment)
        - » Multiple stages, multiple products made from the same equipment
        - » Parallel processing lines

Batch Process Automation

- Batch processing (cont'd)
  - Widely used to manufacture
    - specialty chemicals, metals, electronic materials, ceramics, polymers, food and agricultural materials
    - biochemicals and pharmaceuticals
    - multiphase materials/blends, composites
  - Challenge
    - Consistently manufacture each product in accordance with its specifications while maximizing the utilization of available equipment
  - Benefits
    - Reduced inventories and shortened response times to make a specialty product compared with continuous processing plants

Batch Process Automation

- Batch processing (cont'd)
  - Automation levels in batch systems
    - Batch sequencing and logic controls (levels 1 and 2)
    - Control during the batch (level 3)
    - Run-to-run control (levels 4 and 5)
    - Batch production management (level 5).
  - The focus of control shifts from regulation to
    - set-point changes
    - sequencing of batches
    - sequencing of equipment

Batch Process Automation

- Batch processing (cont'd)
  - *Batch sequencing and logic control*
    - Sequencing of control steps that follow a *recipe*
      - e.g.
        - » 1. mixing of ingredients with specified quantity
        - » 2. heating to a specified temperature with specified velocity
        - » 3. waiting for the reaction to complete
        - » 4. cooling to a specified temperature with specified velocity
        - » 5. discharging the resulting products
      - Discrete logic for the control steps, for safety interlocks to protect personnel, equipment, and the environment from unsafe conditions
        - » Process interlocks ensure that process operations can only occur in the correct time sequence

Batch Process Automation

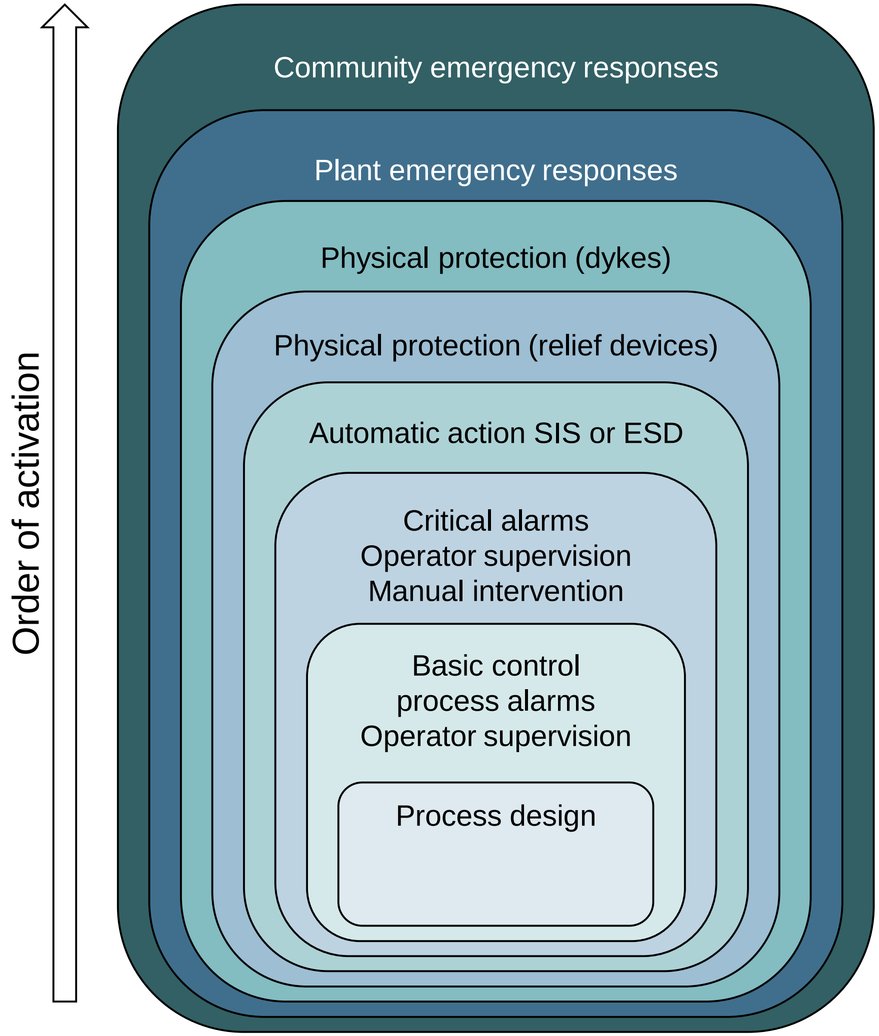
- Batch processing (cont'd)
  - *Control during the batch*
    - Feedback control of flow rate, temperature, pressure, composition, and level, including advanced control strategies, e.g.,
      - specification of an operating trajectory for the batch (that is, temperature or flow rate as a function of time)
      - tracking of set points of the controlled variables
      - holding the controlled variables constant for a prescribed period of time
      - …
- *Run-to-run control* (batch-to-batch control)
  - Supervisory function based on offline product quality measurements at the end of a run
  - Operating conditions and profiles for the batch are adjusted between runs to improve the product quality using optimization tools

Batch Process Automation

- *Batch production management*
  - Advising the plant operator of process status
    - Complete information (recipes) is maintained for manufacturing each product grade
      - names and amounts of ingredients
      - process variable set points
      - ramp rates
      - processing times
      - material and energy balances
      - ….
    - Scheduling of process units, based on availability of raw materials and equipment and customer demand

Automation and Process Safety

- Multiple protection layers
  - In modern chemical plants, process safety relies on the principle of *multiple protection layers*
  - Each layer of protection consists of a grouping of equipment and/or human actions



SIS: Safety Interlock System
ESD: Emergency ShutDown

Automation and Process Safety

- Multiple protection layers

Layer 1

In the inner layer, the process design itself provides the first level of protection

Layers 2 and 3

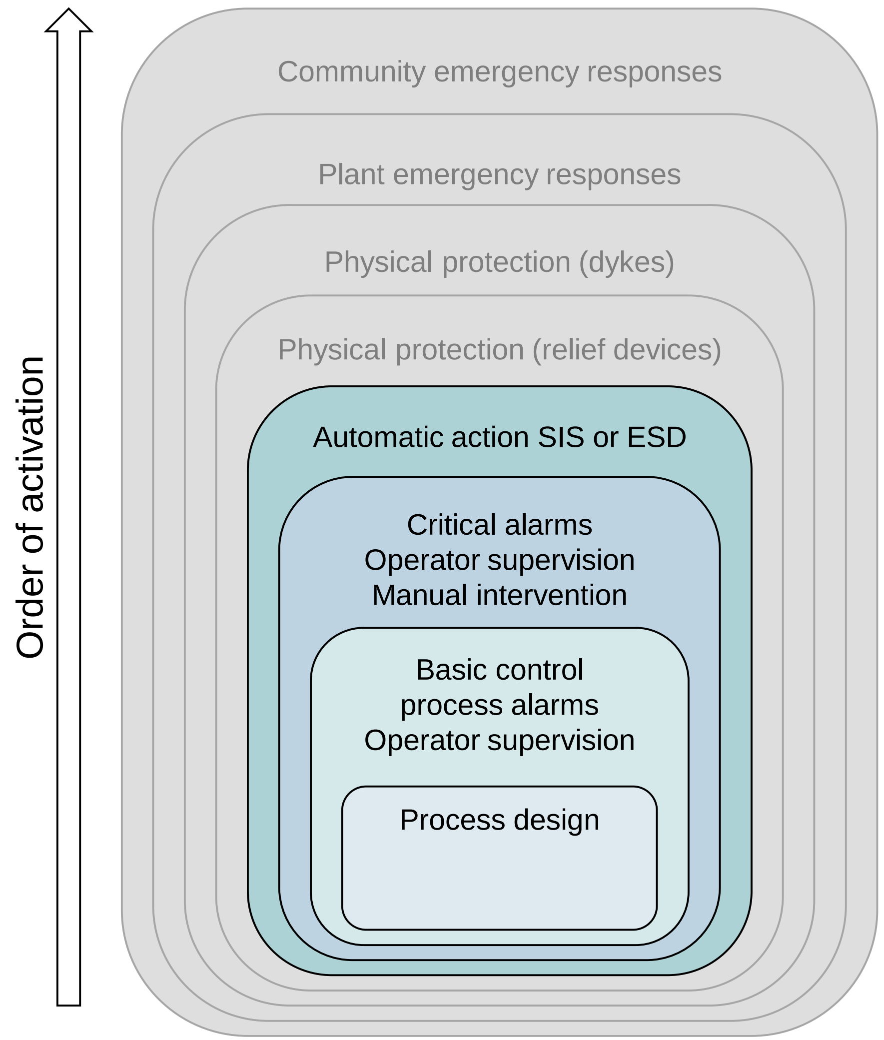
Basic process control system (BPCS) augmented with two levels of alarms and operator supervision or intervention

- Alarms indicate that a measurement has exceeded its specified limits and may require operator action

Layer 4

Safety interlock system (SIS) or as emergency shutdown (ESD) system

- The SIS automatically takes corrective actions when the process and BPCS layers are unable to handle an emergency



SIS: Safety Interlock System
ESD: Emergency ShutDown

Automation and Process Safety

- Multiple protection layers

Layer 5

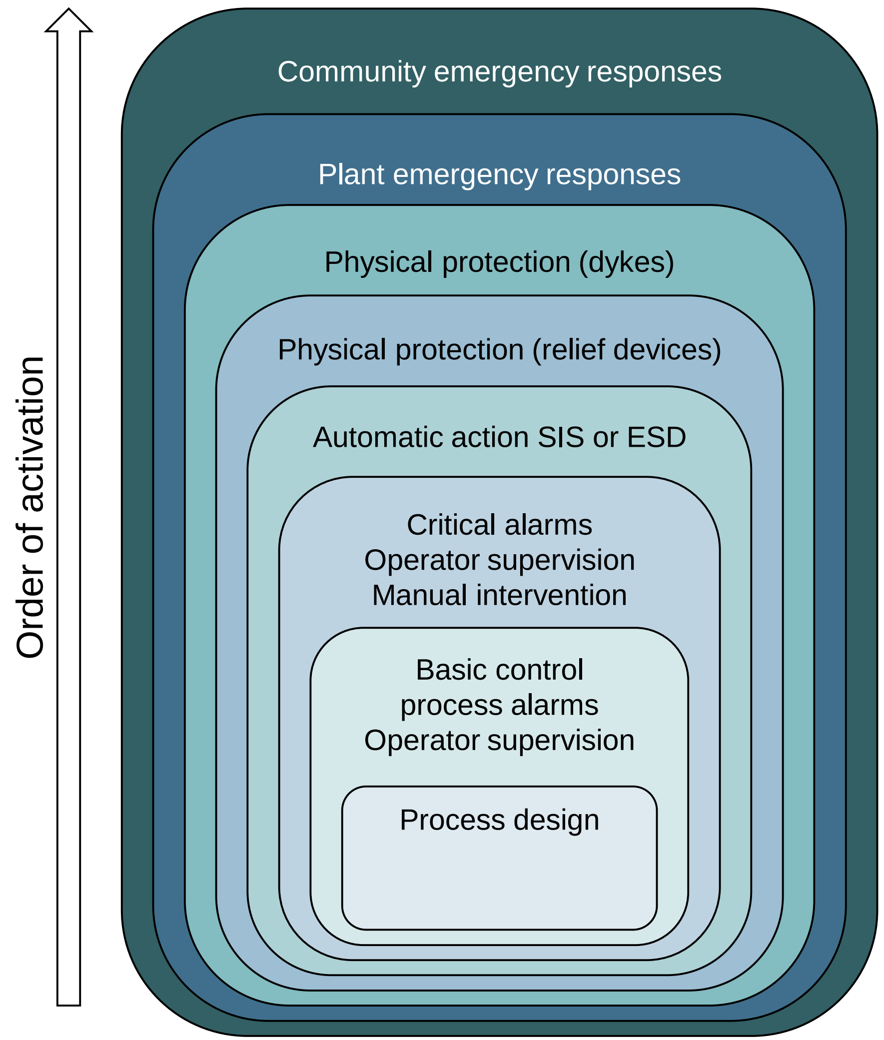
Relief devices (e.g., relief valves) provide physical protection by venting a gas or vapor if over-pressurization occurs

Layers 6

Dikes are located around process units and storage tanks to contain liquid spills

Layers 7 and 8

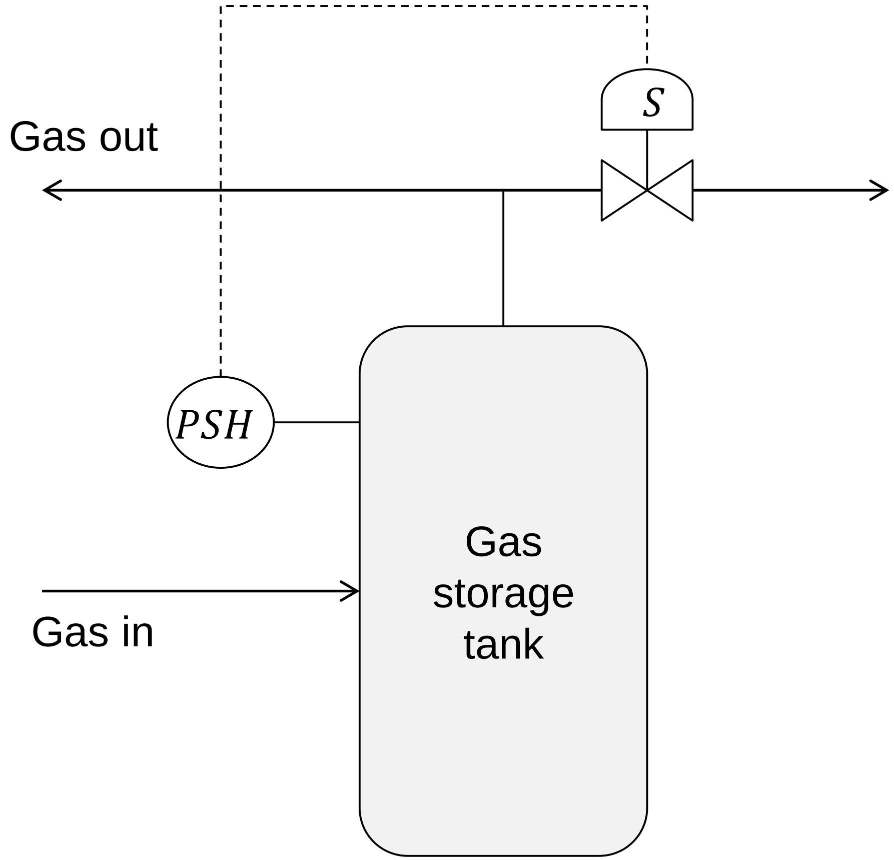
Emergency response plans are used to address emergency situations and to inform the community



SIS: Safety Interlock System
ESD: Emergency ShutDown

Automation and Process Safety

- Multiple protection layers
  - Example of interlock system
    - The solenoid-operated valve S is normally closed
    - If the pressure of the hydrocarbon gas in the storage tank exceeds a specified limit, the high-pressure switch (PSH)
      - activates an alarm
      - causes the valve to open fully, thus reducing the pressure in the tank



Automation and Process Safety

- Multiple protection layers
  - The safety interlock system (SIS) must work *independently* of the basic process control system (BPCS)
    - Emergency protection is still available when the BPCS is not operating (e.g., due to a malfunction or power failure)
  - The SIS should
    - be physically separated from the BPCS
    - have its own sensors and actuators (possibly, with redundancy)
    - have a separate set of alarms so that the operator can be notified when the SIS initiates an action (e.g., turning on an emergency cooling pump), even if the BPCS is not operational.

Summary

- Objectives of process control
- Brief overview of the 5 levels of process control
- Need of dynamic model for effective control
- Brief overview of regulatory control (standard PID approach)
- Steps for the control system development under the model-based approach
- Relevance of model predictive control in multivariable control and its principles
- Brief review of batch process automation
- Brief review of process safety