MACC 2019

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

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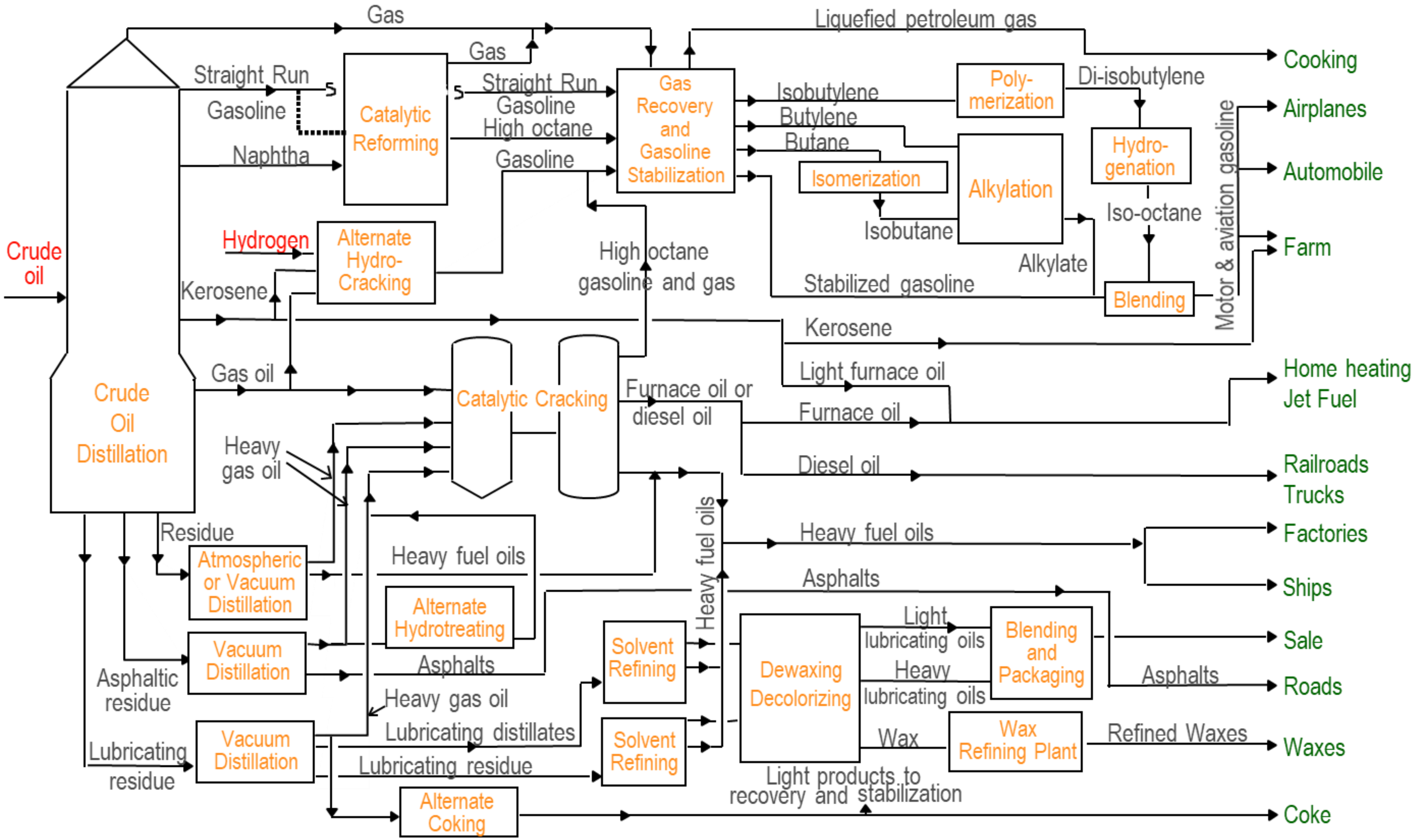
Outline

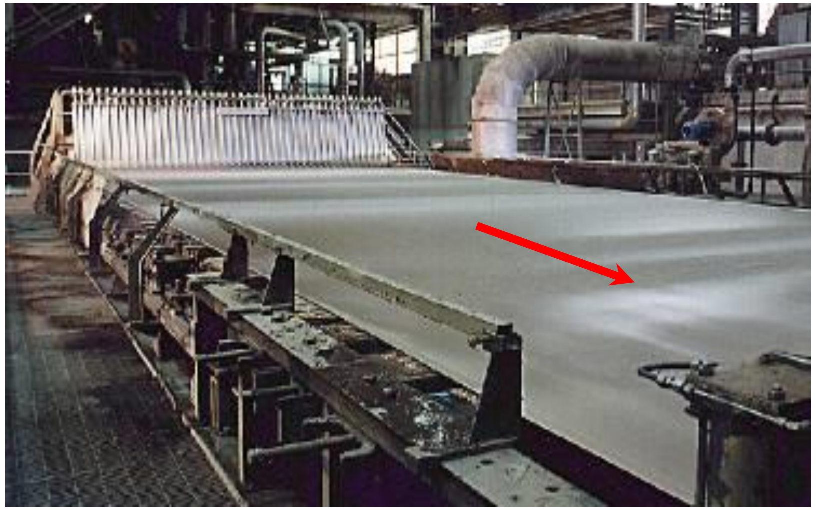
- Complex Engineered Systems—Examples
- Aspects of Complexity
- From Complex Systems to Complex Controllers
- Insights from Control Science for Technology Management and Innovation
- Concluding Message

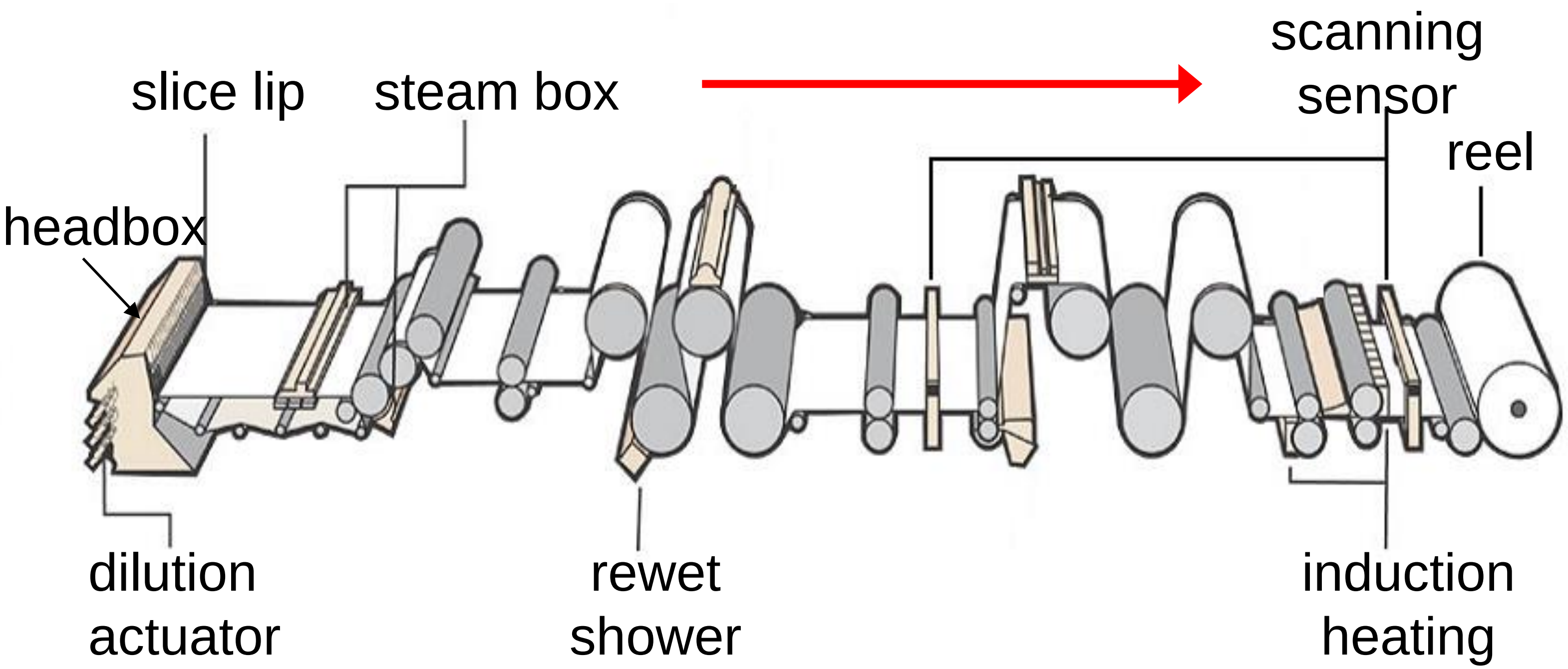
Oil Refinery System



Courtesy of Joseph Lu, Honeywell Process Solutions

Paper Machine System





Aircraft Dynamical System

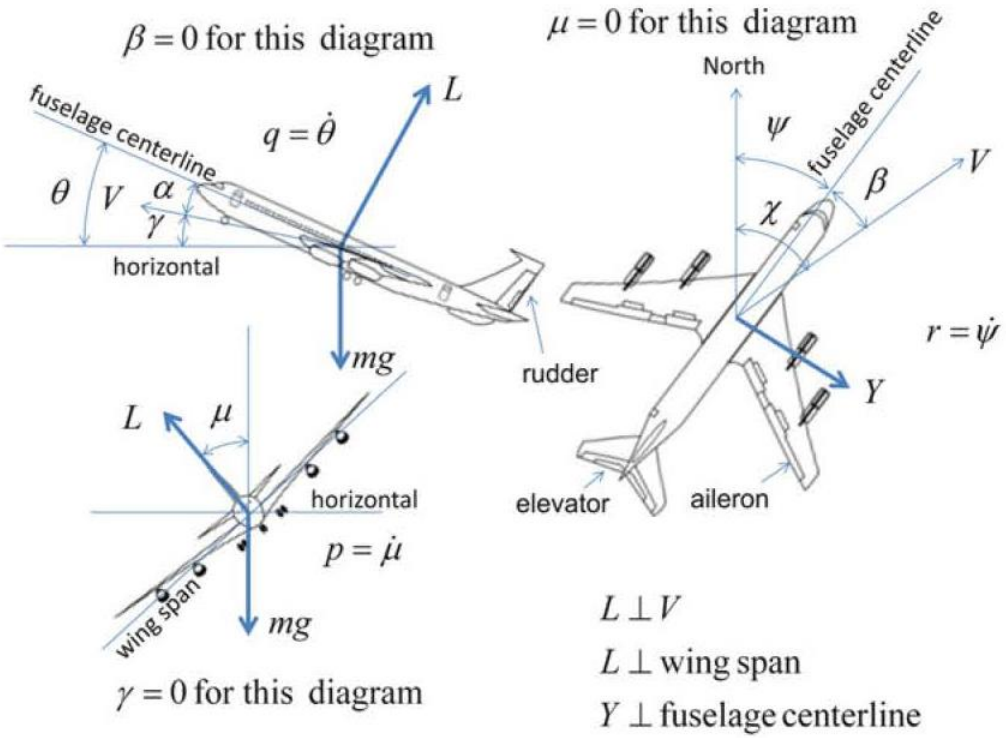
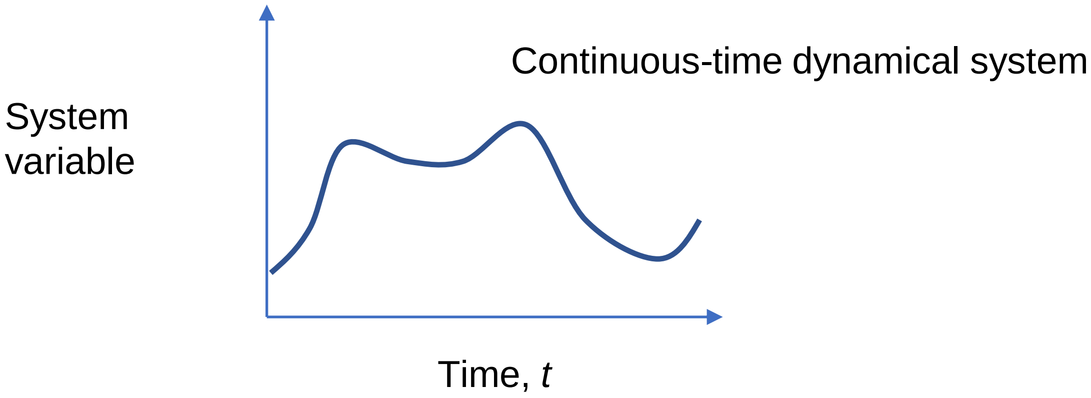


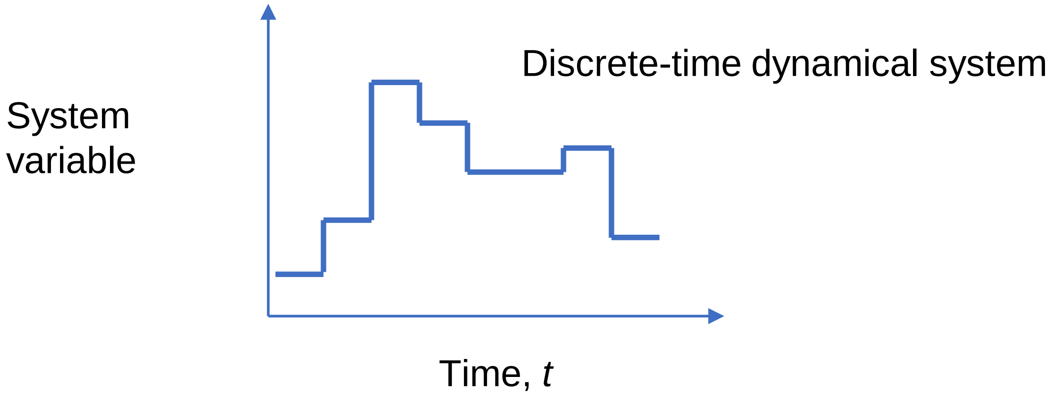
Fig. 1 Flight control variables

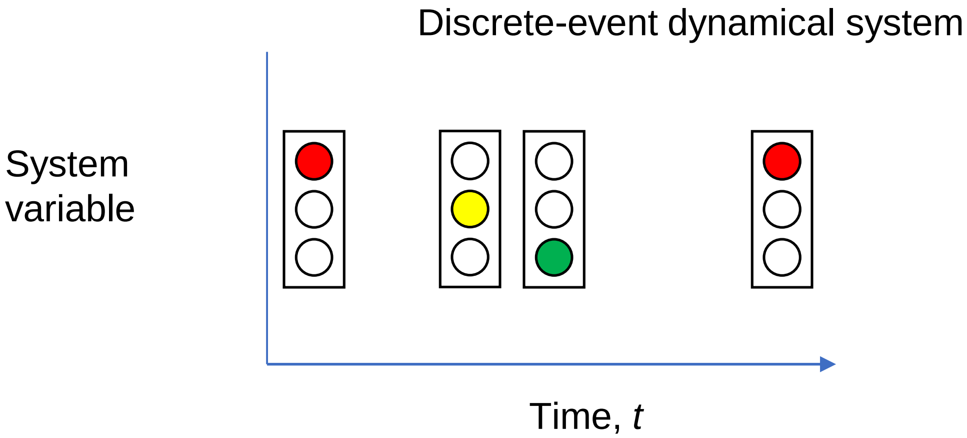
D. Enns (2014), “Aircraft Flight Control,” in *Encyclopedia of Systems and Control*, J.S. Baillieul and T. Samad (eds.), Springer

Q: What is a dynamical system?

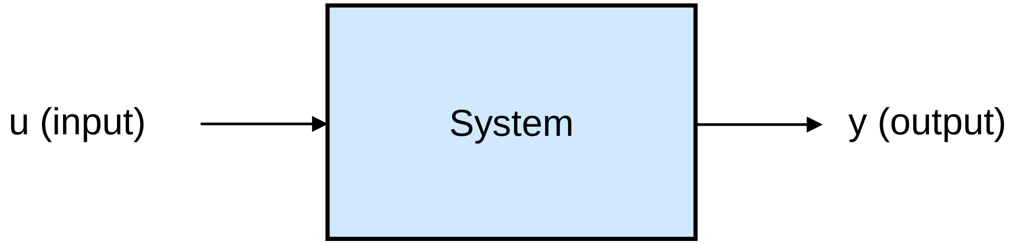
A: A system that exhibits dynamics – i.e., that evolves over time, that isn't static

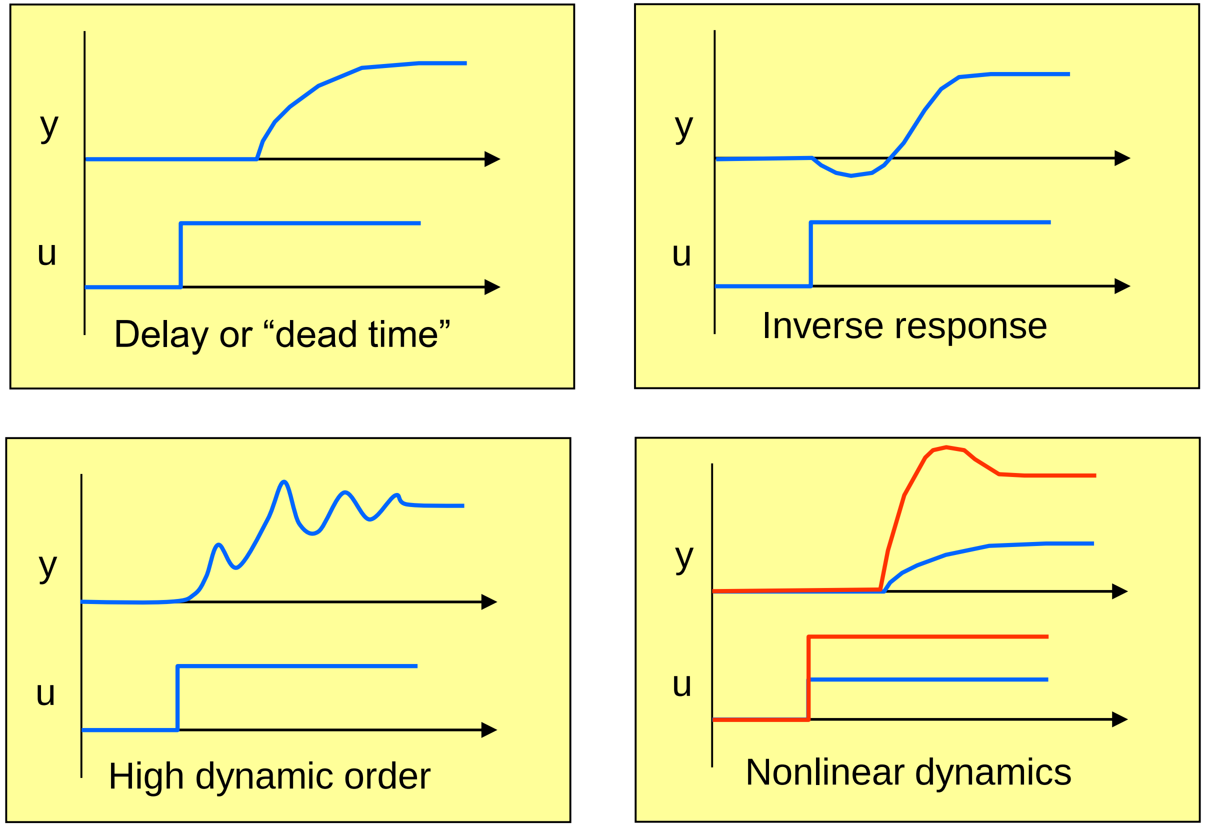






Dynamical Systems—Some Complexities





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

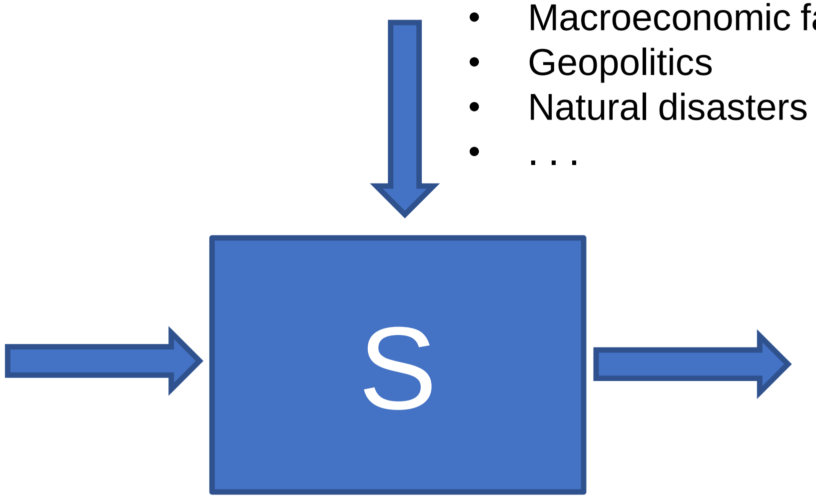
Other Aspects of System Complexity

- High-dimensionality
- Structure
- Noise
- Disturbances

High-dimensional Systems

Disturbances *d*
- Macroeconomic factors
- Geopolitics
- Natural disasters
- . . .

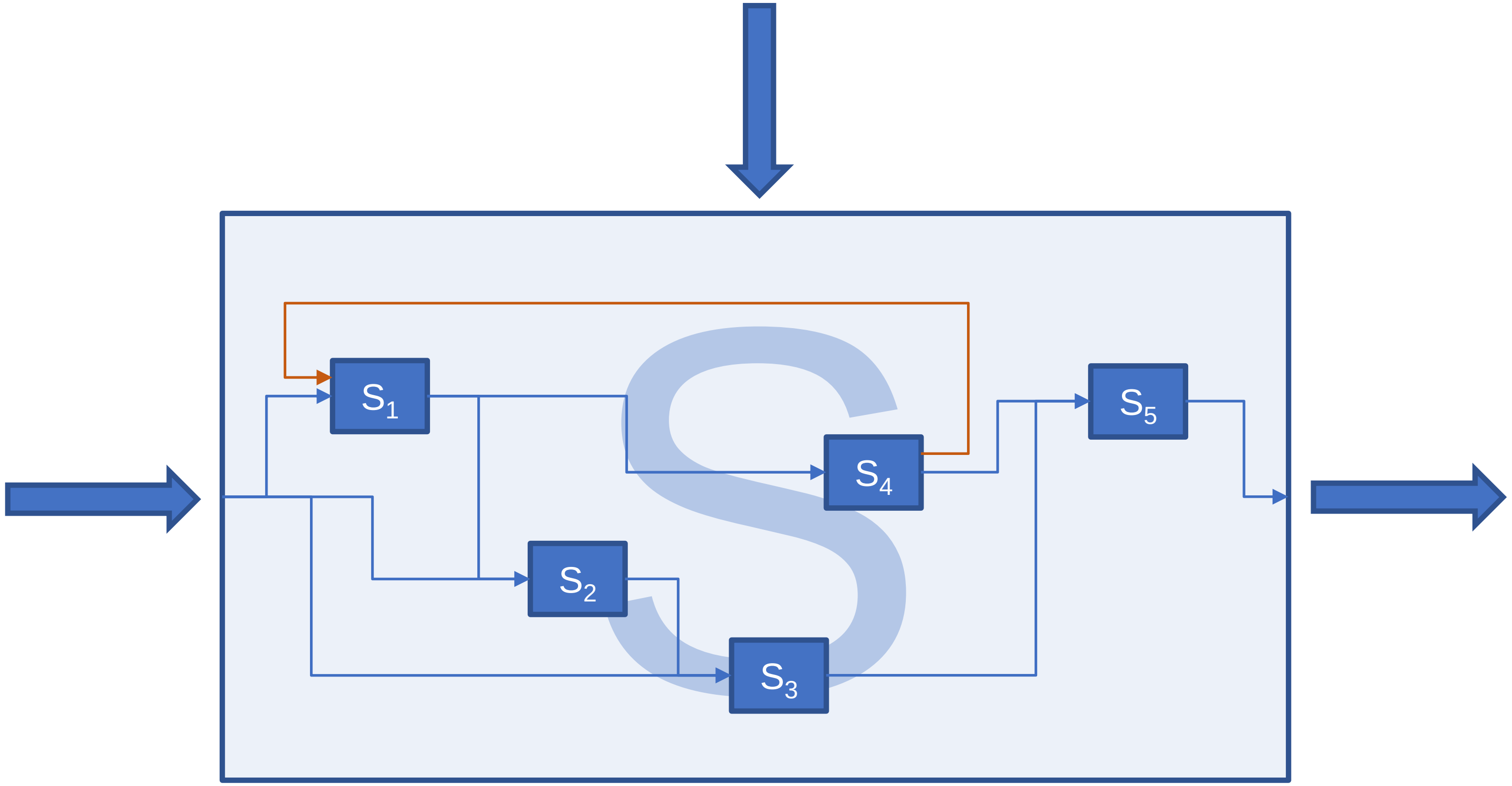
Inputs *u*
- Marketing spend
- R&D expenditures
- Financial management
- Real-estate
- Organizational design
- . . .



Outputs *y*
- Revenue
- Profit/margin
- Market share
- Customer satisfaction
- Share price
- . . .

Example: Multinational Corporate Enterprise

Systems have structure (including feedback)



Example: Functions within an enterprise

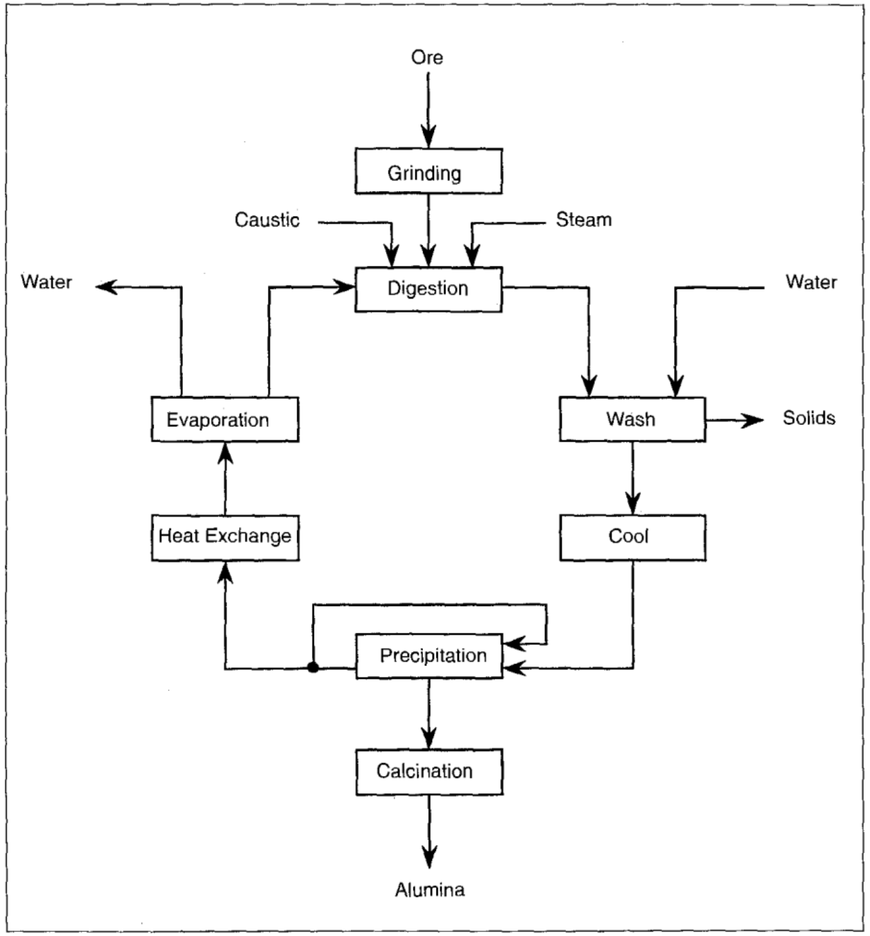


Fig. 2. The liquor loop in aluminum processing. Figure courtesy of Neil Freeman, Honeywell Australia.

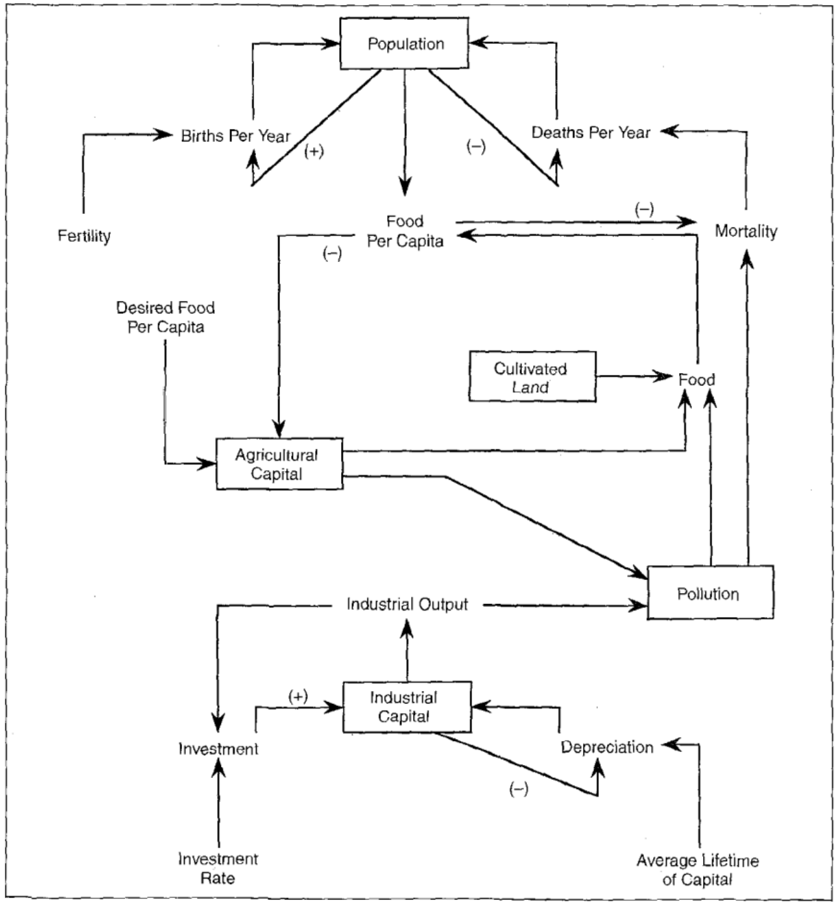
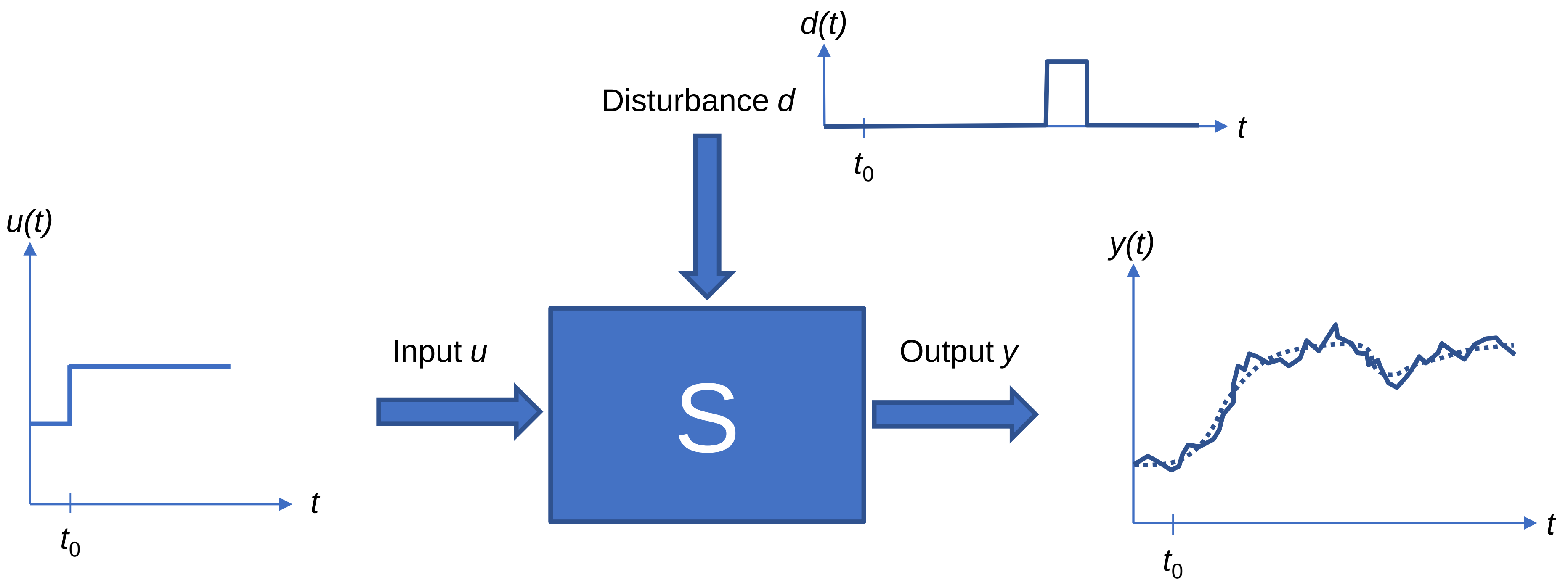


Fig. 1. Feedback loops of population, capital, agriculture, and pollution. From [2, p. 58] as adapted from [3, p. 97]. Published with permission of Potomac Associates, Washington, D.C., U.S.A.

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

Noise + Disturbances



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

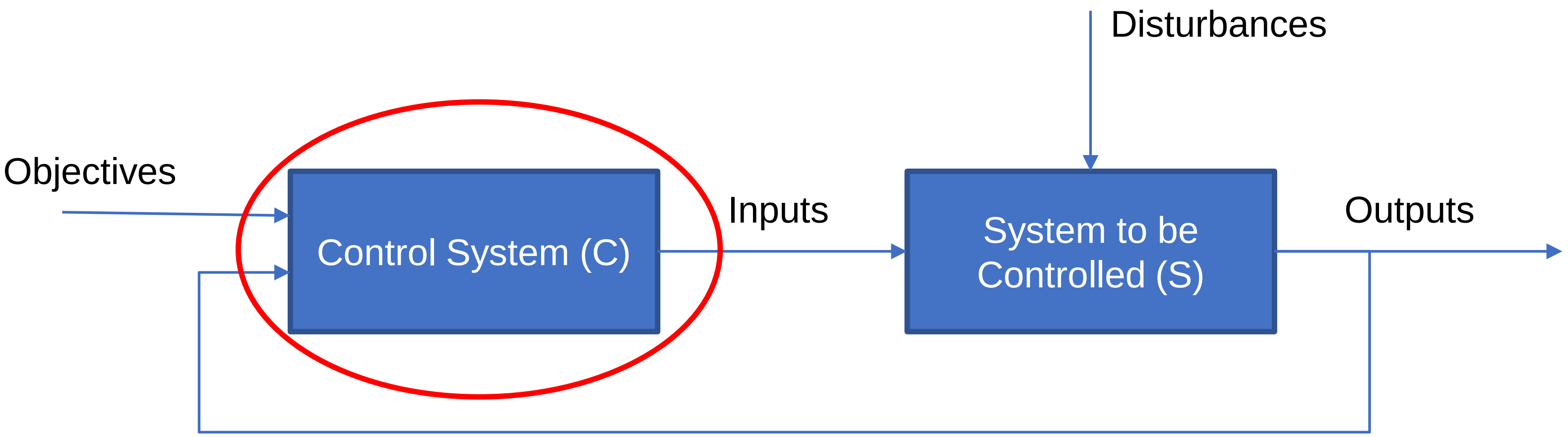
Disturbances: External and adverse influences not under your control, and sometimes not easily measurable either
Examples: New tariffs get suddenly imposed, key developer leaves the team, a customer goes out of business, . . .

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

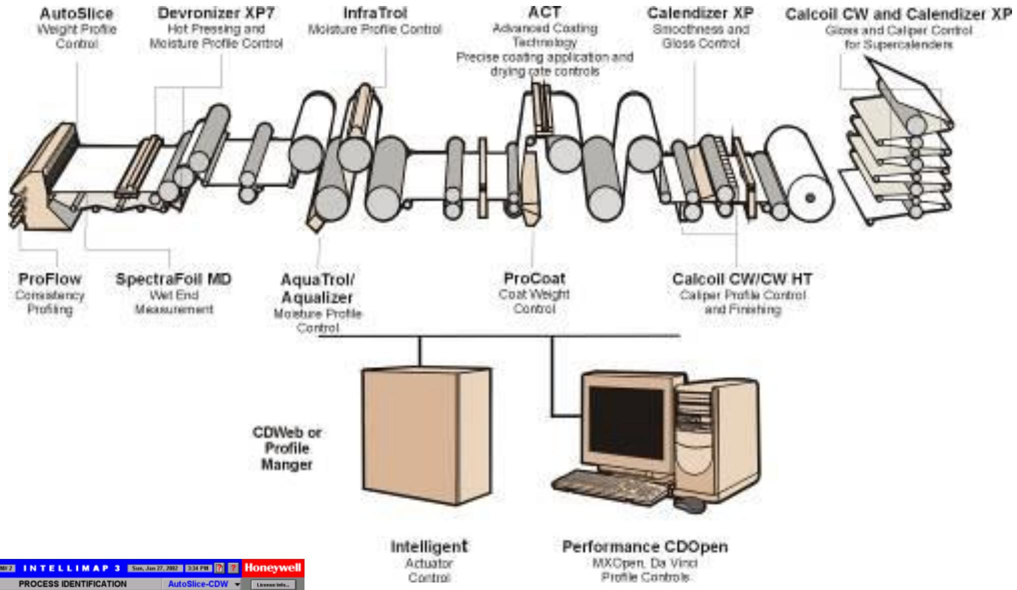


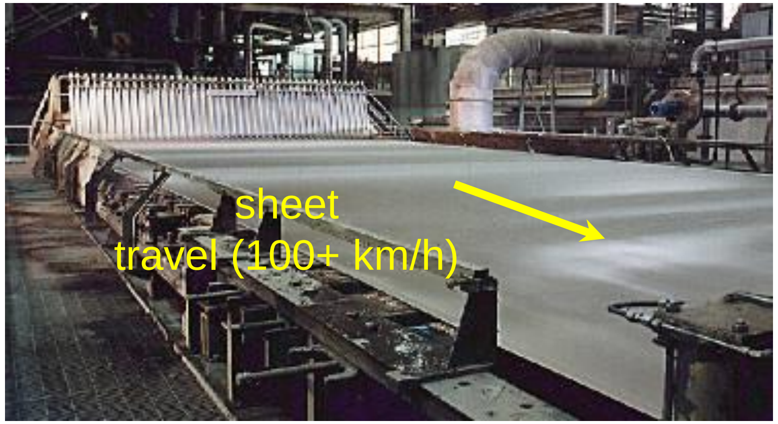
How can we design C to realize our objectives for S?

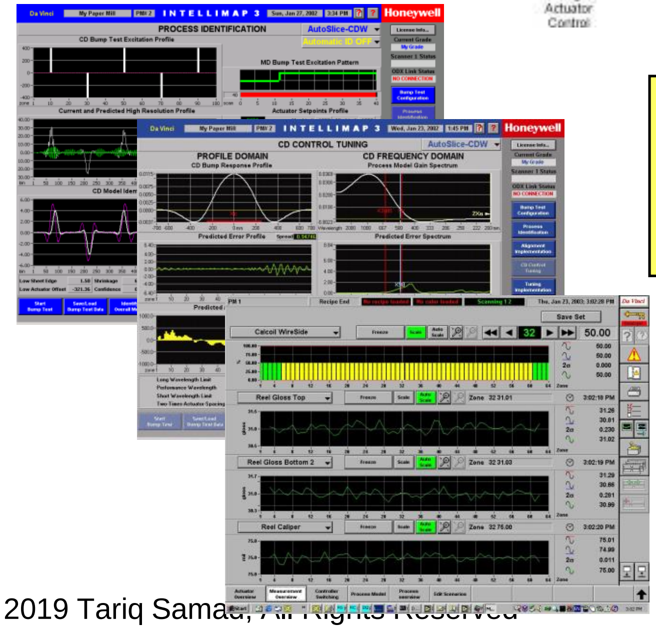
(And, where we have the option, how can we change S to make it easier to control.)

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

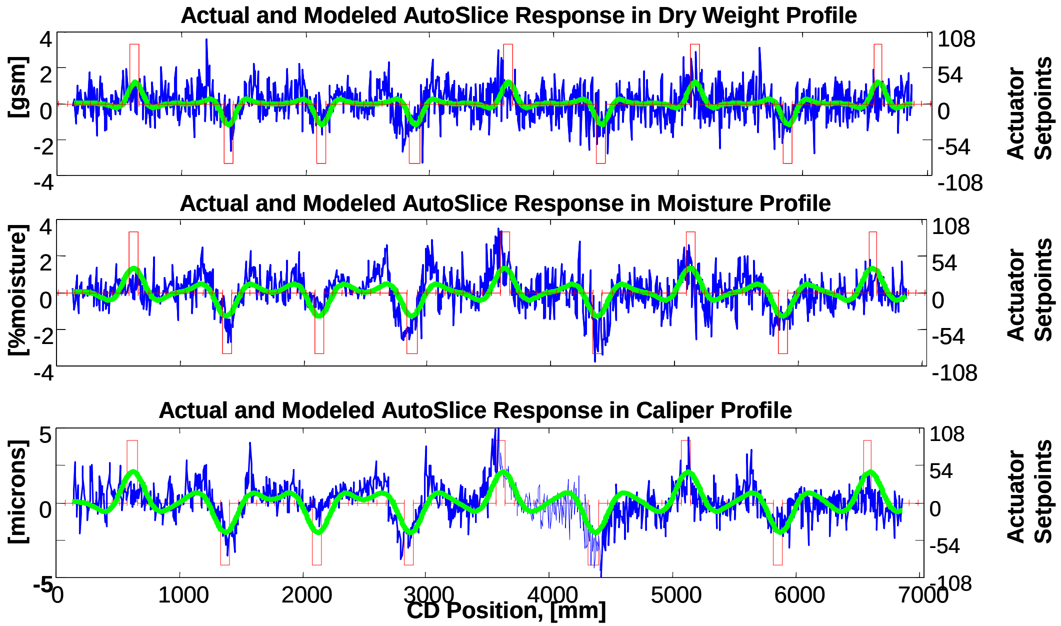
Paper Machine Control



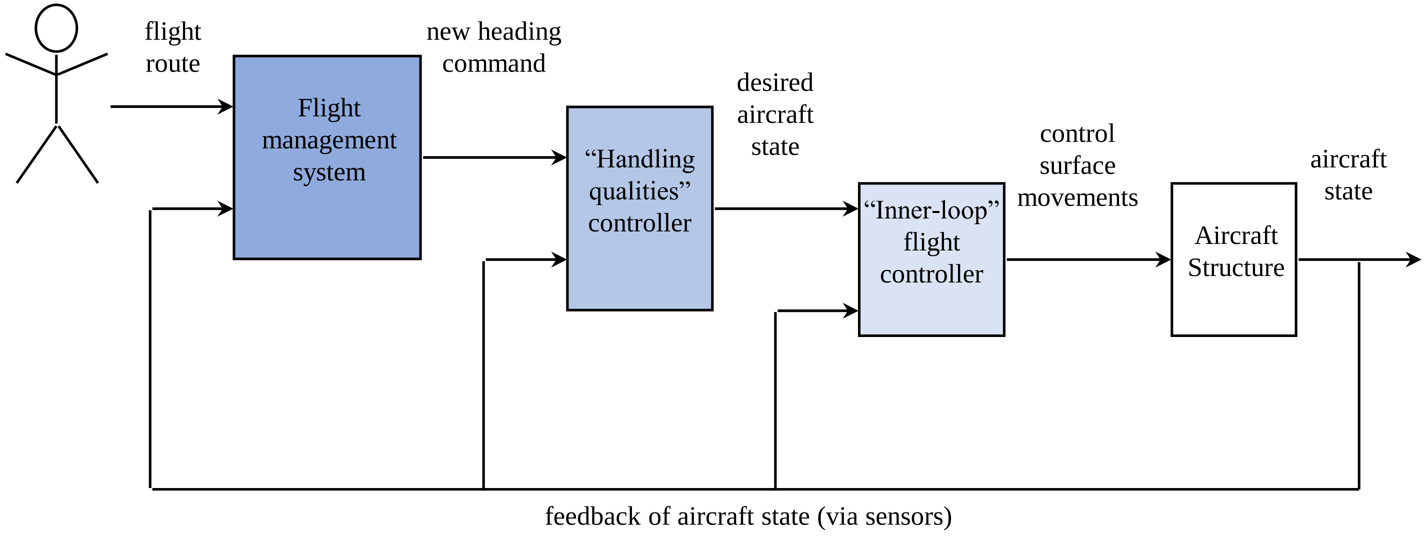




Several hundred sensors and actuators, millisecond operation, controlling paper thickness to within microns!



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	• 2-15% higher production • Refinery: ~$1/barrel for advanced control • 5-20% less energy/unit product
Pulp & Paper 	Cross/Machine Directional Control	• Up to 50% higher performance • 50-80% lower calibration time
Building Control 	HVAC adaptive control	• 7-33% energy cost savings • Low setup costs
Commercial Aircraft 	B787, C919 EPIC, APEX	• Stabilization of unstable aircraft • Level 1 handling qualities
Aero Engines 	AS907-1 HTF 7500E HPW3000	• 99.7% fault coverage • Optimized engine start • Improved engine life with power assurance
Space 	Orion Multi-Purpose Crew Vehicle	• Reduced propellant requirements by 20% • Optimal steering of control moment gyro
Military & Unmanned Aircraft 	Reusable Launch Vehicle, T-Hawk	• Stabilization, vehicle utility & operability • Fourfold reduction in development time • Missions completed after component failures
Automotive 	Diesel Engine Control Aftertreatment Control	• > 50% reduction in control design time

Benefits of advanced control (Honeywell)

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

The Impact of Control Technology, 2nd ed., T. Samad & A. Annaswamy (eds.), IEEE Control Systems Society, 2014; www.ieeecss.org/general/IoCT2-report

Important Control Concepts!

Feedback

State

Stability

Disturbance rejection

Filtering

Feedforward

Robustness

Time delays

Estimation

System identification

Adaptive control

Models

Controllability

Optimization

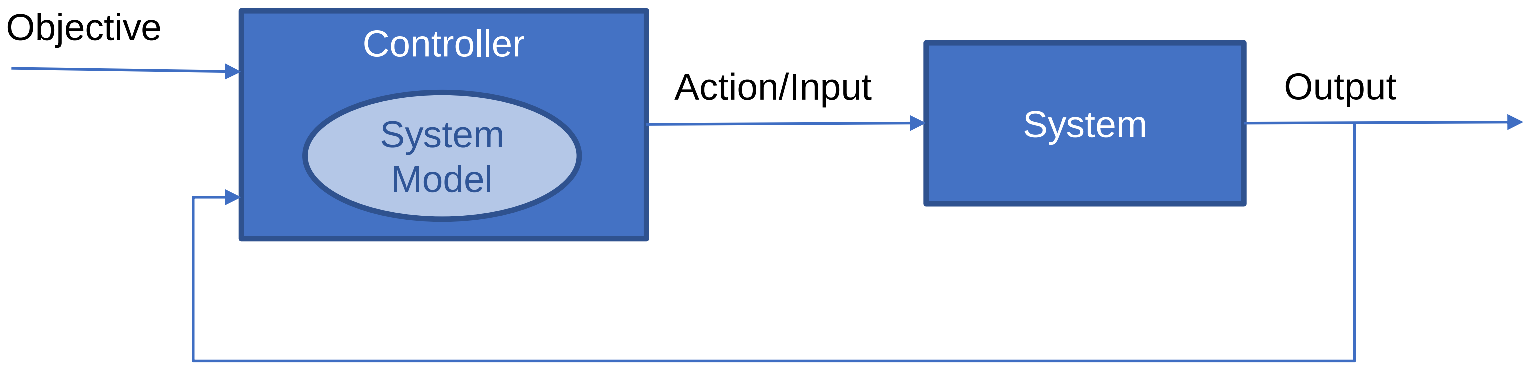
Inverse Response

Observability

Predictive control

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

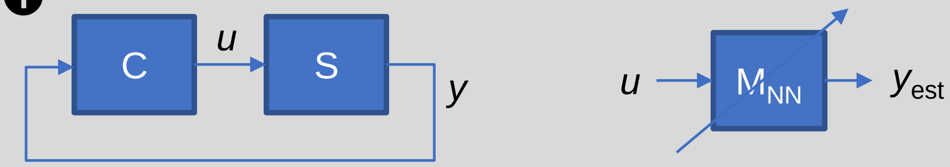
Applications for machine learning (e.g., deep neural networks)

- “System identification” for dynamical systems

Challenges (especially in dynamical systems):

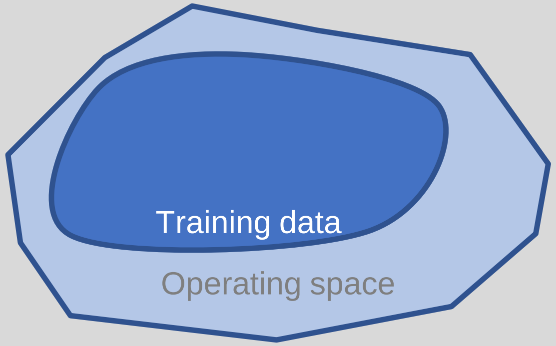
- “Sufficient excitation” ❶
- Representative data ❷
- The bias-variance dilemma ❸
- System drift
- . . .

❶



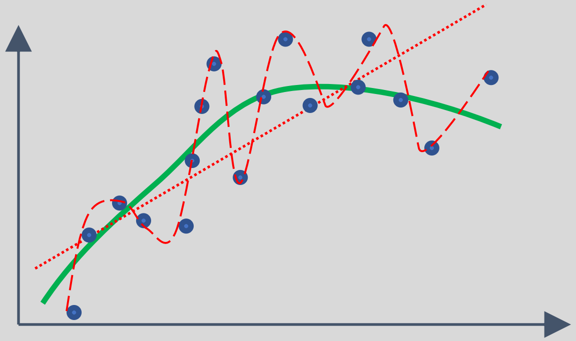
How can you be sure you’re learning a model of S and not (an inverse) model of C?!

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

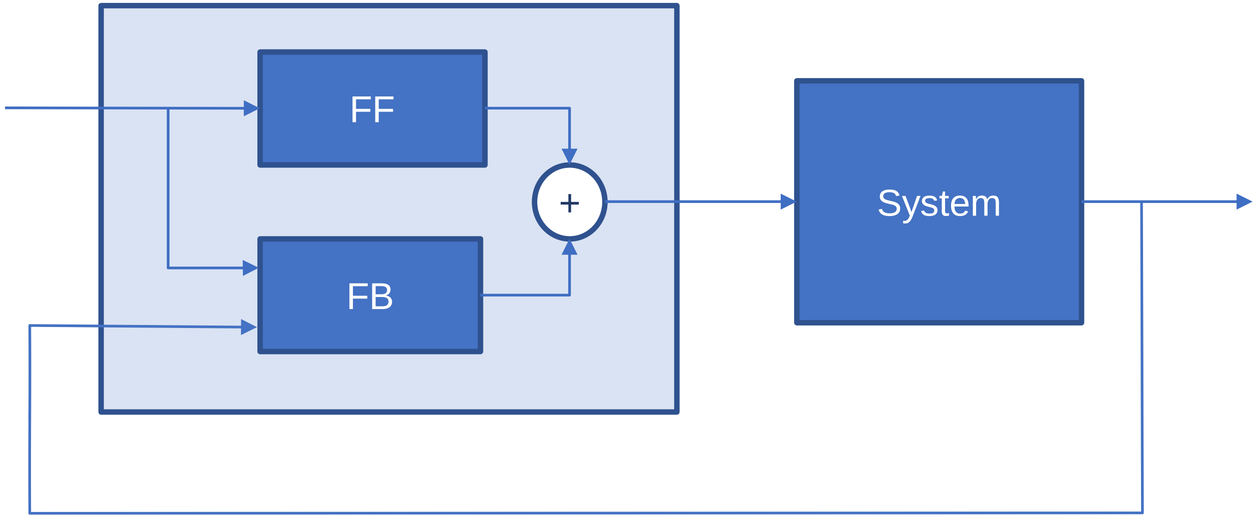


Underfit? Overfit? The right model?

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



	Feedforward	Feedback
Speed of response	*Faster*	*Slower*
Tolerance of uncertainty	*Lower*	*Higher*
Complementary functions	*“In the ballpark” quickly*	*Fine-tuning; adaptation*

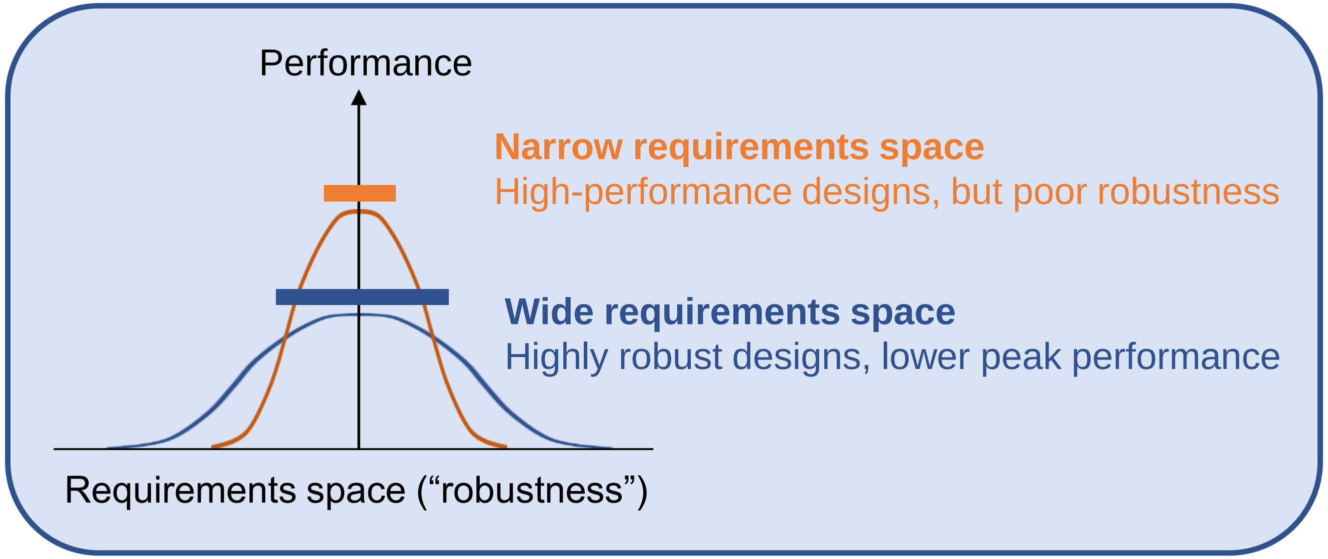
Example 1: You need to give a task to a developer in your team:

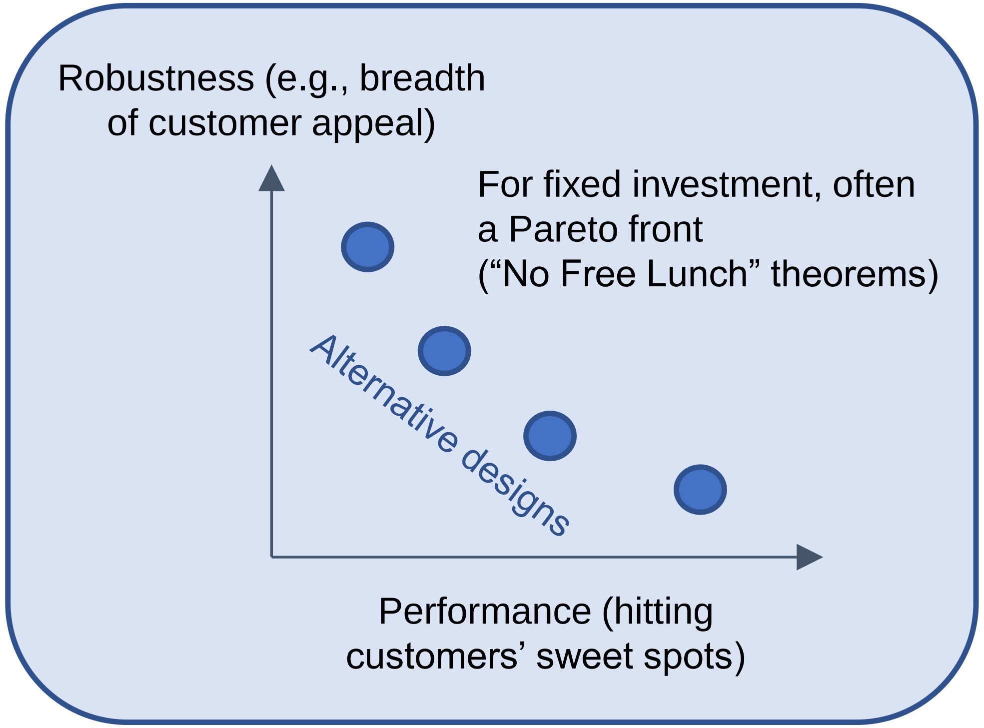
- A colleague you know well: Detailed spec with minimal oversight
- A newbie: General direction with frequent feedback/updates

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

Performance versus Robustness





What user “model” should you assume for a new application development?
Example: Which Windows versions should your application be compatible with?

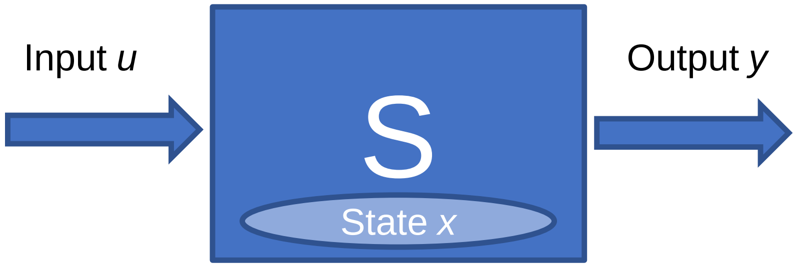
- Model 1: All users will be on Windows 8+
  - Higher performance for Windows 8+ users
  - If your model is wrong many potential users may be lost
- Model 2: All users will be on Windows XP+
  - Greater dilution of effort for the same investment
  - Less concern about reduced customer reach
- “Intermediate” 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?

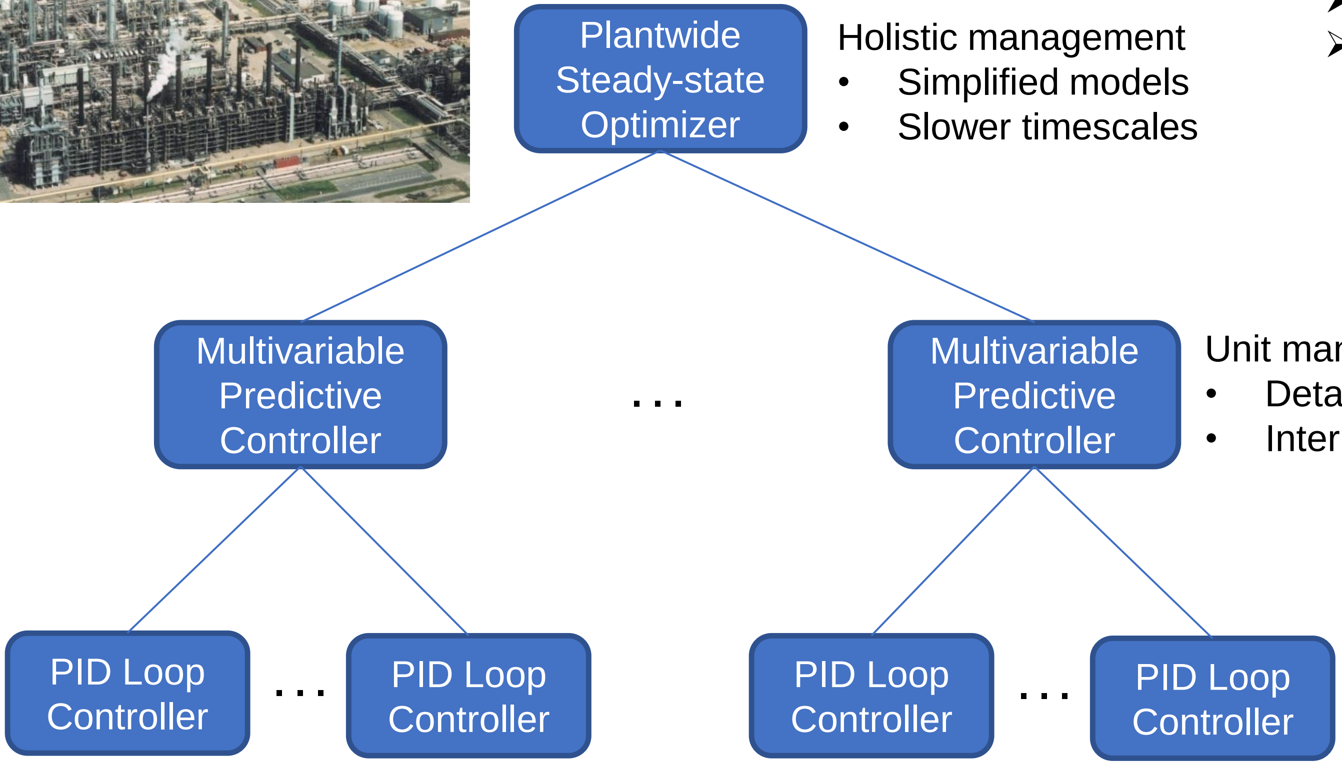
Other Insights on Feedback and Control

- **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**



Holistic management
- Simplified models
- Slower timescales

Unit management
- Detailed (dynamic) models
- Intermediate timescales

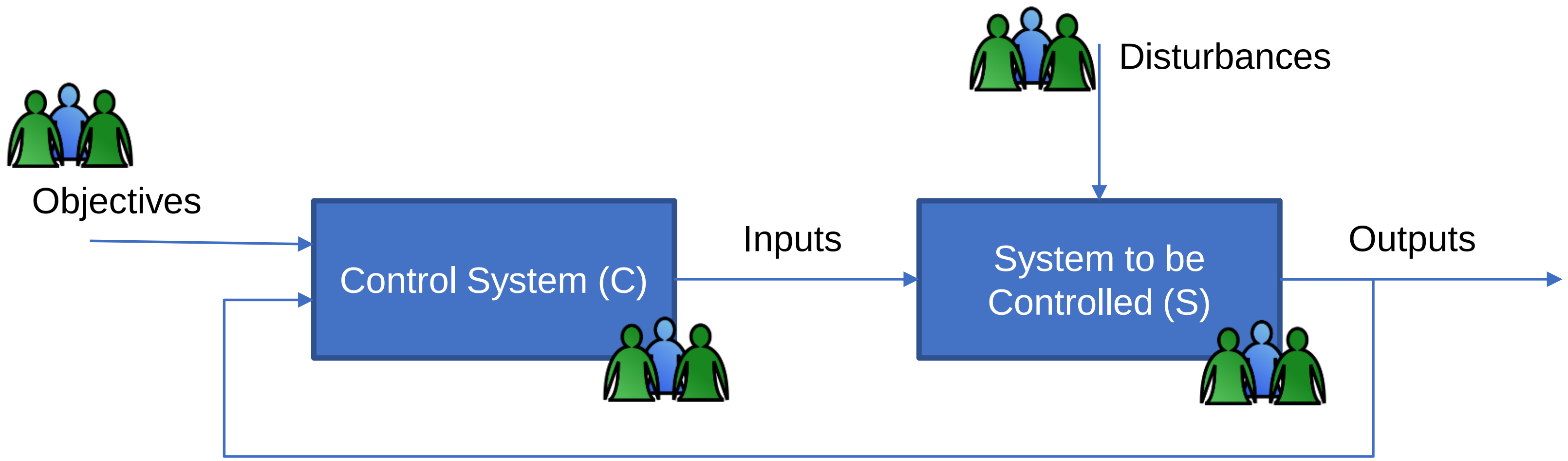
Sensor-/actuator-level execution
- Fast timescales

[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

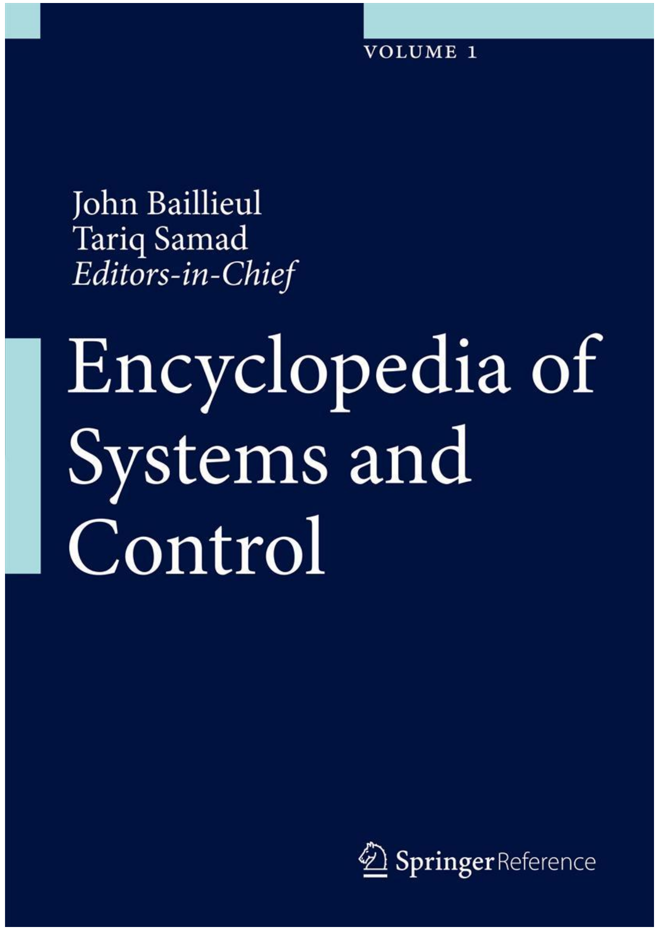
. . . And many other topics in the management of technology and innovation

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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