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학습기반 공정 동적최적화

Lecture 02: Introduction of Model Predictive Control

A Multivariable Control Technique for
the Process Industry

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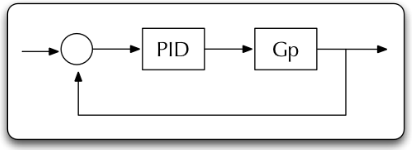
What is MPC?

Process

Actuator

or



Low-level Loops

Sensor

Up-to-date Process Information

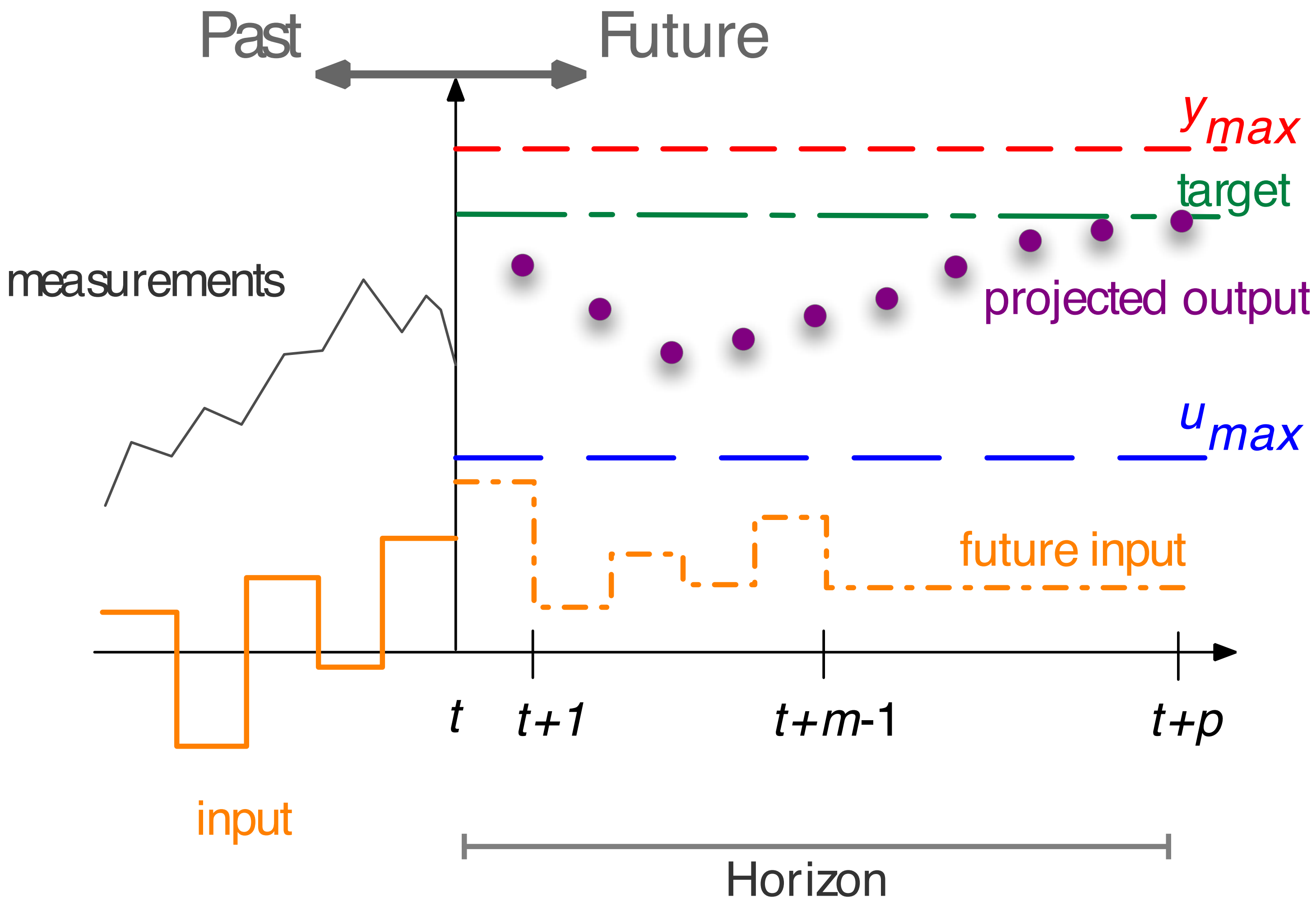
Optimal Process Adjustment

Computer

Simulation/Optimization Package
Database

Dynamic Process Model
Objective & Constraints
Connection to Information System

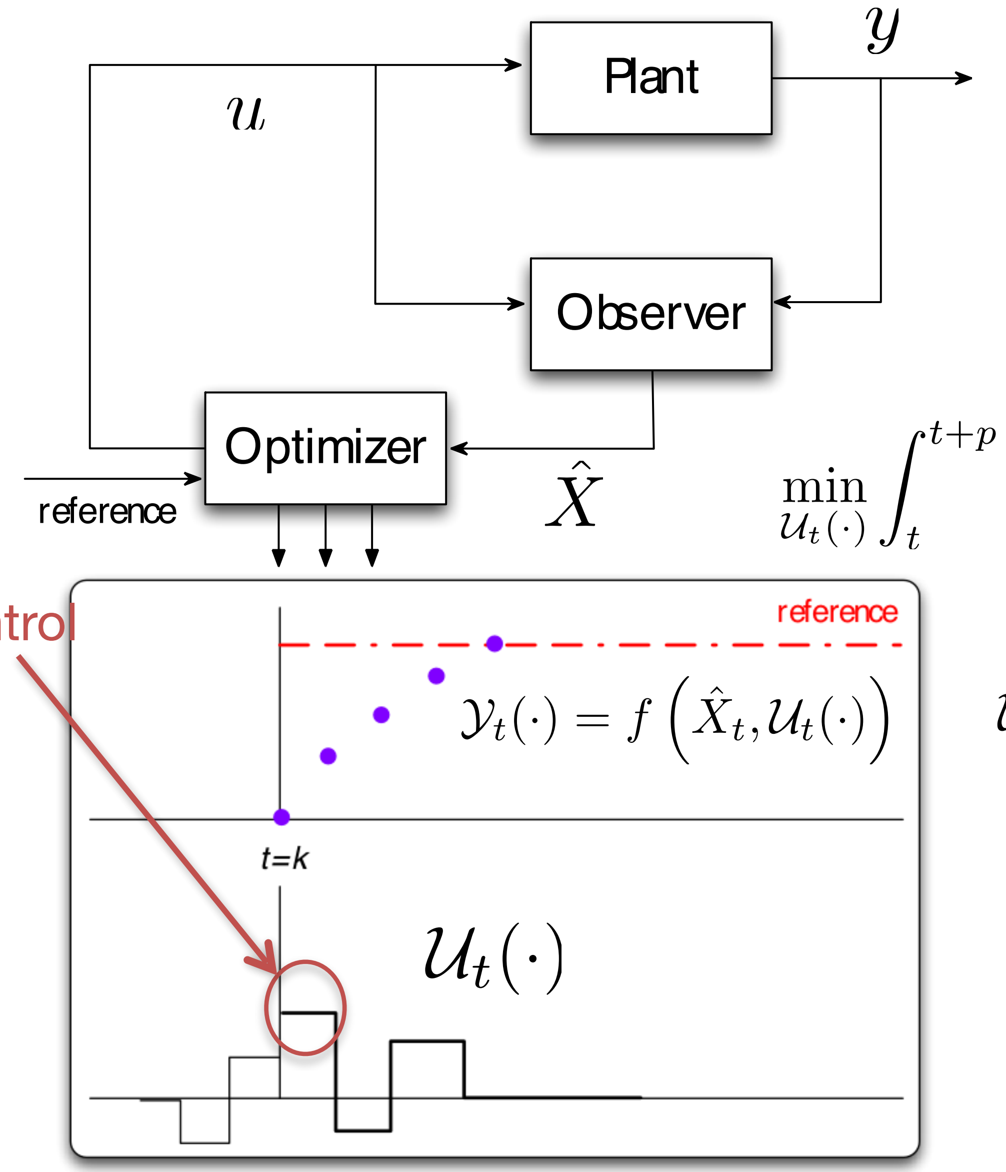
Main Algorithm



Some Key Features

- Computer based: sampled-data control
- Model based: requires a dynamic process model
- Predictive: makes explicit prediction of the future time behaviour of CVs within a chosen window
- Optimization based: performs optimization (numerical search) online for optimal control adjustments. No explicit form of control law – just model, objective, and constraints are specified
- Integrated: constraint handling and economic optimization with regulatory and servo control
- Receding Horizon Control: repeats the prediction and optimization at each sample time step to update the optimal input trajectory after a feedback update

Exemplary Algorithm



Control Objective

$$\min_{\mathcal{U}_t(\cdot)} \int_t^{t+p} \ell_1 \left[\text{Error}(\tau)\right] + \ell_2 \left[\text{Input}(\tau)\right] d\tau$$

Constraints

$$\mathcal{U}(\cdot) \in U, \quad \mathcal{Y}_t(\cdot) \in Y$$

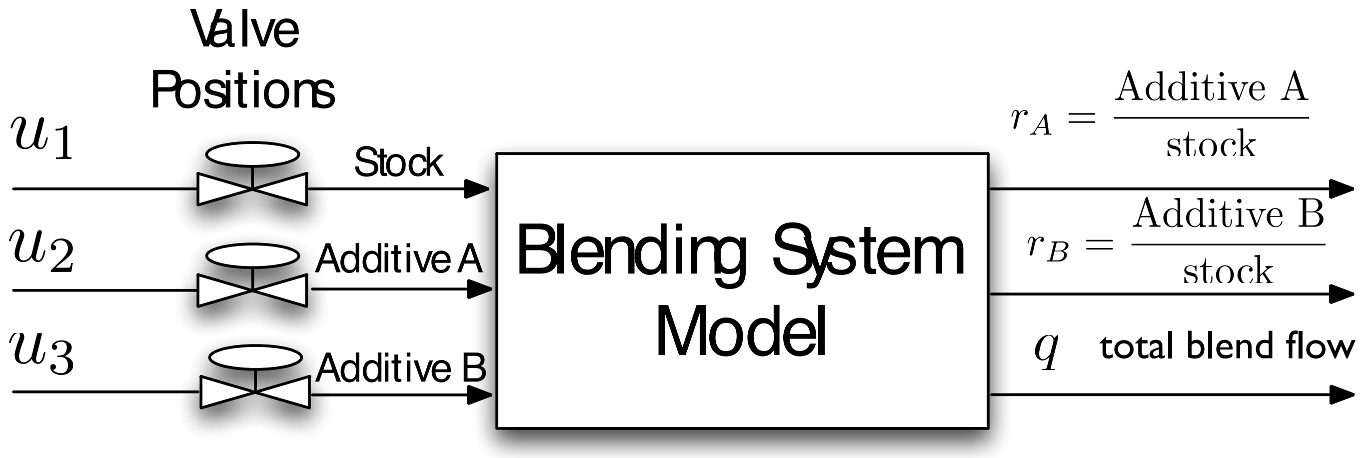
Receding Horizon Control

only the adjustment for the current sample time is implemented and the rest are re-optimized at the next sample time step after a new feedback update.

Industrial Use of MPC

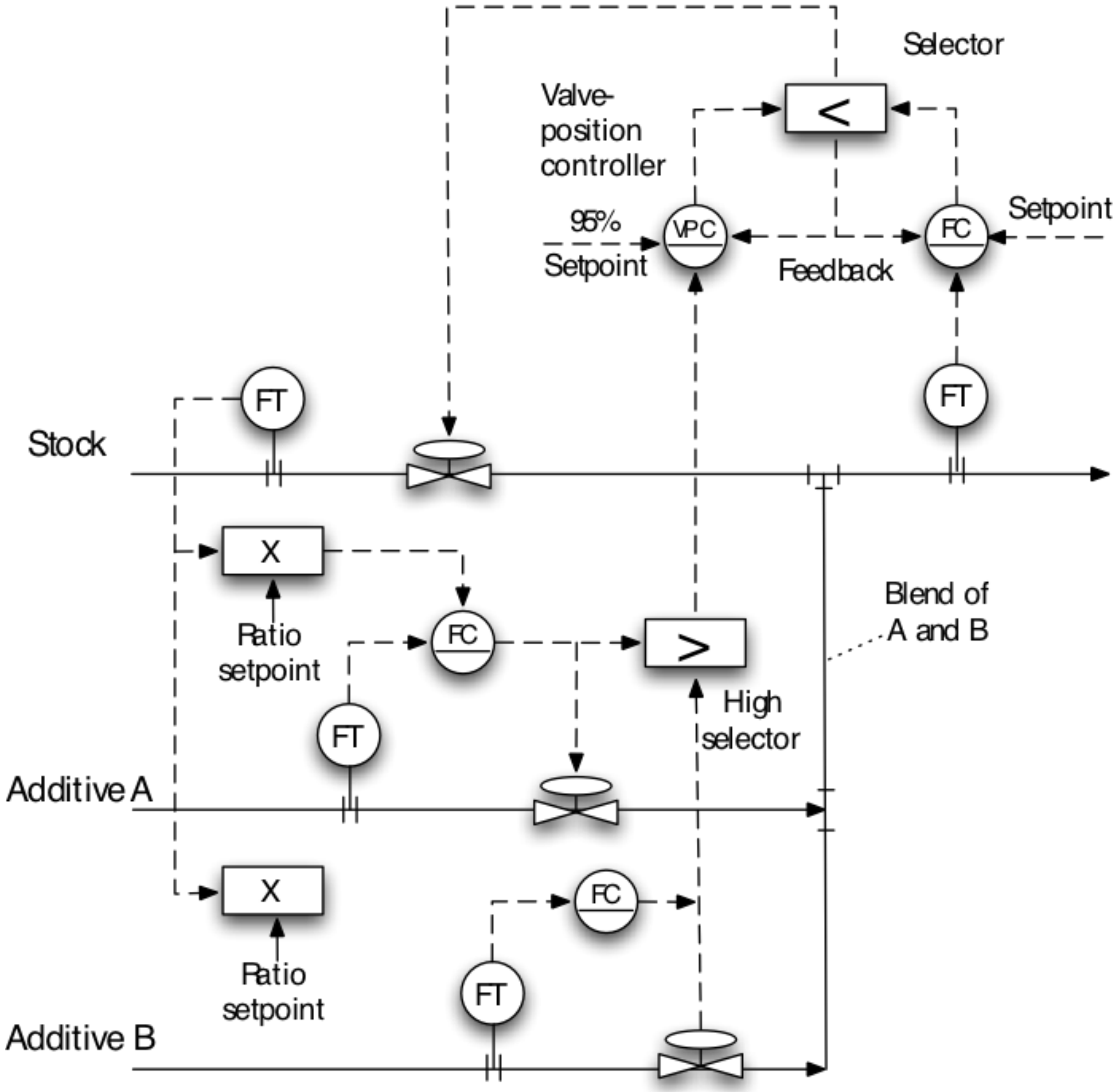
- Initiated at Shell Oil and other refineries during late 70s and early 80s.
- Various commercial software
  - DMCplus – Aspen Tech
  - RMPCT – Honeywell
  - Dozen+ other players (e.g., 3DMPC-ABB)
- > 3000 worldwide installations
- Predominantly in the oil and petrochemical industries but the range of applications is expanding.
- Models used are predominantly empirical models developed through plant testing.
- Technology is used not only for multivariable control, but for most economic operation within constraint boundaries.

Example 1: Blending System Control



- Control r_A and r_B.
- Control q if possible.
- Flowrates of additives are limited

Classical Solution



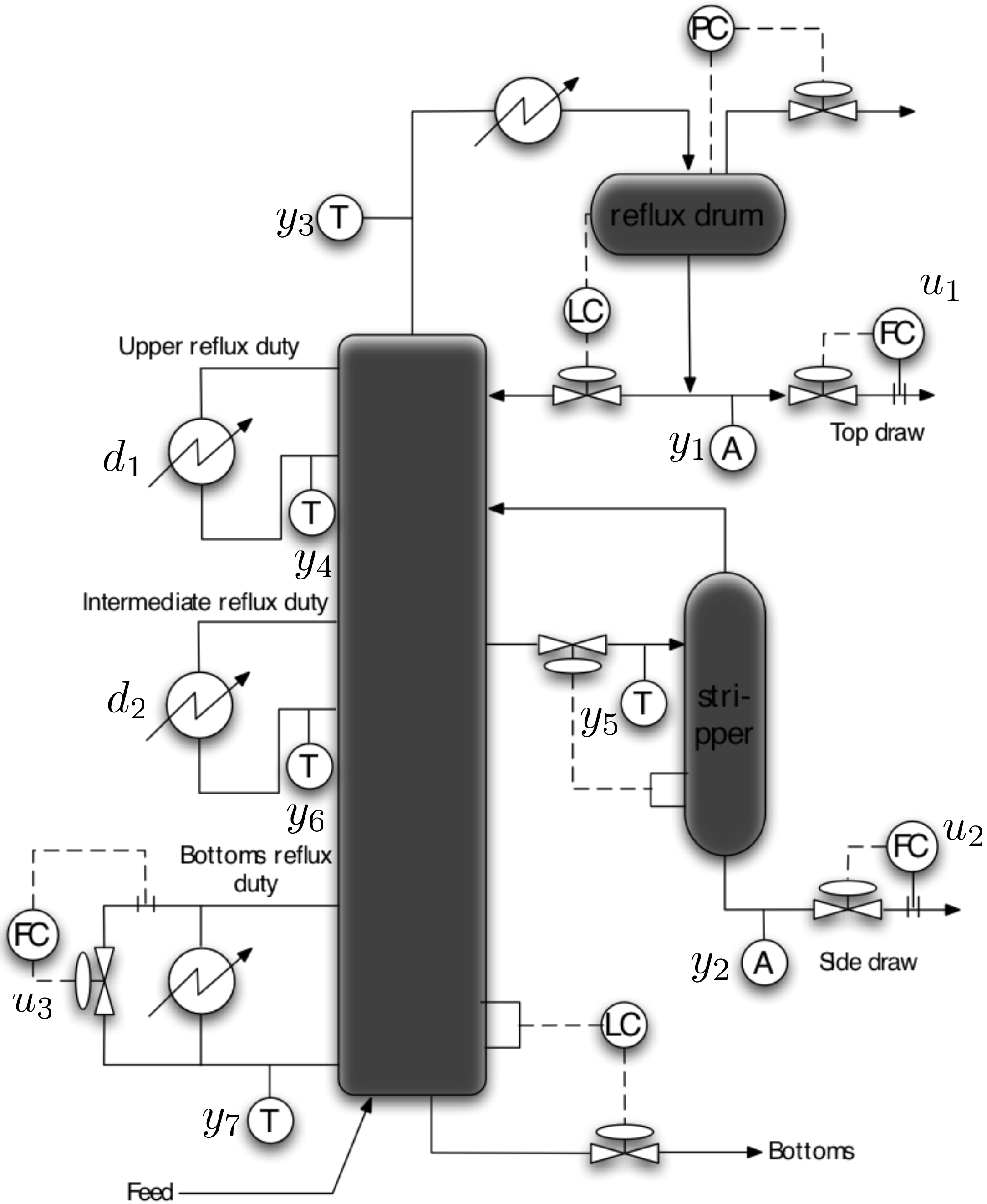
MPC: Solve @ each time k

p: size of prediction window

$$\min_{\substack{u_1(j),u_2(j),u_3(j) \\ j=k,\ldots,k+p-1}} \sum_{i=1}^{p} \left(r_A(k+i|k) - r_A^*\right)^2 + \left(r_B(k+i|k) - r_B^*\right)^2 + \gamma\left(q(k+i|k) - q^*\right)^2$$

$$(u_i)_{\min} \leq u_i(j) \leq (u_i)_{\max}, \quad i = 1, \ldots, 3, \quad \gamma << 1$$

Example 2: Heavy Oil Fractionator



- Keep $y_7 \geq T_{\min}$
- Control the two compositions

  y_1 and y_2
- Minimize u_3 to maximize the heat recovery

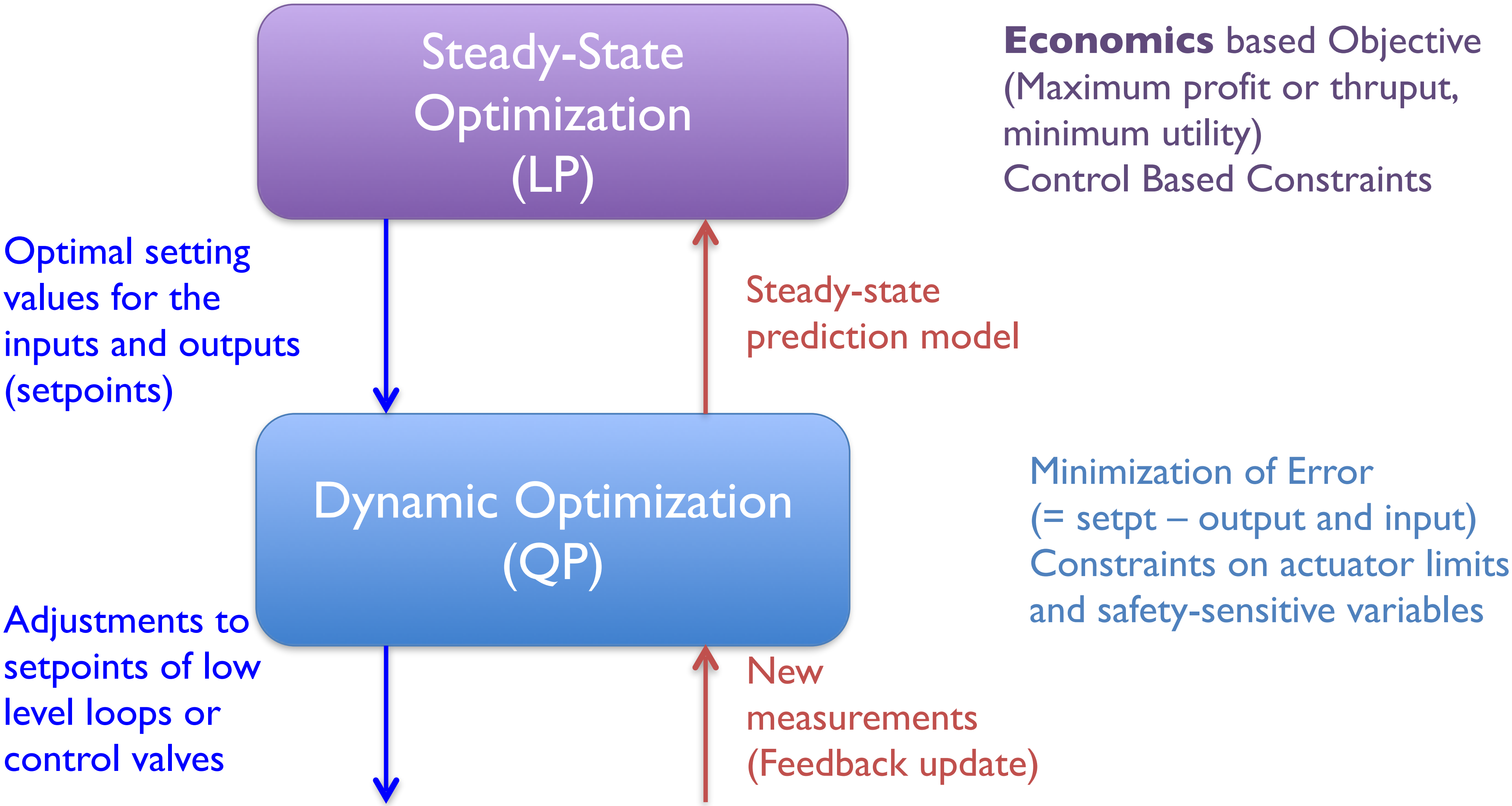
Solution using the classical tools will be very complicated and a satisfactory solution is not known.

It is fairly easy to translate the above objective (as well as the valve limits) as a minimization function and inequality constraints as required by MPC

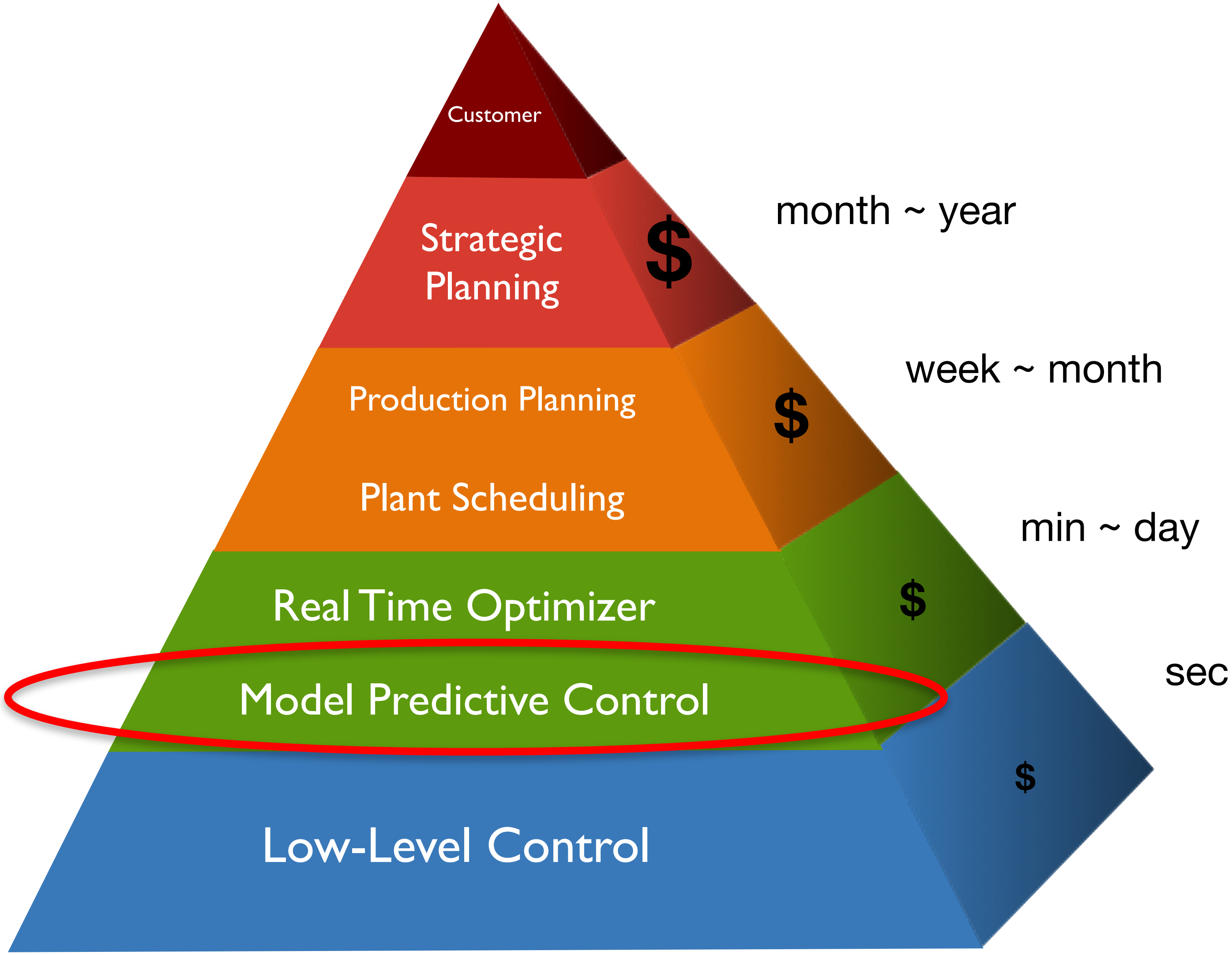
Advantages of MPC over Traditional APC

- Integrated solution
  - Automatic constraint handling
  - Feedforward/feedback
  - No need for decoupling or delay compensation
- Efficient utilization of degrees of freedom
  - Can handle nonsquare systems (e.g., more MVs and CVs)
  - Assignable priorities, ideal settling values for MVs
- Consistent, systematic methodology
- Realized benefits
  - Higher online times
  - Cheaper implementation
  - Easier maintenance

Bi-Level Optimization Used in MPC

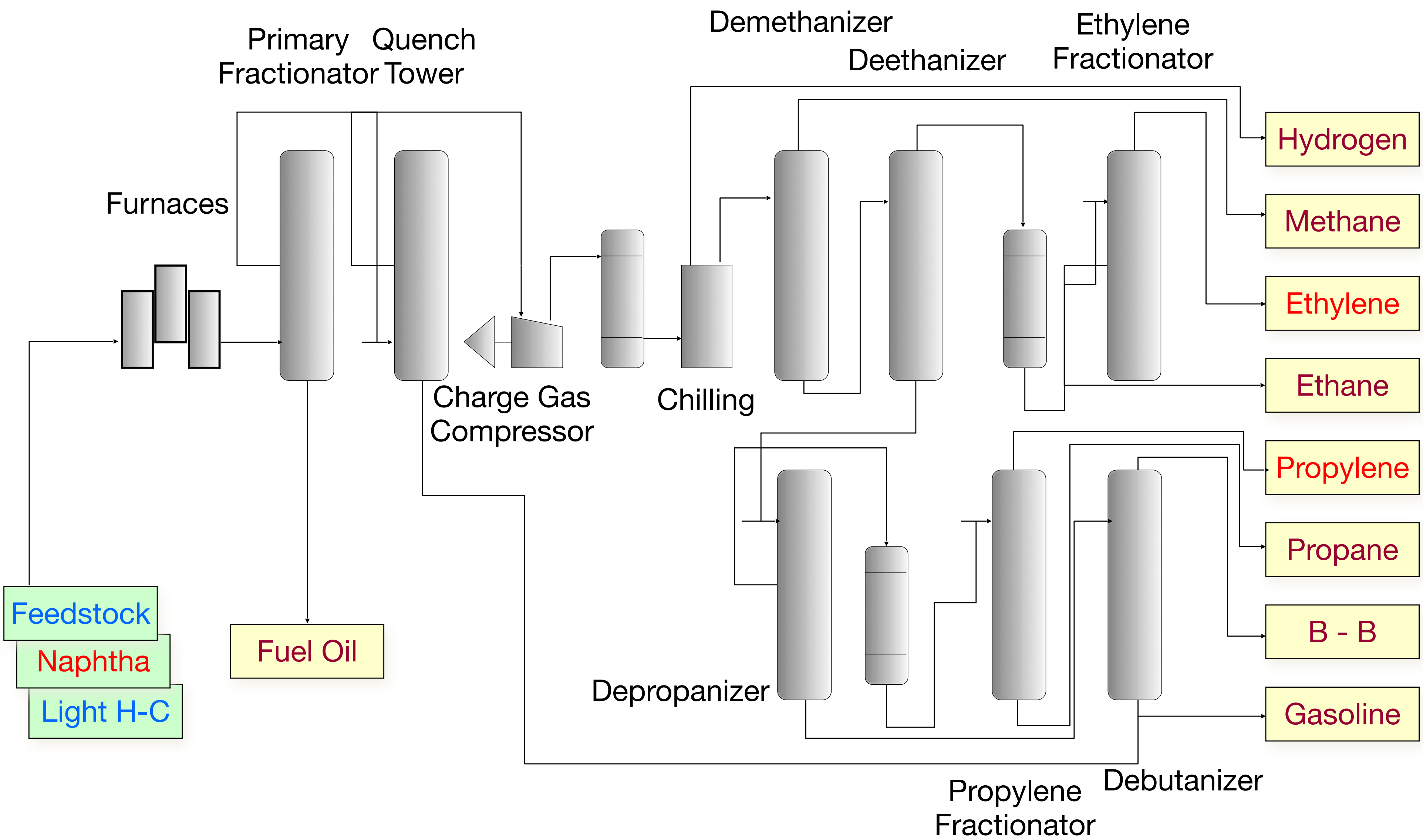


New Operational Hierarchy and Role of MPC



Move the plant to the current optimal condition fast and smoothly w/o violating constraints: Local optimization + control

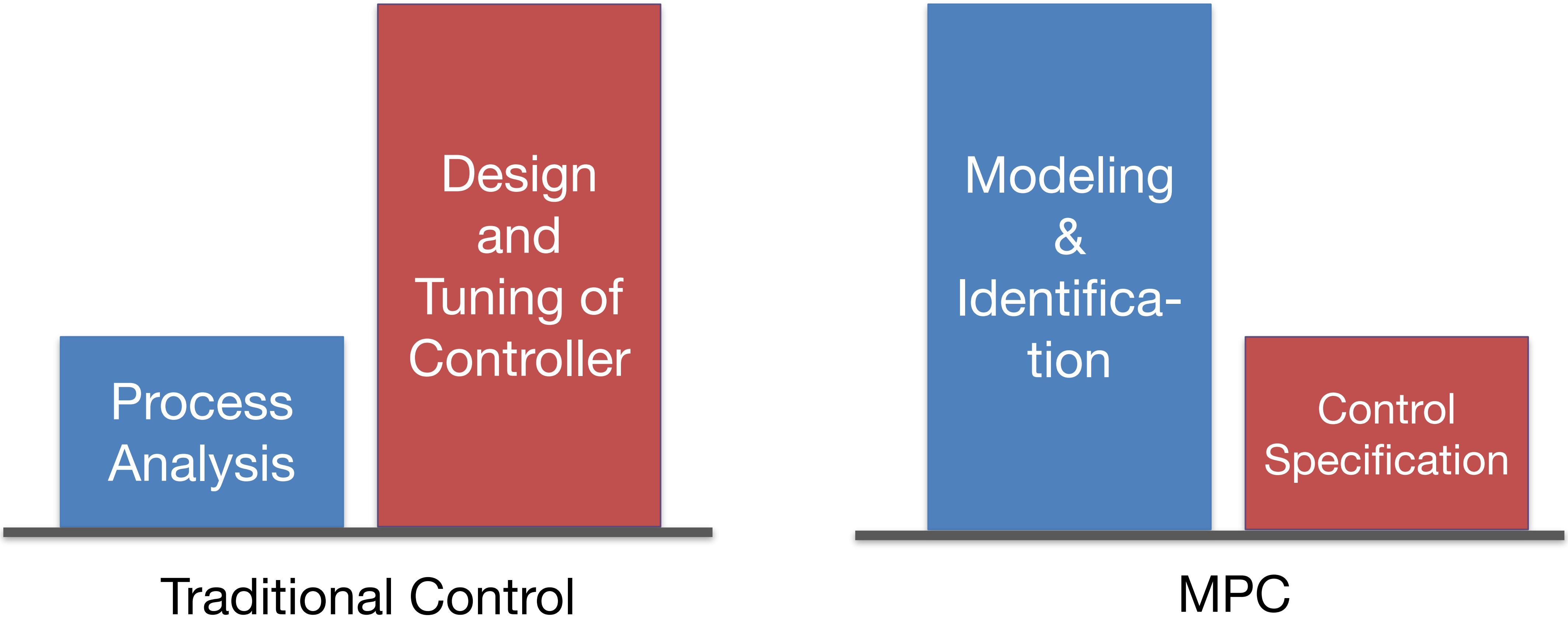
An Exemplary Application: Ethylene Plant



Importance of Modeling/Sys-ID

- Model is the most critical element of MPC that varies the most from application to application.
- Almost all models used in MPC are typically **empirical models identified through plant tests** rather than first-principles models.
  - Step responses, pulse responses from plant tests
  - Transfer function models fitted to plant test data
- Up to **80% of time and expense** involved in designing and installing a MPC is attributed to modeling/system identification
- Keep in mind that obtained models are **imperfect** (both in terms of structure and parameters)
  - Importance of **feedback** update to correct model prediction or model parameters/ states.
  - Penalize excessive input movements.

Design Effort for Two Approaches



Challenges for MPC

- Efficient identification of control-relevant model
- Managing the sometimes exorbitant online computational load
  - Nonlinear models ➔ Nonlinear Programs (NLP)
  - Hybrid system models (continuous dynamics + discrete events or switches, e.g., pressure swing adsorption) ➔ Mixed Integer Programs (MIP)
  - Difficult to solve these reliably online for large-scale problems
- How do we design model, estimator (of model parameters and state), and optimization algorithm as an integrated system – that are simultaneously optimized, rather than as disparate components?
- Long-term maintenance of control system

Control Relevant Modeling

Coupling between Modeling and Control

Model Quality (Error or "Uncertainty")

System ID

- Test signal characteristics
- Model structure
- Data filtering
- Parameter fitting

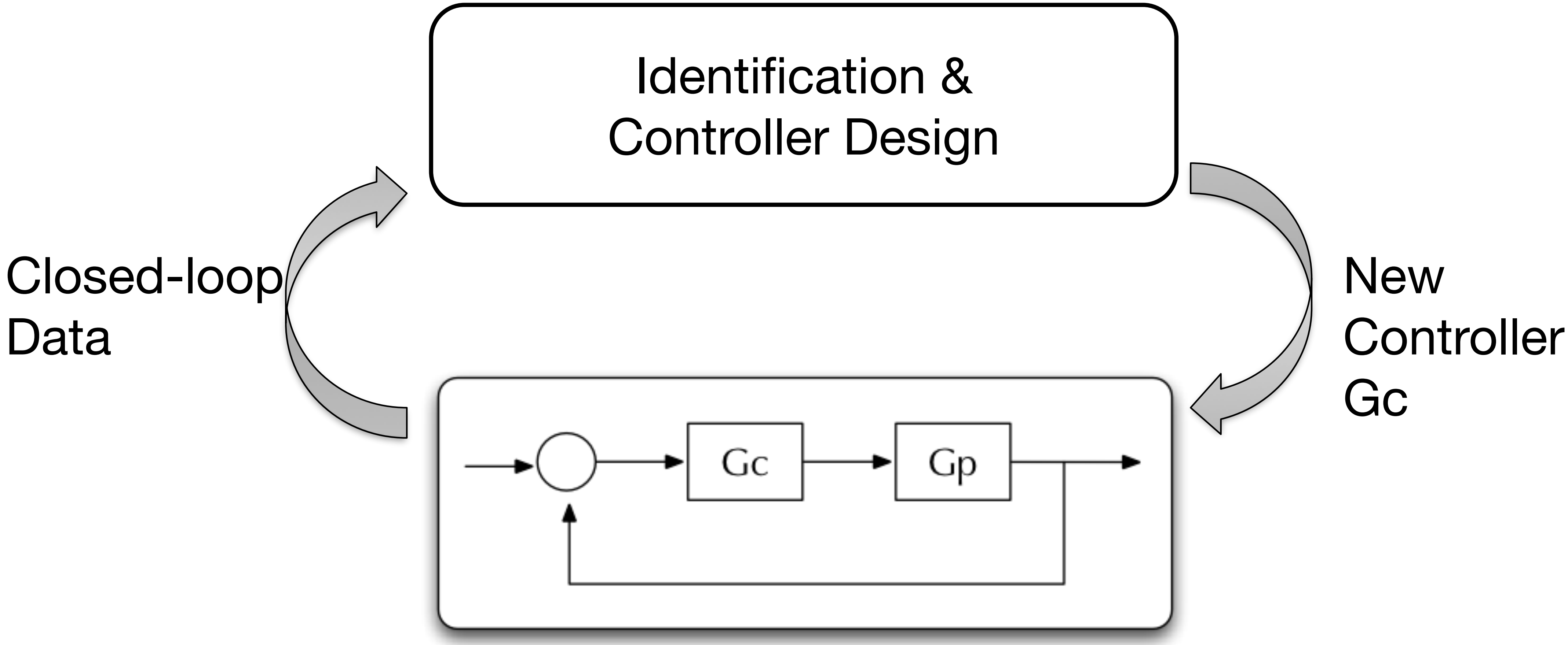
Model

MPC Design

- Choice of objective function and constraints
- Choice of horizon sizes
- Choice of online estimator

Sensitivity of Control Performance to Model Errors

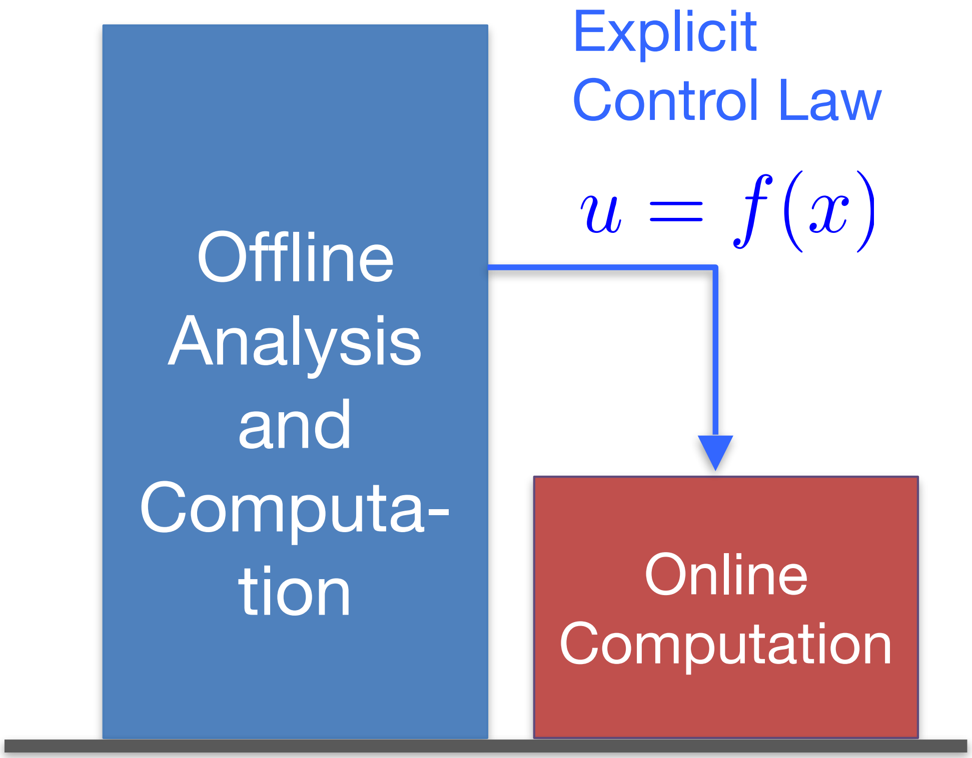
Iterative Model/Controller Refinement



Closed-loop Operation and Testing

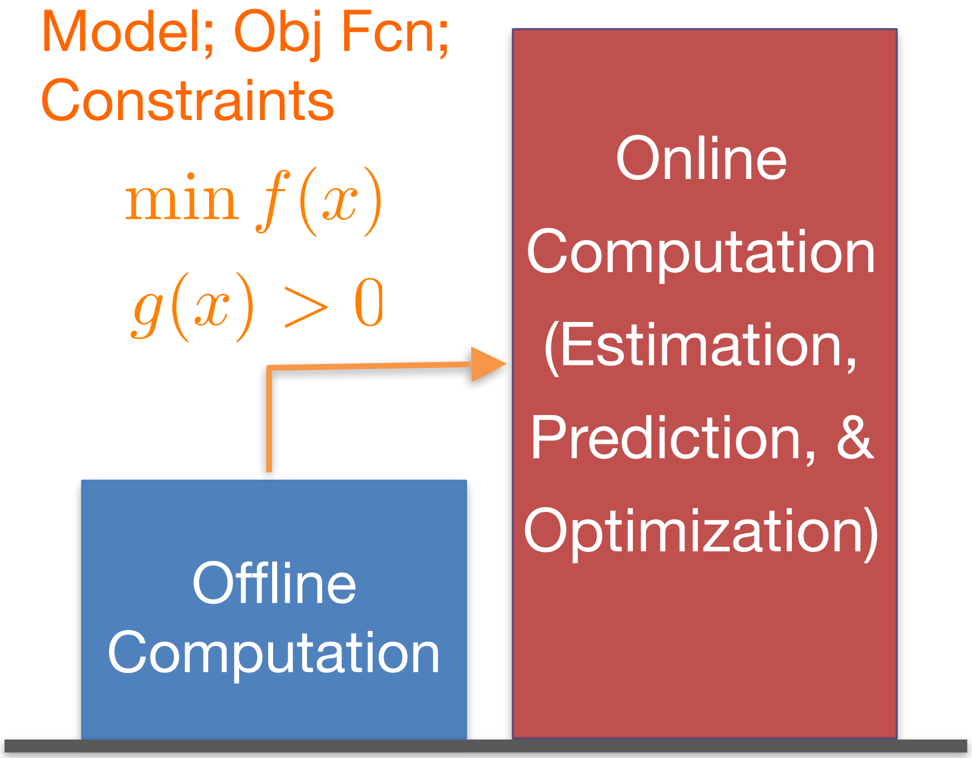
Comparison of Computational Load

Classical Optimal Control



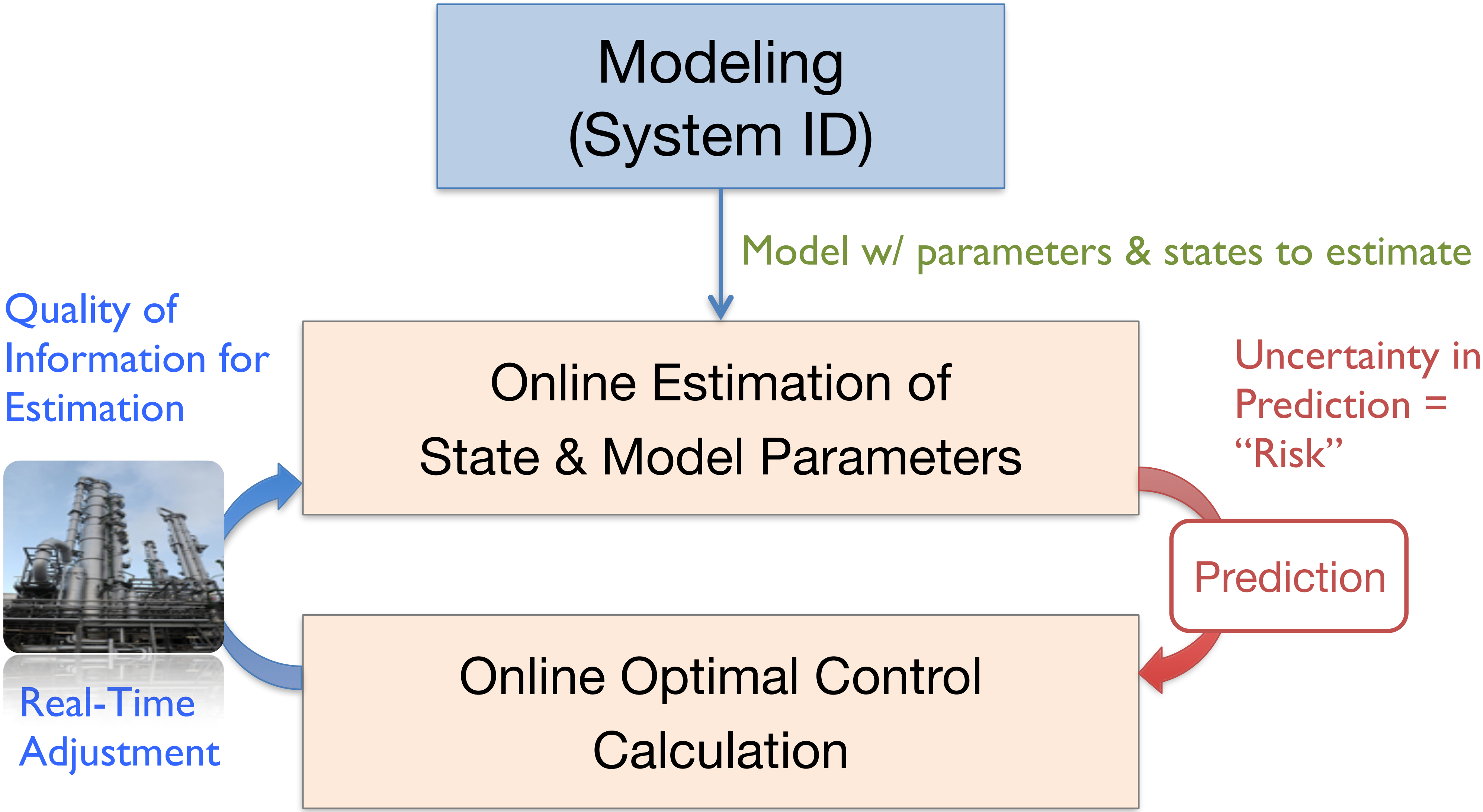
Limited by the ability to derive the explicit control law analytically or with reasonable offline computation

MPC

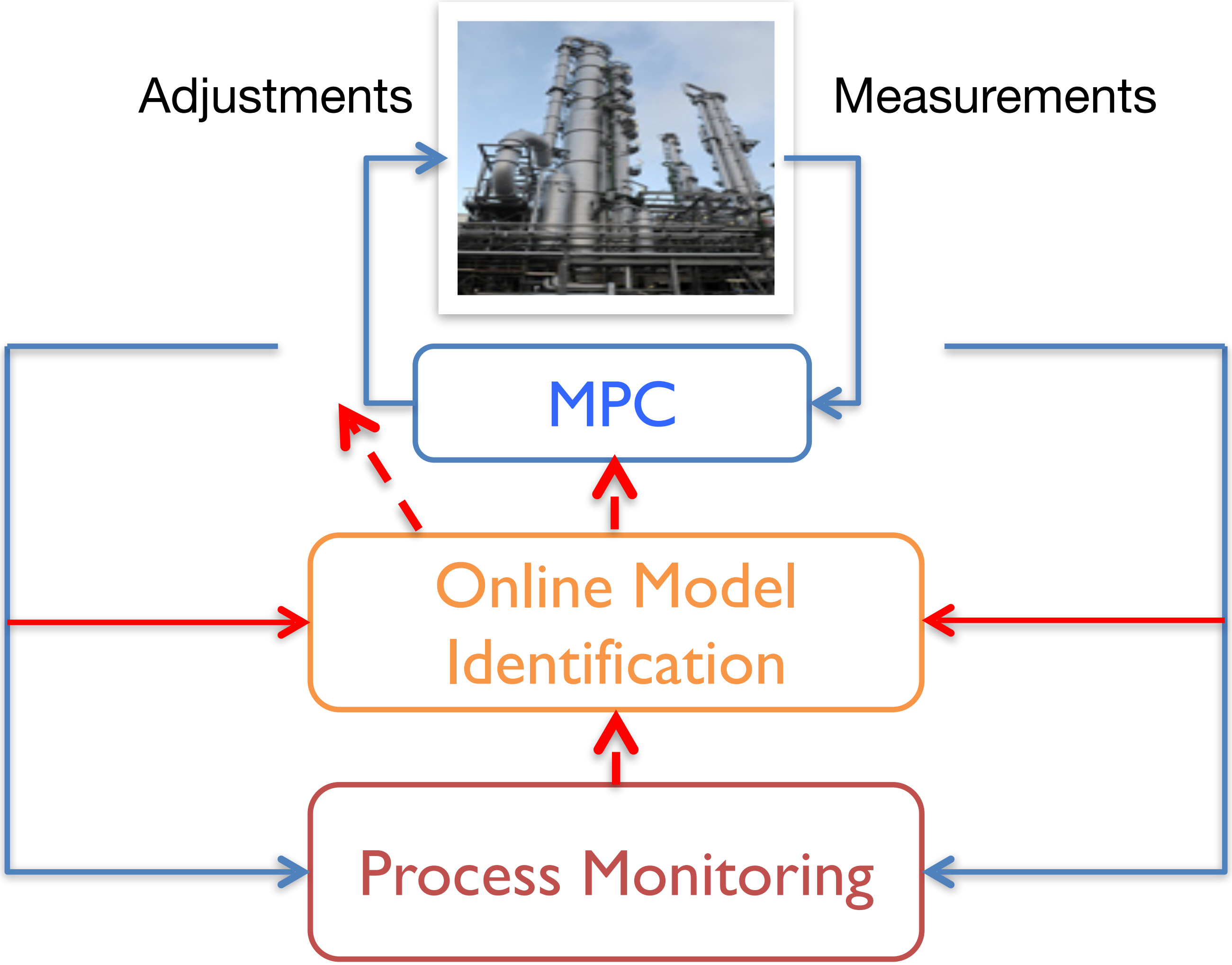


Limited by available online computational power and numerical methods to solve online optimization reliably

Coupling between Online Estimation and Control Calculation



Integrated MPC, Performance Monitoring, and Closed-Loop Identification



Detection and Diagnosis of Abnormal Situation

- Operation shifts: model parameter changes
- Abnormal disturbances (size & pattern)
- Instrumentation/Equipment Faults, Poisoning, etc.

Conclusion

- MPC is the established advanced multivariable control technique for the process industry. It is already an indispensable tool and its importance is continuing to grow.
- It can be formulated to perform some economic optimization and can also be interfaced with a larger-scale (e.g., plant-wide) optimization scheme.
- Obtaining an accurate model and having reliable sensors for key parameters are key bottlenecks.
- A number of challenges remain to improve its use and performance.