

MACC 2019

Control Science as a Source of Insight and Inspiration for Managing Innovation

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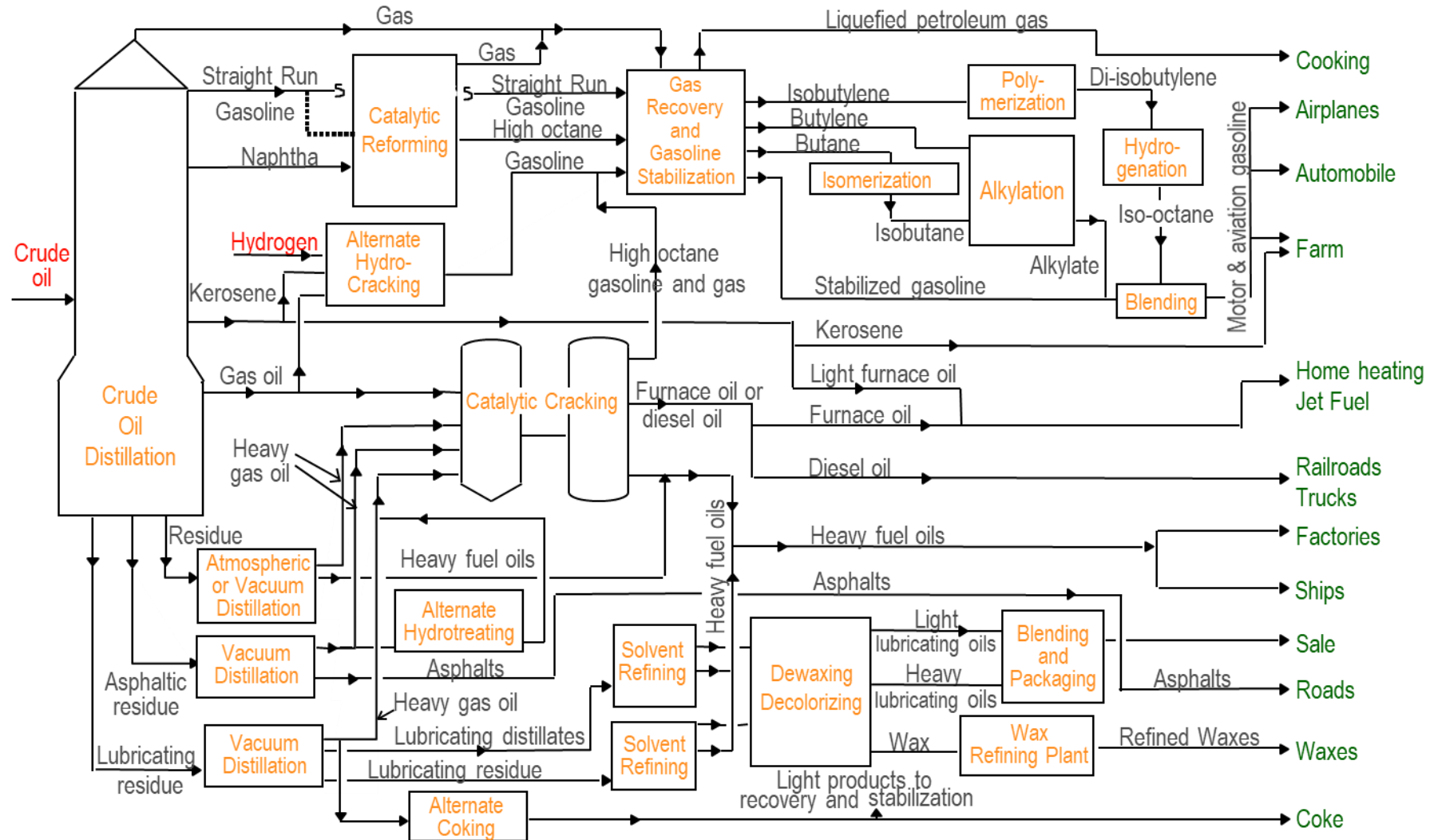


Outline

- **Complex Engineered Systems—Examples**
- **Aspects of Complexity**
- **From Complex Systems to Complex Controllers**
- **Insights from Control Science for Technology Management and Innovation**
- **Concluding Message**

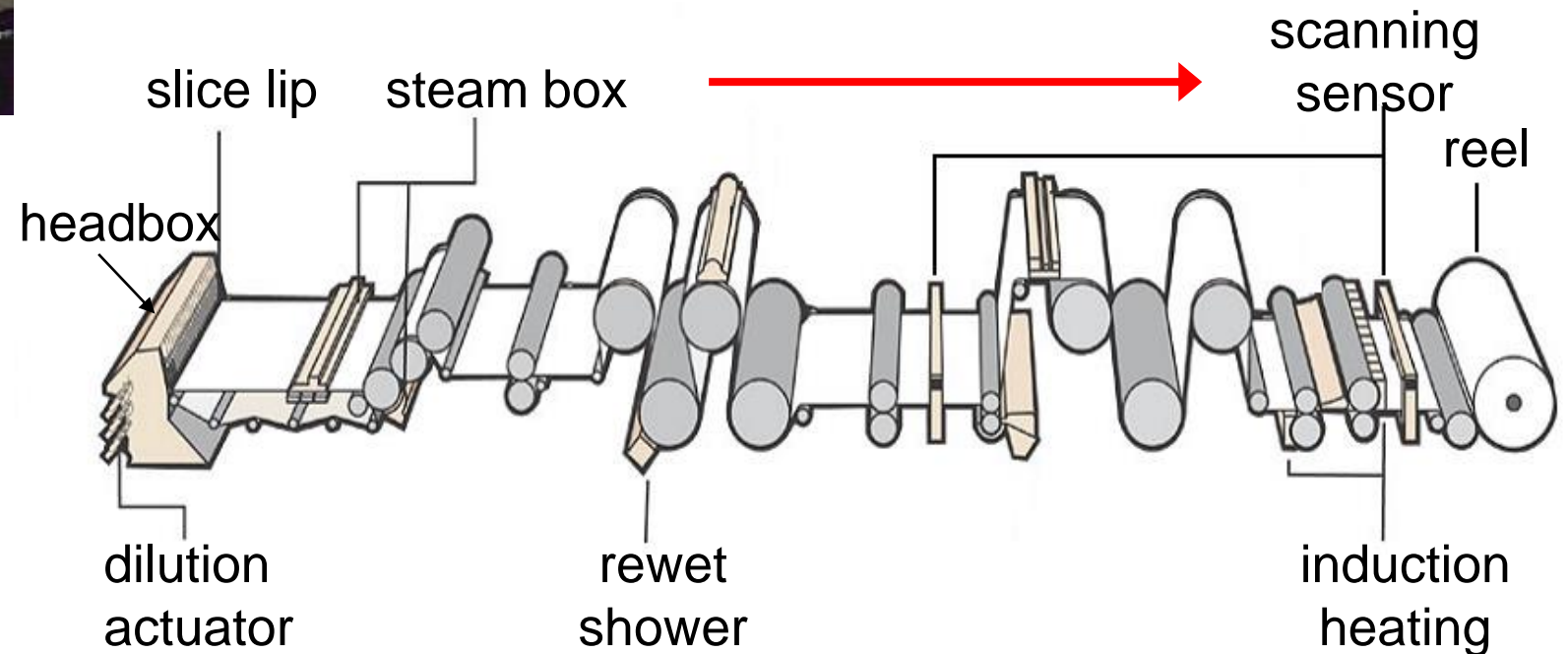
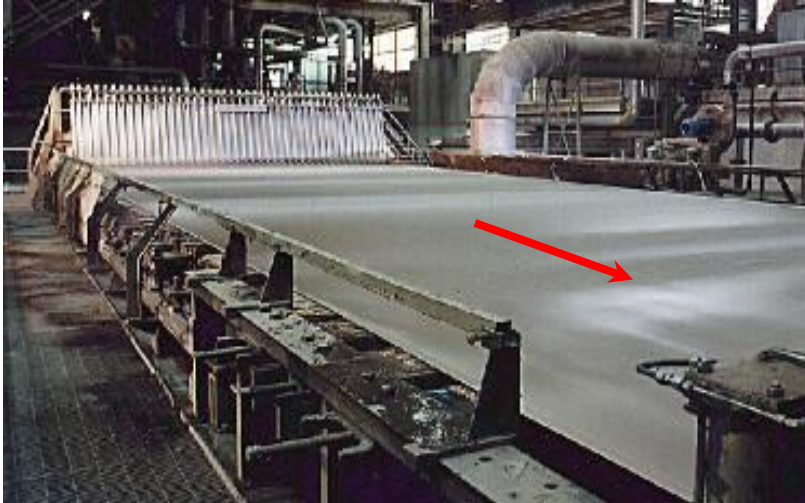


Oil Refinery System



Courtesy of Joseph Lu, Honeywell Process Solutions

Paper Machine System



Aircraft Dynamical System

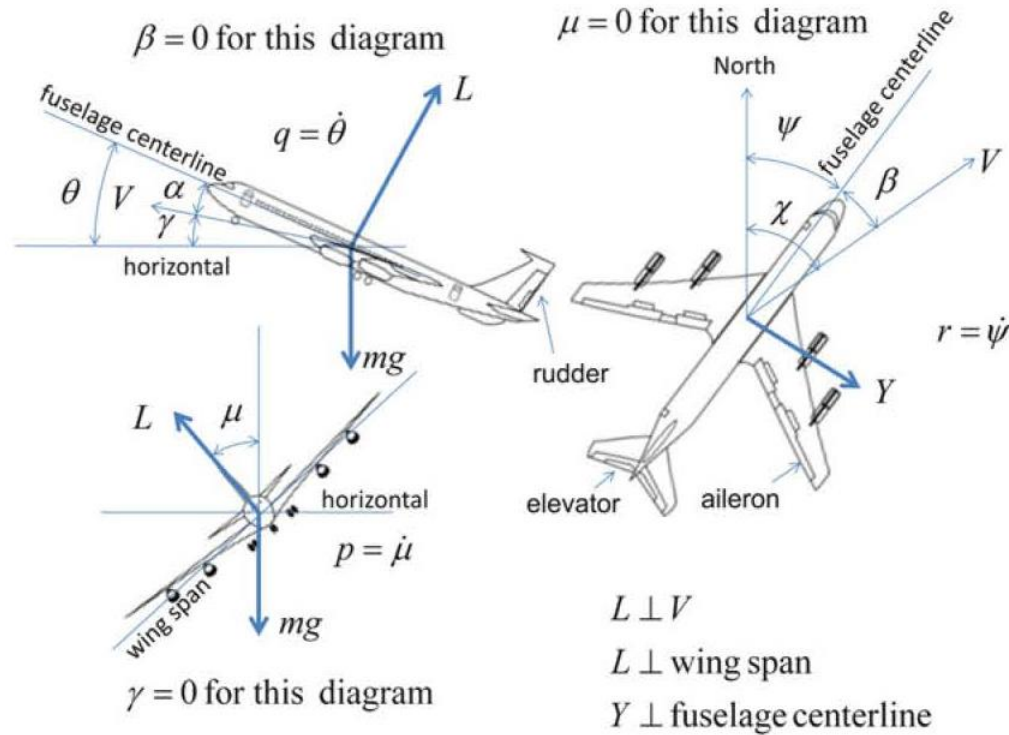
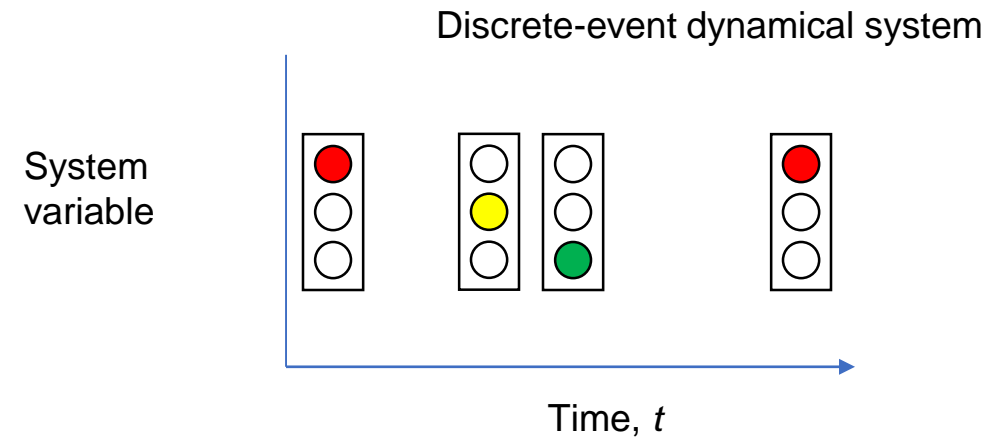
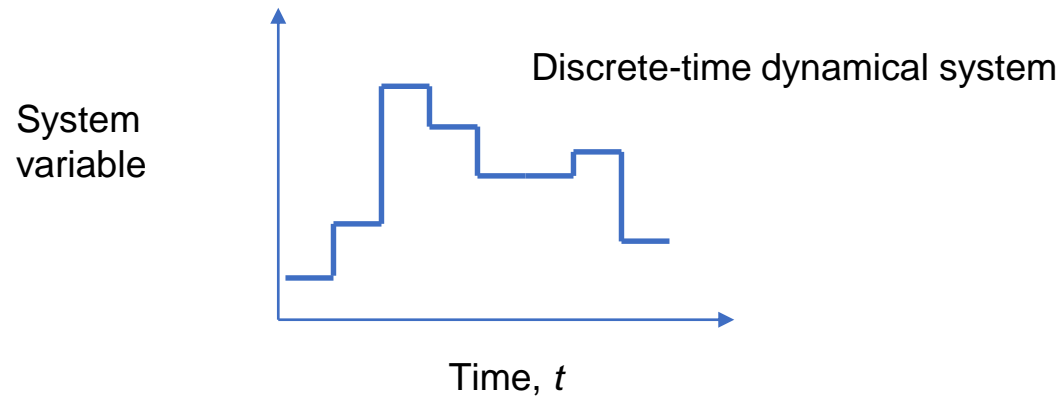
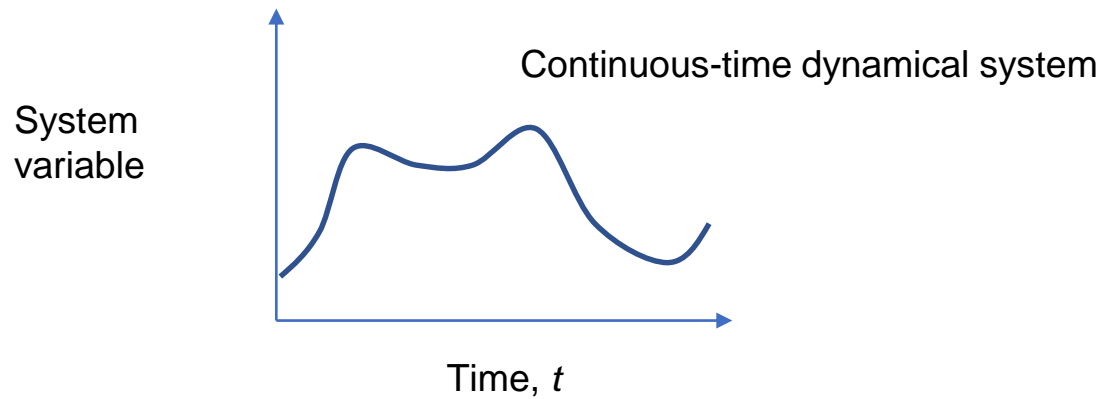


Fig. 1 Flight control variables

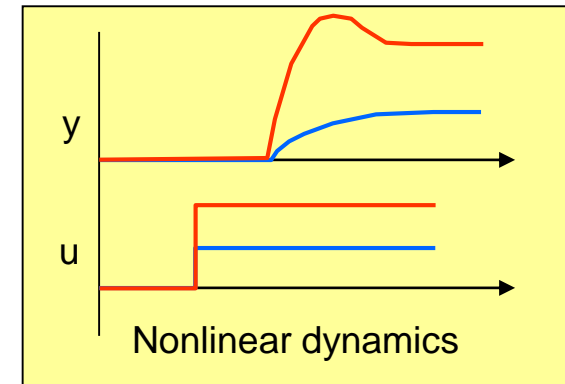
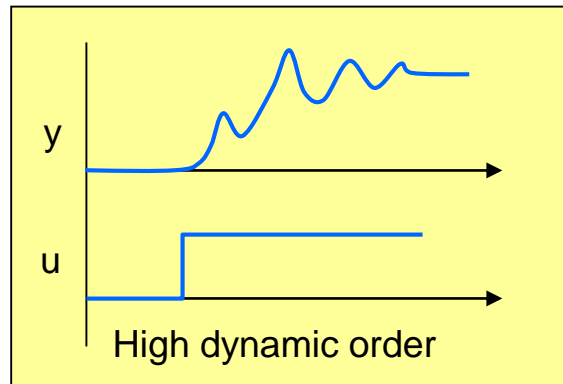
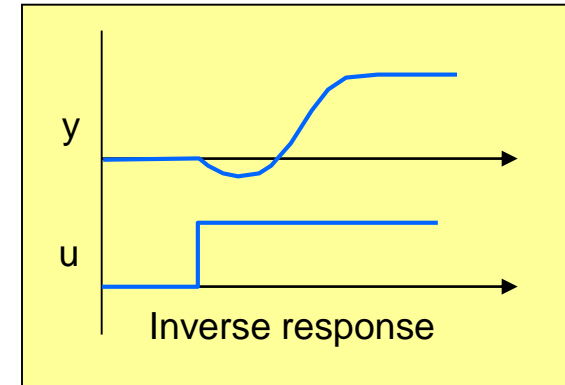
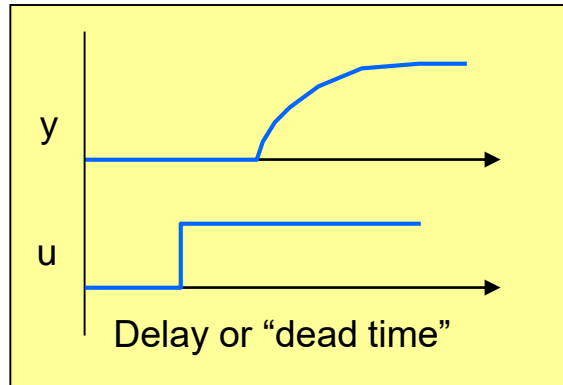
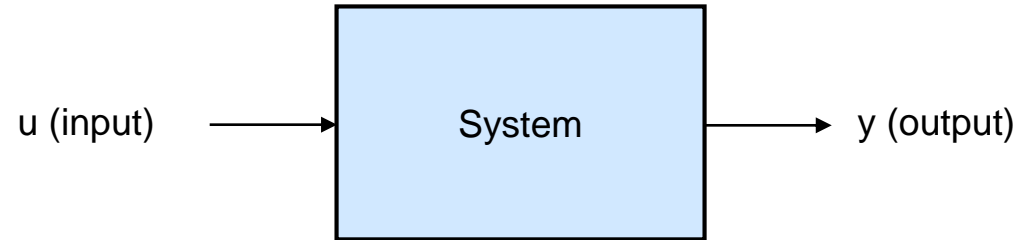
D. Enns (2014), "Aircraft Flight Control," in *Encyclopedia of Systems and Control*, J.S. Baillieul and T. Samad (eds.), Springer

Q: What is a dynamical system?

A: A system that exhibits dynamics – i.e., that evolves over time, that isn't static



Dynamical Systems—Some Complexities



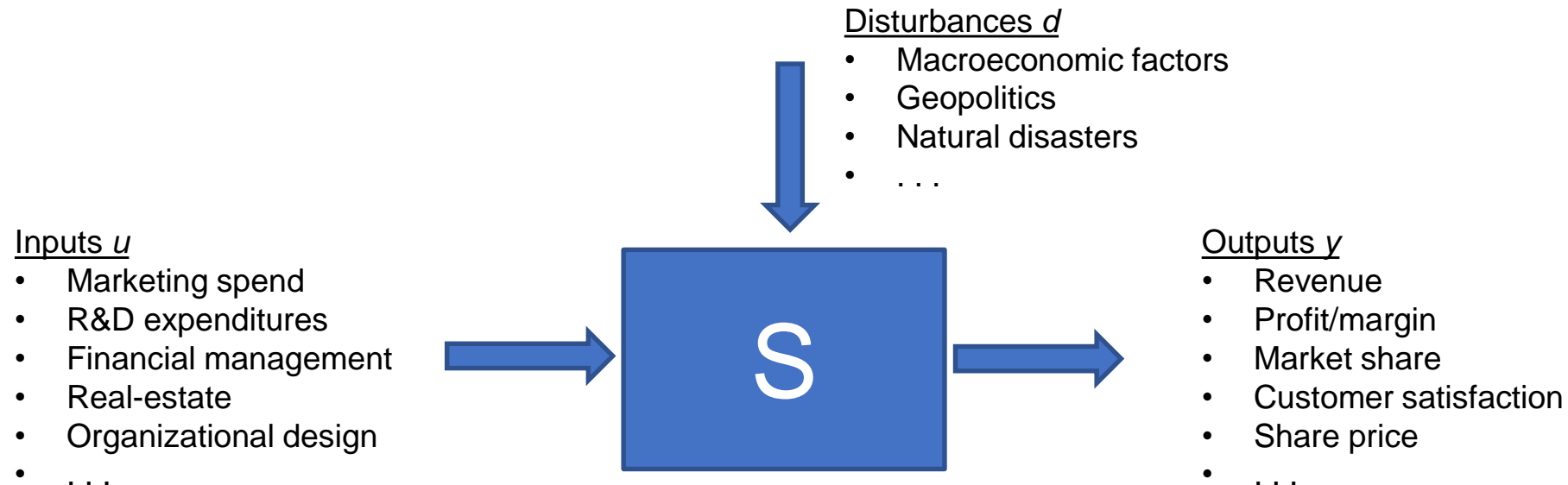
Examples for single-input, single-output (SISO) systems—these complexities are compounded for multi-input, multi-output (MIMO) systems

Other Aspects of System Complexity

- **High-dimensionality**
- **Structure**
- **Noise**
- **Disturbances**

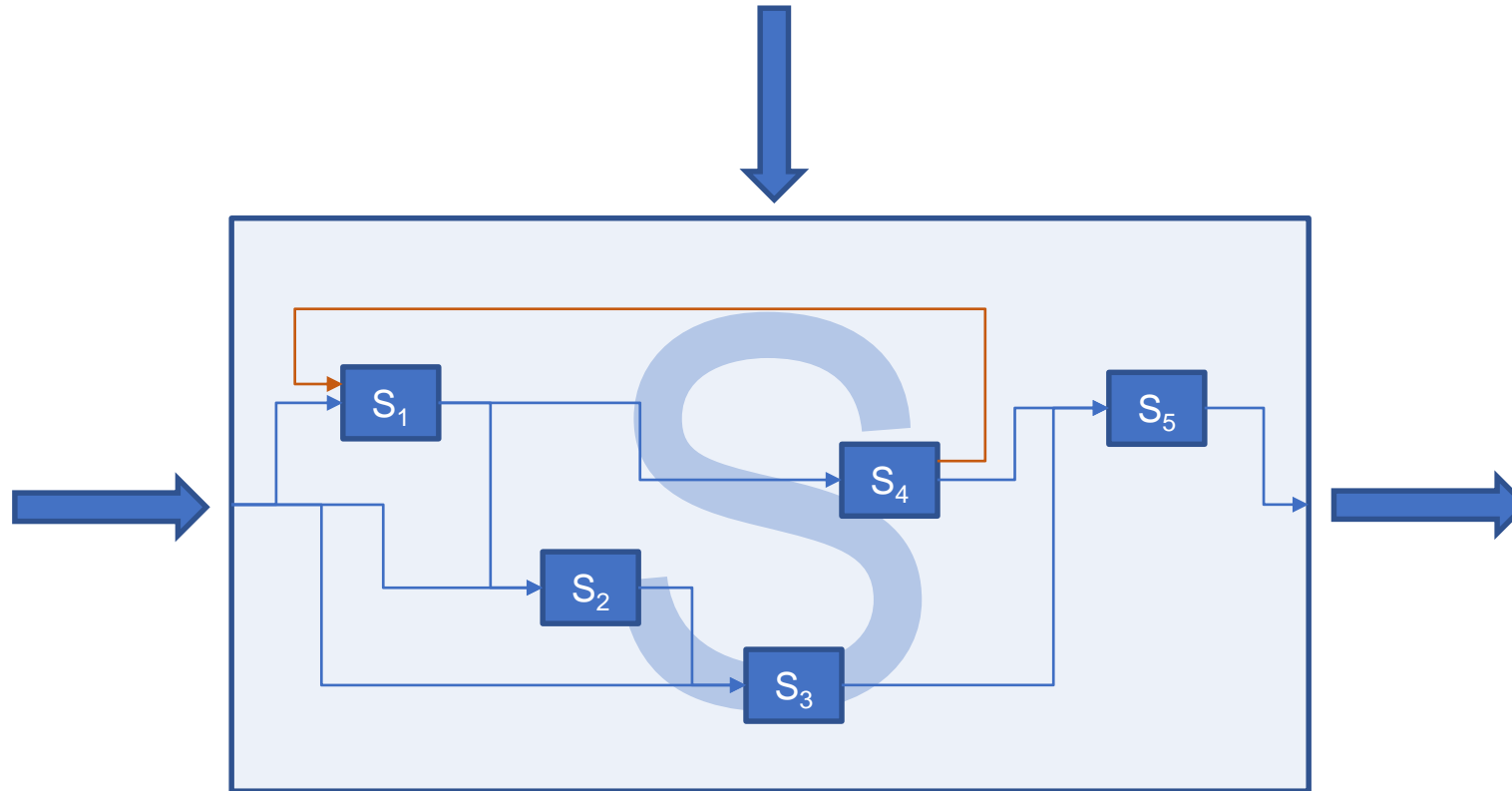


High-dimensional Systems



Example: Multinational Corporate Enterprise

Systems have structure (including feedback)



Example: Functions within an enterprise

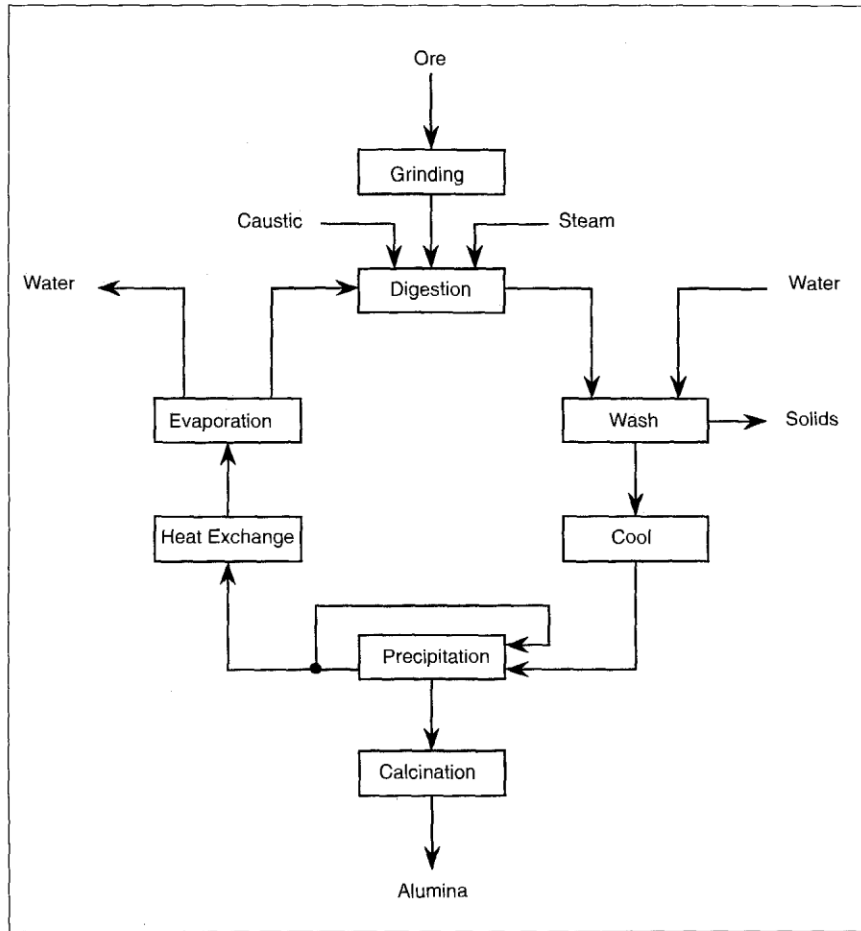


Fig. 2. The liquor loop in aluminum processing. Figure courtesy of Neil Freeman, Honeywell Australia.

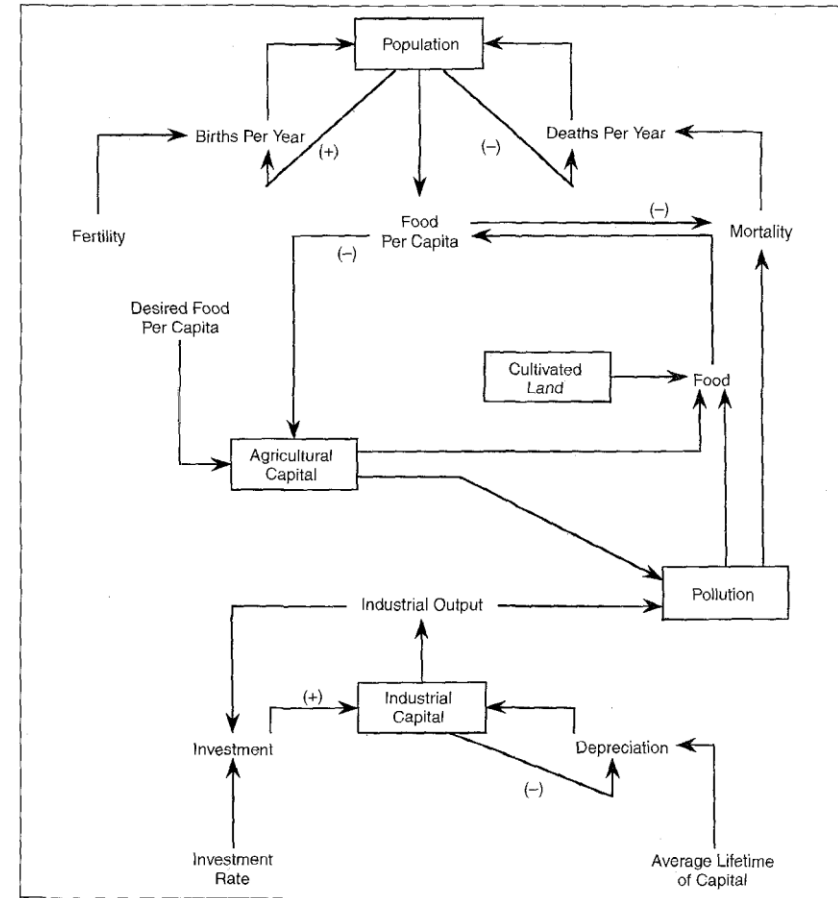
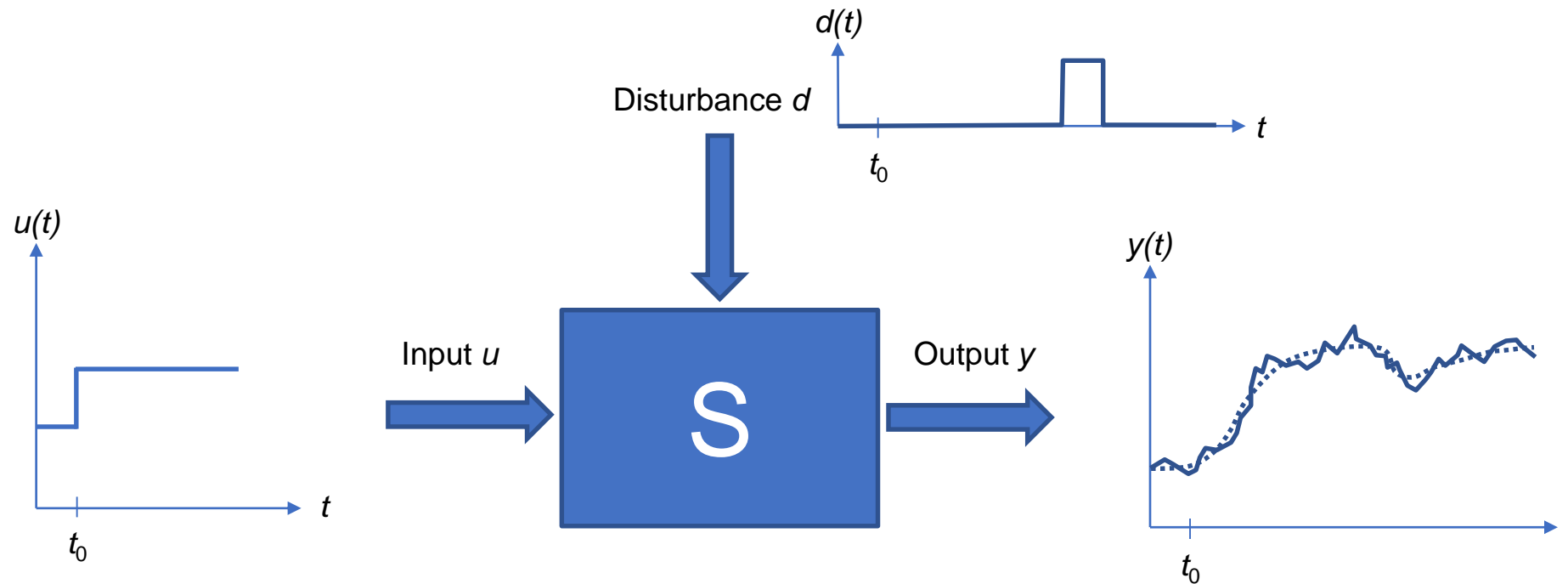


Fig. 1. Feedback loops of population, capital, agriculture, and pollution. From [2, p. 58] as adapted from [3, p. 97]. Published with permission of Potomac Associates, Washington, D.C., U.S.A.

from T. Samad (1997), "Visions of Control," *IEEE Control Systems Magazine*, Feb. 1997

Noise + Disturbances



Noise: Random variations—e.g., sensor measurement errors

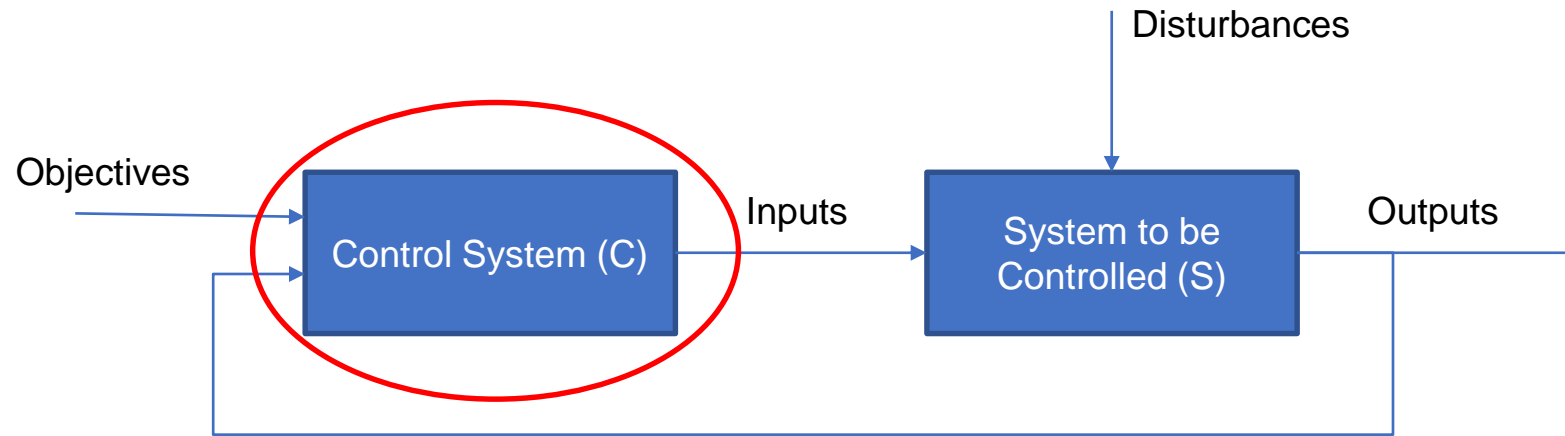
Disturbances: External and adverse influences not under your control, and sometimes not easily measurable either
Examples: New tariffs get suddenly imposed, key developer leaves the team, a customer goes out of business, . . .

How can management minimize sensitivity to noise and enhance “disturbance rejection”?

Controlling Complex Systems

- Understanding complex systems is important . . .
- But we want to do more . . . We want to manage and control them!
 - Develop more effective services and products
 - Reduce costs without compromising quality
 - Meet targets for revenue and margins
 - Improve our net promoter score (NPS)
 - Etc.
- How can we control or manage complex dynamical systems?

Systems and Control

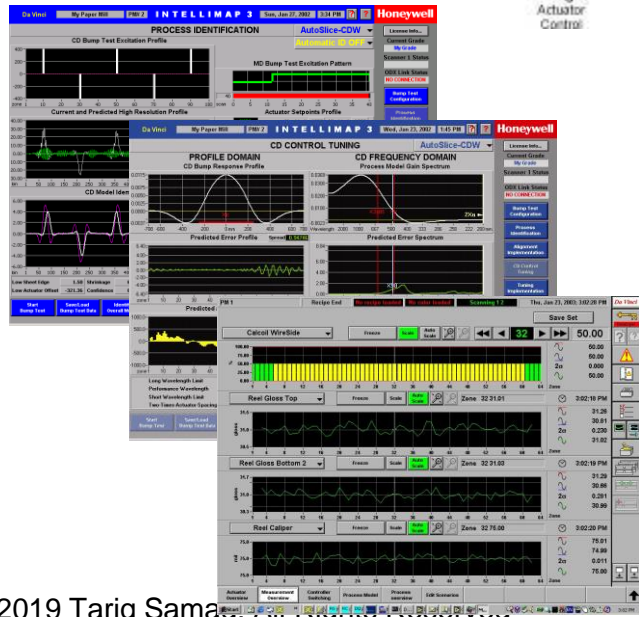
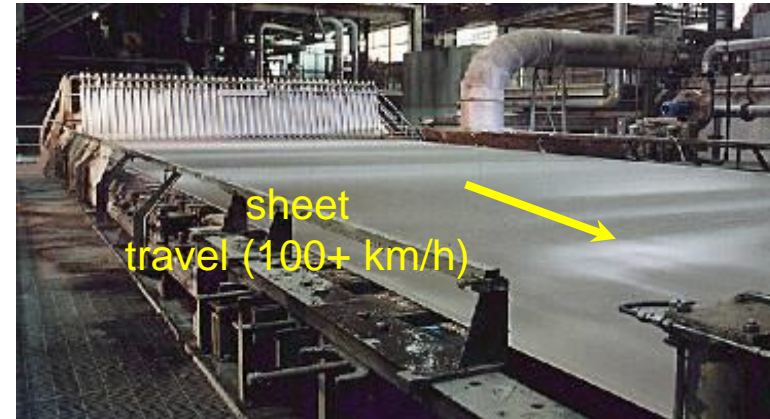
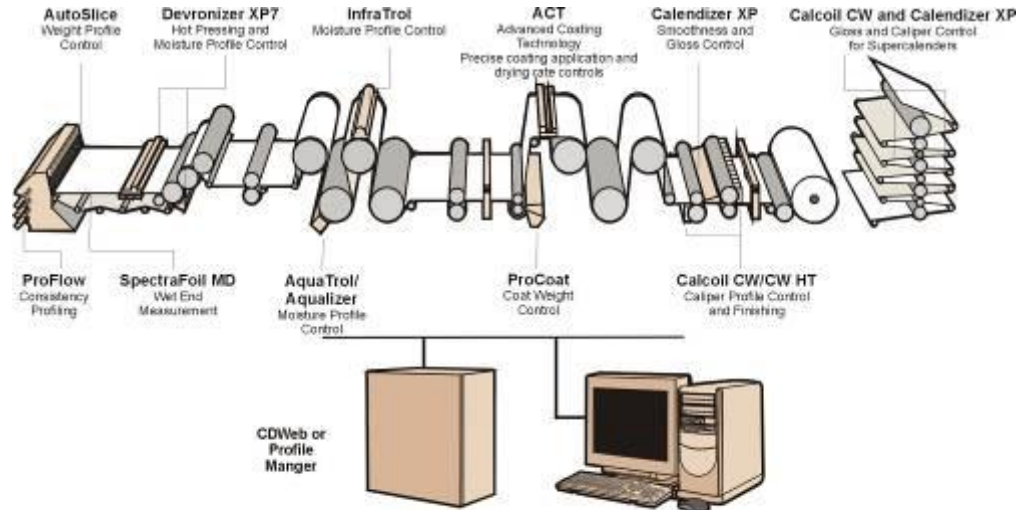


How can we design C to realize our objectives for S?

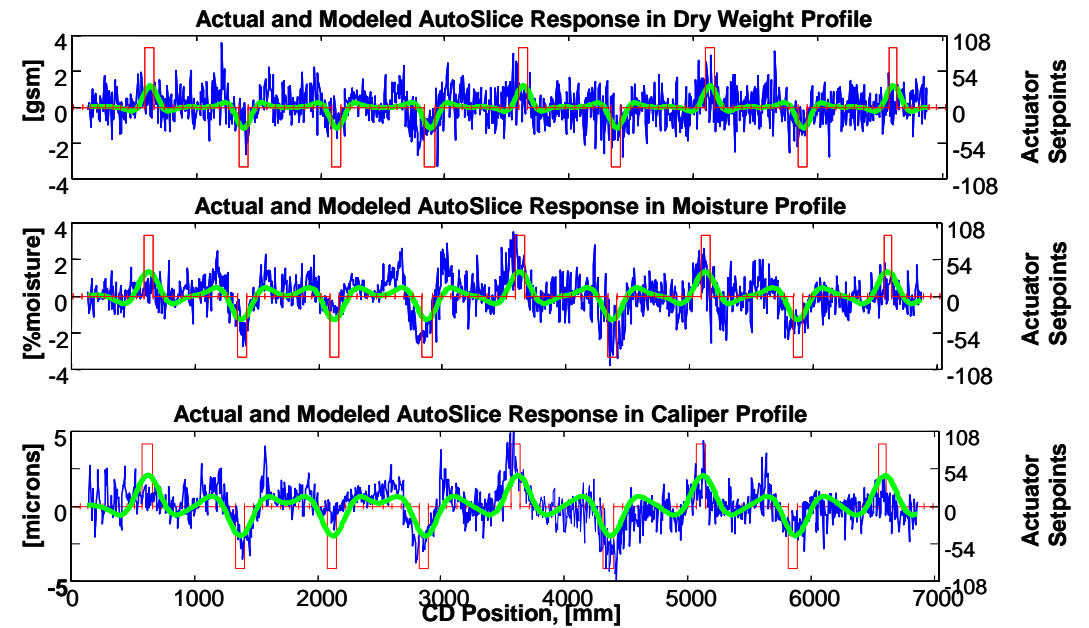
(And, where we have the option, how can we change S to make it easier to control.)

Do we have examples of effective control of complex dynamical systems? **Of course!**

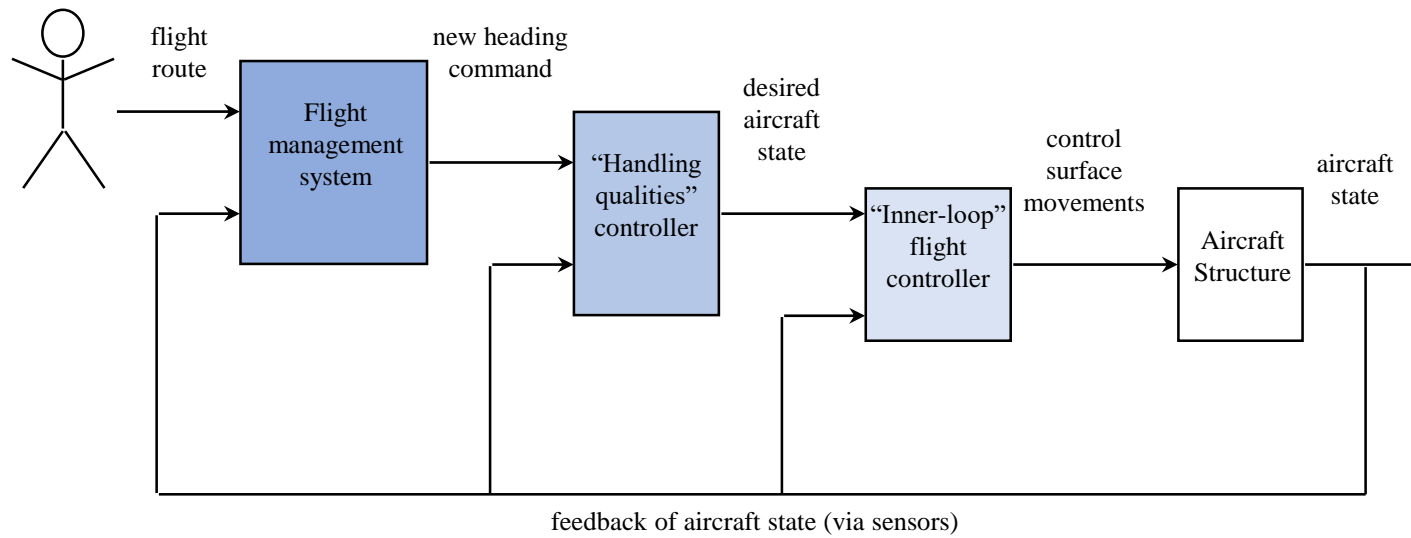
Paper Machine Control











Several hundred sensors and actuators, millisecond operation, controlling paper thickness to within microns!



Control Hierarchy in Commercial Aviation



Benefits of Advanced Control

Industry	Example Applications	Realized Benefits
Oil Refining Petrochemicals Oil and Gas	 Refinery, Ethylene Plant, Aromatics, Xylene, Gas Processing, LNG/LPG	<ul style="list-style-type: none"> • 2-15% higher production • Refinery: ~\$1/barrel for advanced control • 5-20% less energy/unit product
Pulp & Paper	 Cross/Machine Directional Control	<ul style="list-style-type: none"> • Up to 50% higher performance • 50-80% lower calibration time
Building Control	 HVAC adaptive control	<ul style="list-style-type: none"> • 7-33% energy cost savings • Low setup costs
Commercial Aircraft	 B787, C919 EPIC, APEX	<ul style="list-style-type: none"> • Stabilization of unstable aircraft • Level 1 handling qualities
Aero Engines	 AS907-1 HTF 7500E HPW3000	<ul style="list-style-type: none"> • 99.7% fault coverage • Optimized engine start • Improved engine life with power assurance
Space	 Orion Multi-Purpose Crew Vehicle	<ul style="list-style-type: none"> • Reduced propellant requirements by 20% • Optimal steering of control moment gyro
Military & Unmanned Aircraft	 Reusable Launch Vehicle, T-Hawk	<ul style="list-style-type: none"> • Stabilization, vehicle utility & operability • Fourfold reduction in development time • Missions completed after component failures
Automotive	 Diesel Engine Control Aftertreatment Control	<ul style="list-style-type: none"> • > 50% reduction in control design time

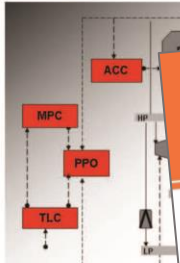
Benefits of advanced control (Honeywell)

Success Stories FOR CONTROL

Advanced Energy Solutions for Power Plants

Fuel costs, energy conversion efficiencies, and environmental impacts of fossil-fueled plants have become priorities in both developed and developing countries. Advanced Energy Solutions (AES), a product of Honeywell Process Solutions, is an advanced process control product that significantly improves power plant efficiency and reduces plant emissions.

AES provides combustion control in boilers; coordinates multiple boilers, turbines, and heat recovery systems for optimal operation of entire power plants; and provides balancing of power production to demand.



Success Stories FOR CONTROL

Advanced Control for the Cement Industry

The cement industry of the 21st century is confronted with disparate goals that at

Solution Overview

Success Stories FOR CONTROL

Dynamics and Control for Deep-Sea Marine Risers

A marine riser is a pipe that connects a



Success Stories FOR CONTROL

Control in Stroke Rehabilitation

Stroke is the foremost cause of disability in developed countries. Less than 15 percent of patients with upper-limb impairment following stroke regain full function, which restricts their ability to perform everyday reaching and grasping tasks. Functional electrical stimulation (FES) used to assist stroke patients in moving their impaired limbs has been shown to increase upper-limb function; however, the benefits of FES are greatest when combined with maximal voluntary effort from the patient to perform the movement. This presents a control problem:

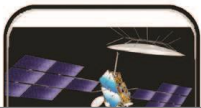


Success Stories FOR CONTROL

Road Grade Estimation for Advanced Driver Assistance Systems

A plethora of examples of societal impact with control systems, across virtually all industry and application sectors

H-infinity Control for European Telecommunications



Telecommunication Satellite Challenges and Needs

Geostationary telecommunication satellites and large (deployable) antennae together are rotating with respect to the Earth's

Due to winds, waves, and water currents, the floating platform on the sea surface responds in six-degree-of-freedom motions.

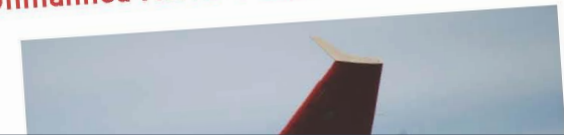
Advanced Control of Pharmaceutical Crystallization

Nearly all pharmaceutical manufacturing processes use crystallization as the primary means for separating



Autopilot for Small Unmanned Aerial Vehicles

Small unmanned aerial vehicles (UAVs) have numerous applications in civilian sectors. These



Success Stories FOR CONTROL

Coordinated Ramp Metering for Freeways

Freeways were originally conceived to provide virtually unlimited mobility to road users, but the continuous increase in car ownership and demand has led to a steady increase (in space and time) of recurrent and nonrecurrent freeway congestion, particularly in and around metropolitan areas. Freeway congestion causes excessive delays, increases fuel consumption and environmental pollution, and deteriorates traffic safety.



Ramp metering, the most direct and efficient

Success Stories FOR CONTROL

Controlling Energy Capture from Wind

Wind energy is currently the fastest growing power-generation technology worldwide, reaching a 30% annual growth rate and an installed capacity of 300 GW. To realize these achievements, wind turbine designs have overcome multiple technical challenges to be competitive with predominant energy sources. Control technology has played a crucial role in this quest. The control system dynamically adapts to a wide range of wind conditions and maintains structural integrity while maximizing energy production. In addition, the controller must manage weather conditions, abnormal wind disturbances, and fault scenarios that may occur unexpectedly during the life span of the



Success Stories FOR CONTROL

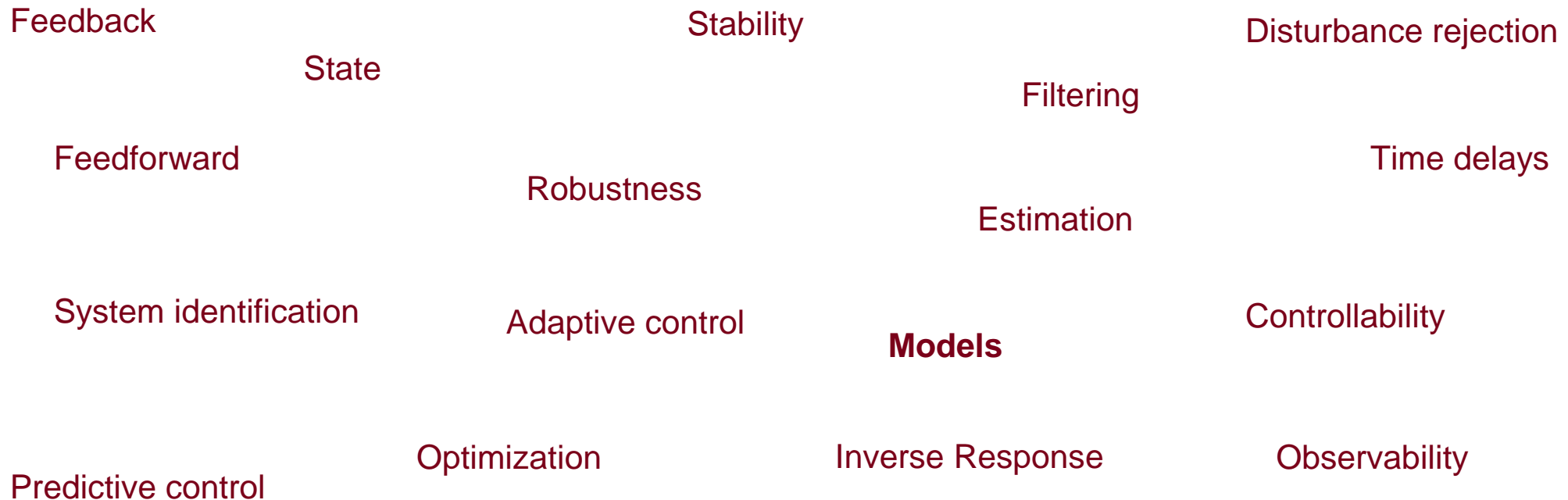
Trip Optimizer for Railroads

On-time arrival with the least fuel expenditure is a key priority for freight and passenger railroads worldwide. North American railroads consumed 4 billion gallons of fuel in 2008, 26% of operating costs.

Trip Optimizer is an easy-to-use control system that allows the crew or dispatcher to achieve on-time arrival with the least possible fuel use.

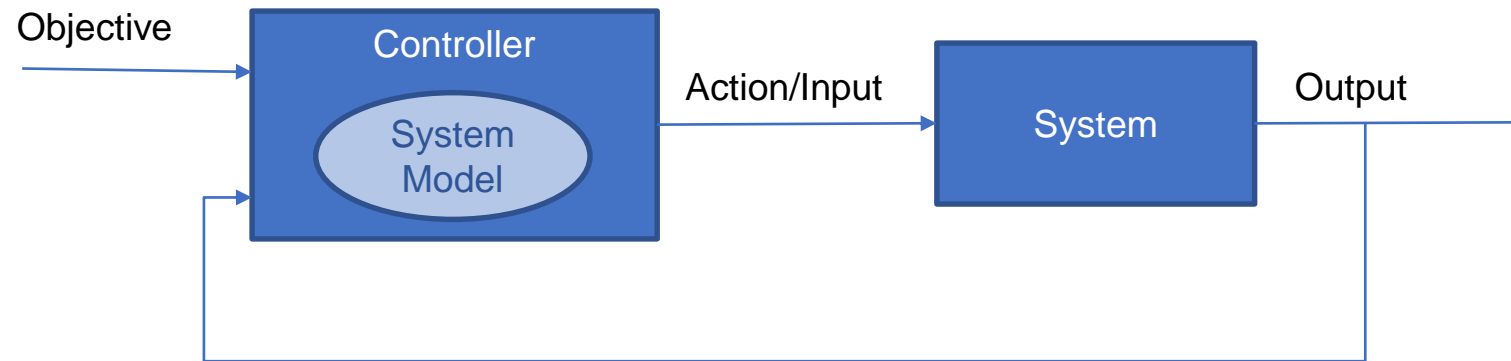


Important Control Concepts!



Fundamental concepts for all decision making in complex dynamical systems!

“Models” for control . . . and decision making



“All models are wrong, but some are useful” –George Box

Model Development with Machine Learning

For many applications, we have vast quantities of data available today—these can be used to develop models

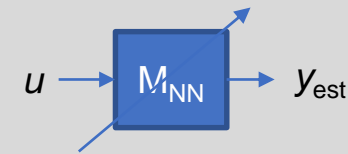
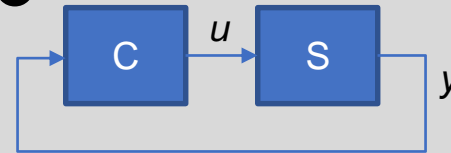
Applications for machine learning (e.g., deep neural networks)

- “System identification” for dynamical systems

Challenges (especially in dynamical systems):

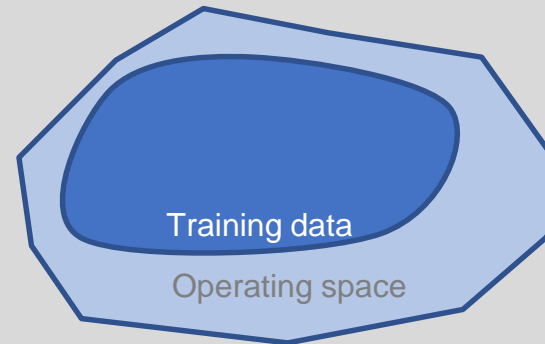
- “Sufficient excitation” ❶
- Representative data ❷
- The bias-variance dilemma ❸
- System drift
- . . .

❶



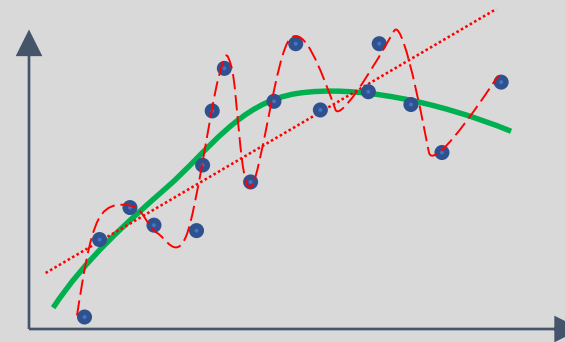
How can you be sure you're learning a model of S and not (an inverse) model of C?!

❷



It's not enough to make sure the training data covers the operating space for S . . . Data *distributions* should be similar too. Models will have poor accuracy in regions where data is scarce.

❸

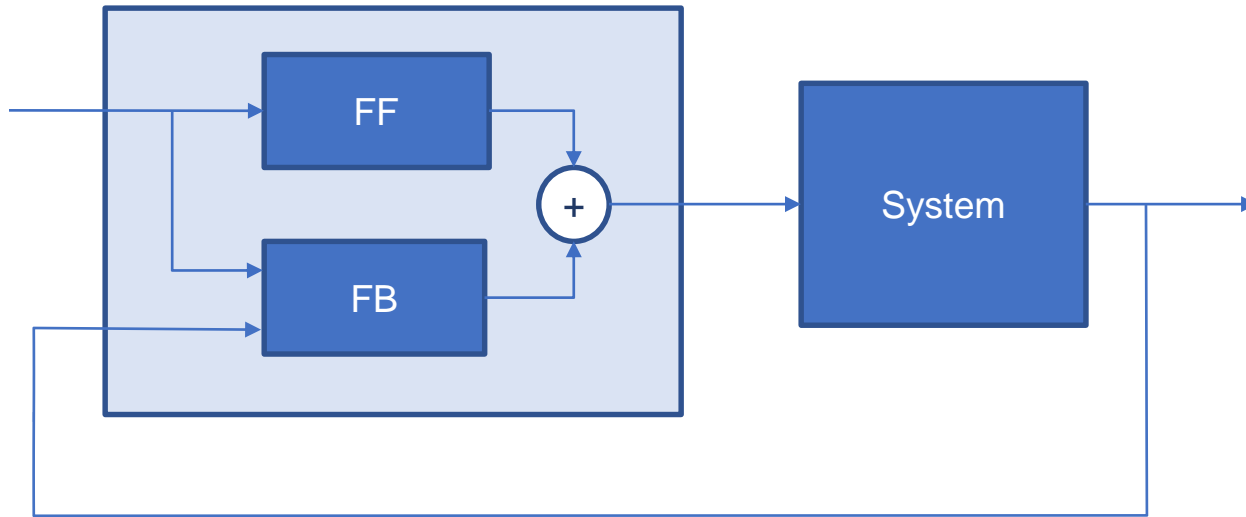


Underfit? Overfit? The right model?

Models are not just of the mathematical variety!

- **All informed managerial decision making is “model-based” too!**
 - But the “models” are in the minds of the decision makers!
 - The better the manager’s models of her organization, her industry, the market, etc., the better her decisions!
 - Models = knowledge + assumptions
- **Decision makers need to be aware of:**
 - the “model-based” nature of their decision making
 - the gap between their models and reality
 - the need to improve their “models”
- **Insights from machine learning and system identification are relevant for “mental models” too!**

Feedback and Feedforward Control



Example 1: You need to give a task to a developer in your team:

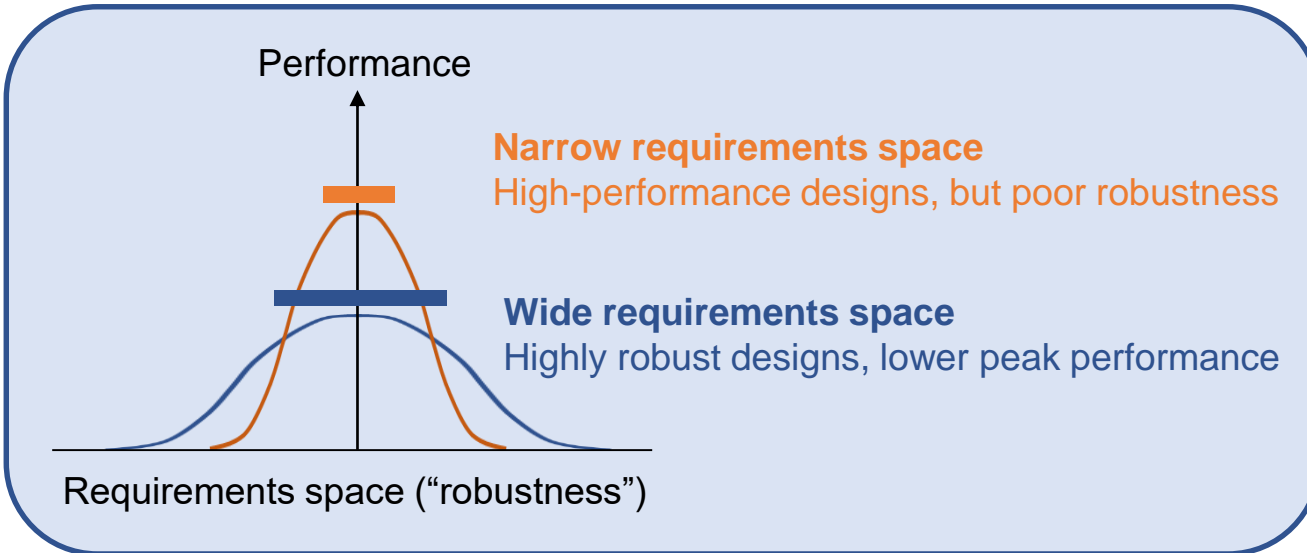
- A colleague you know well: Detailed spec with minimal oversight
- A newbie: General direction with frequent feedback/updates

Example 2: You're releasing a new product; do you know your user-base well?

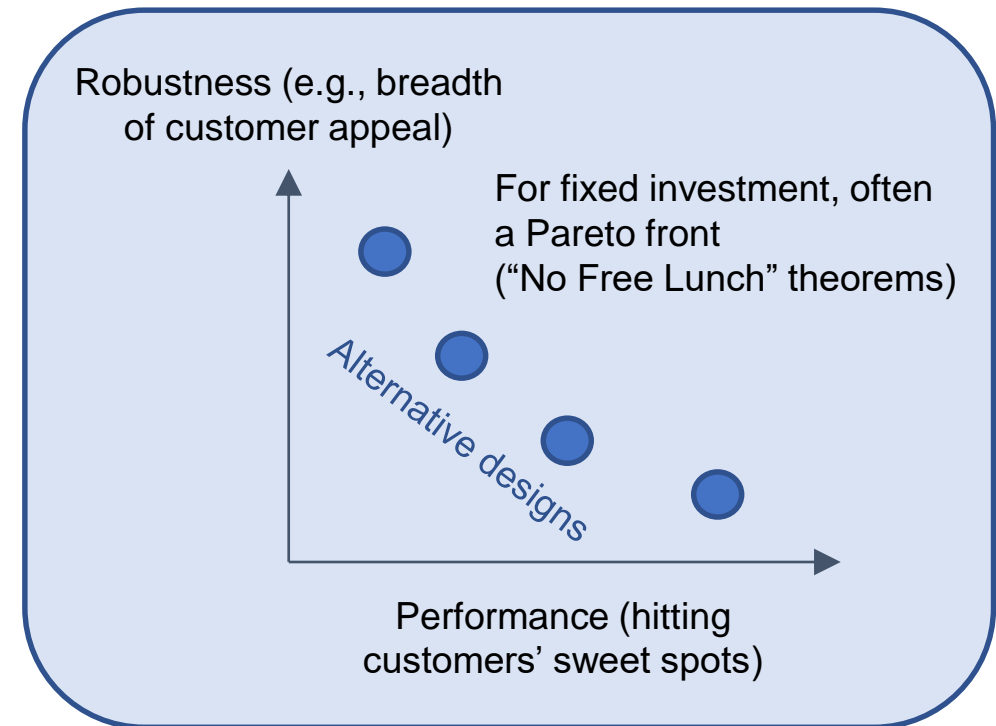
- Yes: Full-fledged launch
- Perhaps not: Beta releases for user feedback

	Feedforward	Feedback
Speed of response	<i>Faster</i>	<i>Slower</i>
Tolerance of uncertainty	<i>Lower</i>	<i>Higher</i>
Complementary functions	<i>"In the ballpark" quickly</i>	<i>Fine-tuning; adaptation</i>

Performance versus Robustness



- What user "model" should you assume for a new application development?
Example: Which Windows versions should your application be compatible with?
- Model 1: All users will be on Windows 8+
 - Higher performance for Windows 8+ users
 - If your model is wrong many potential users may be lost
 - Model 2: All users will be on Windows XP+
 - Greater dilution of effort for the same investment
 - Less concern about reduced customer reach
 - "Intermediate" models: More/less attention to more/less popular OSs

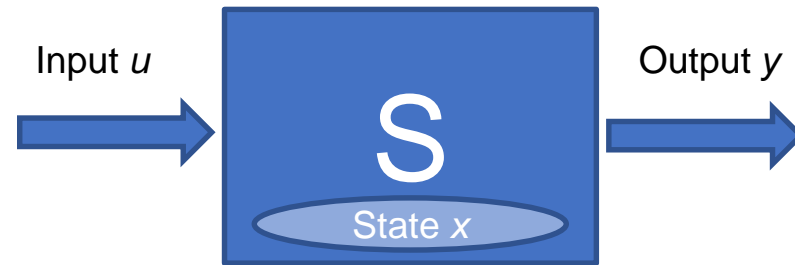


Exploration vs. Exploitation

- **Questions for technology managers:**
 - Should we change our process for project selection and funding?
 - Should we do a re-org?
 - Should we go with a different supplier/vendor/distributor?
- **Questions to ask as you think about changes:**
 - How well is it working now?
 - How likely is it that we could do better?
 - How important is it to do better, and how bad would it be if we did worse?
- **Rigorous ways of approaching these problems exist in control theory, machine learning, statistics, optimization, and related disciplines**
 - “Exploit” what you know, or “explore” new options? Pros and cons (and no free lunches!)

You can't do better without exploration . . . But all exploration entails risk!

“States” and State Estimation



$$x[t + 1] = F(x[t], u[t])$$
$$y[t + 1] = G(x[t + 1])$$

Advanced control systems include “state estimators”—and technology managers also need to estimate the true “state” of the systems they are managing

Examples:

- You’re leading a software development program. Your dashboard indicates the lines of code each team is producing each day. Does this “output” tell you how well the program is going relative to plan?
- Your CEO says that the company needs to get its stock price up to fend off hostile acquisition threats. What are the internal parameters that influence the stock price?

Other Insights on Feedback and Control

■ Feedback and stability

- Feedback can make an unstable system stable—controllers enable highly unstable aircraft for high-performance flight
- But feedback, if inappropriately applied, can make a stable system unstable—especially if the system has significant delays or inverse response

■ Feedback and sampling times

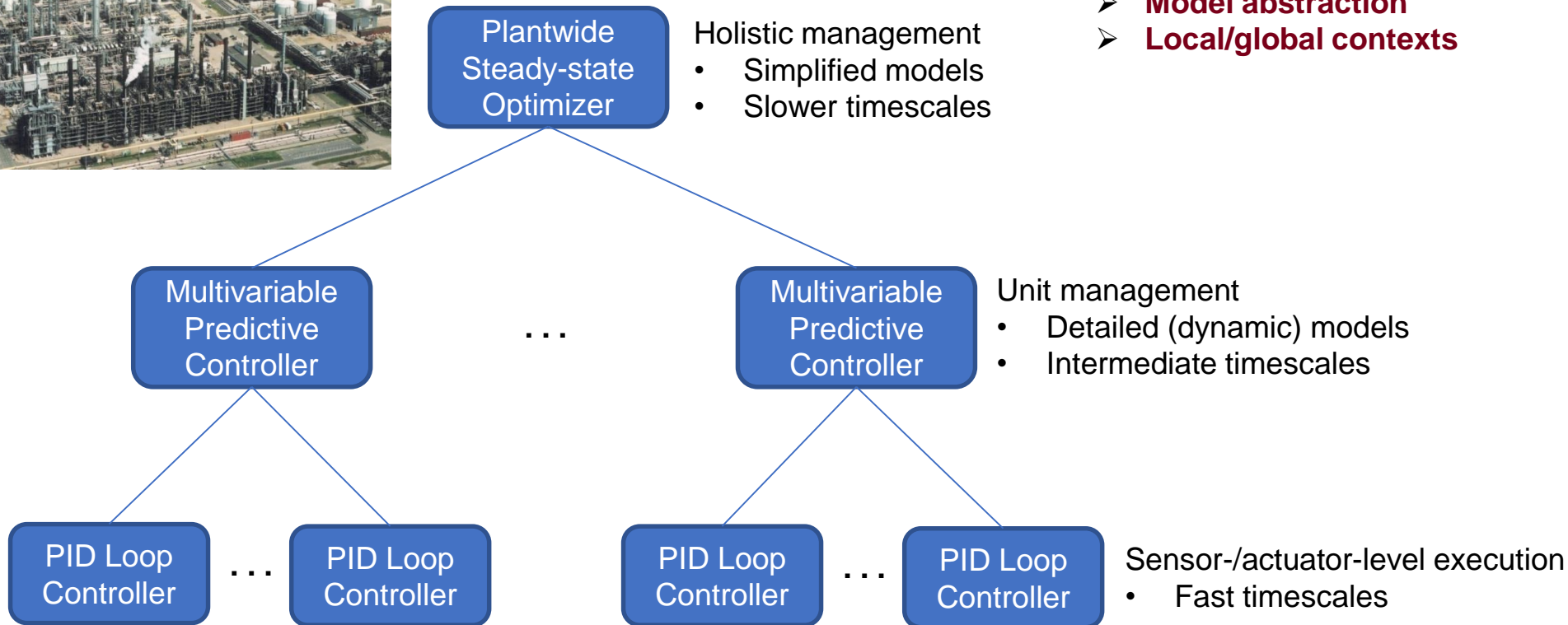
- System outputs must be measured frequently enough to ensure corrective actions are taken before it's too late
- But over-sampling is also ill-advised: a waste of time and energy; decision making is responding to “noise” instead of the “signal”
- “Data-rate theorem” in control theory

Control and Managerial Hierarchies



Lessons from Enterprisewide optimization and control:

- **Timescale separation**
- **Model abstraction**
- **Local/global contexts**

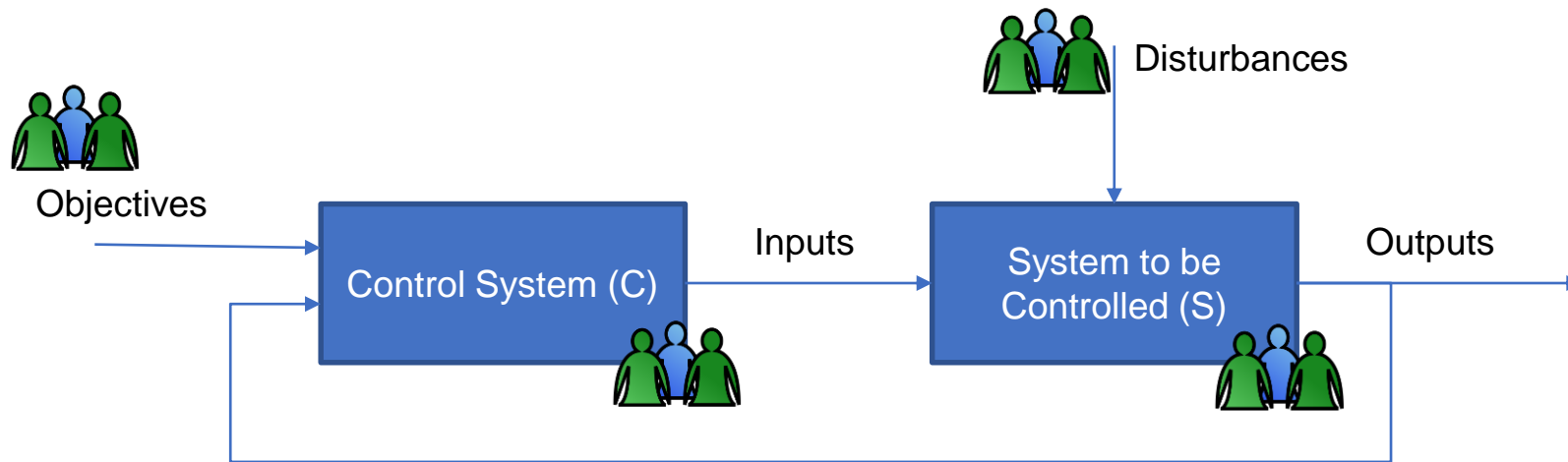


[Process optimization and control hierarchy]

Insights from Control Science for Decision Making

- **Models** are essential for improving performance—and they are in the crania of decision makers!
- **Uncertainty, noise, and disturbances**: rigorous methods available to handle each
- **Feedback** and **feedforward**—counteracting uncertainty and improving response time
- Distinctions—and tradeoffs—between **performance** and **robustness**
- **Exploration** versus **exploitation**—there's no free lunch
- Control loops and **stability**: Well-designed control can make an unstable system stable; poor control can make a stable system unstable
- **Sampling rates** should be sensitive to system dynamics—over-sampling can result in over-reaction, waste resources
- The right variables for effective decision-making are not outputs but **states**—**estimation** is necessary
- Hierarchical and multi-level control—theory extends to **systems of systems**

Human-in-the-Loop Control Systems



Program and project management

Technology research and development

Portfolio management

New product introduction

Innovation processes

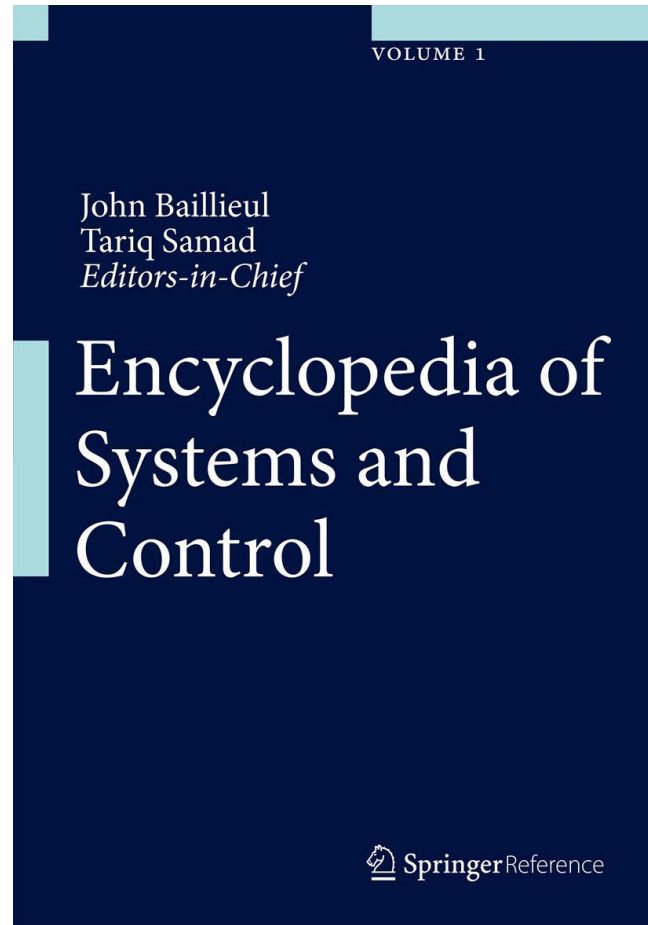
. . . And many other topics in the management of technology and innovation

For the full technical machinery of control theory to be applied to MOT applications, we'll need to mathematically model humans and human teams

- An exciting topic for research, but far from real-world application

However . . . Control theory also provides important *insights* into rigorous decision making, and these can be useful for innovators and managers today

A comprehensive resource on control science . . .



Available online and in print

Published in 2014, 250+ articles, 2 volumes

2nd edition to be published in 2020, probably in 3 volumes

. . . Admittedly not an easy read for the lay person!

**Control science is the only rigorous approach
for effective decision making in complex
dynamical systems!**

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