Decision Making in Technology Management—Applying Concepts from Systems Thinking and Control Systems

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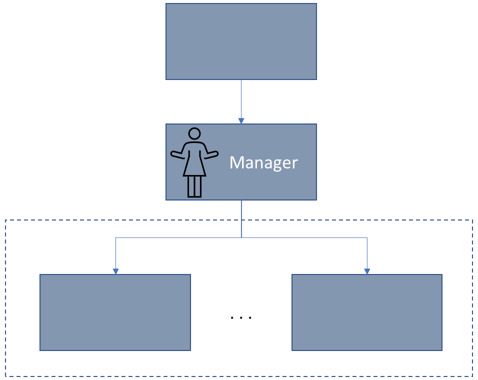
Outline

- Introduction to systems thinking
- Dynamical systems—a brief overview
- Control (or management) of dynamical systems
- Examples from my world
- TLI and the Management of Technology program

Managerial Decision Making

- The business world: Decisions must be made for effective . . .
  - Project and program management
  - Portfolio investments
  - Organizational changes
  - . . .
- Social change: Policies must be enacted for . . .
  - Enhancing diversity
  - Enhancing fairness and equity
  - Reducing recidivism
  - . . .
- The planetary ecosystem: Global action urgently needed for . . .
  - Mitigating climate change
  - Reducing pollution
  - Pandemic response
  - . . .



Decision making for complex dynamical systems!

Blind men and an elephant (parable)

https://en.wikipedia.org/wiki/Blind_men_and_an_elephant

"This ancient Sufi story was told to teach a simple lesson but one that we often ignore: The behavior of a system cannot be known just by knowing the elements of which the system is made."

"You think that because you understand 'one' that you must therefore understand 'two' because one and one make two. But you forget that you must also understand 'and.'"

-- Donella Meadows, *Thinking in Systems: A Primer*

Systems Thinking – the Iceberg

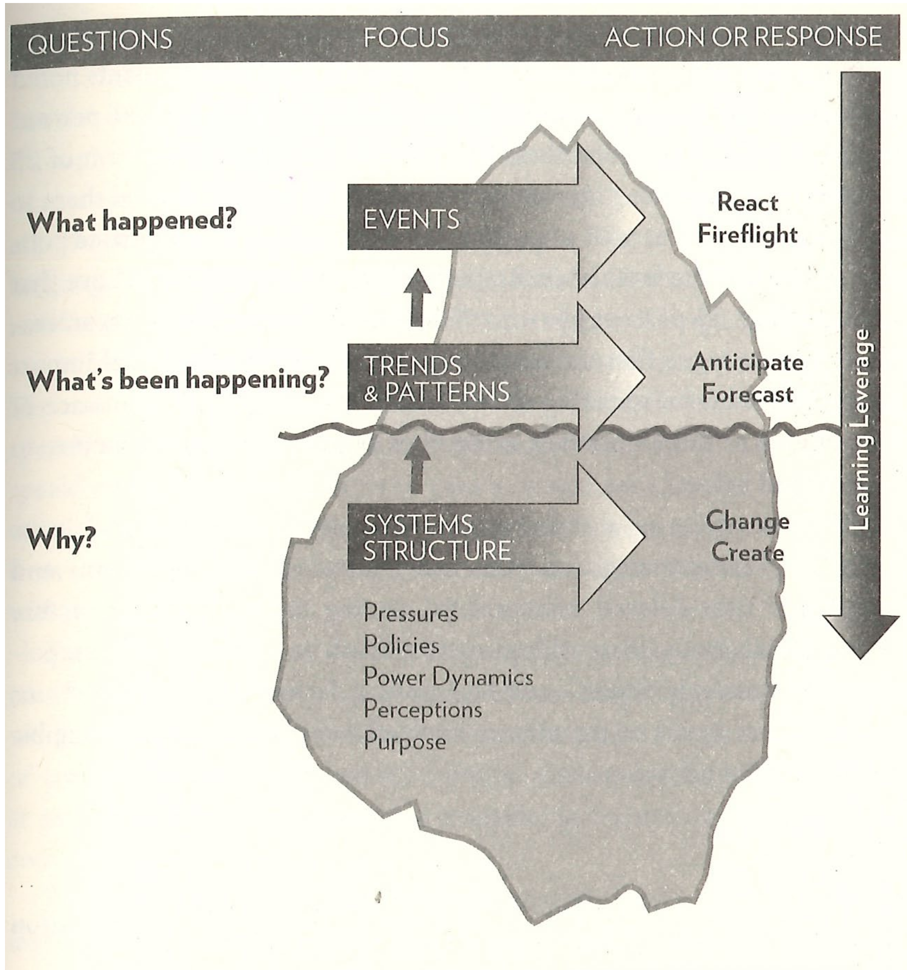
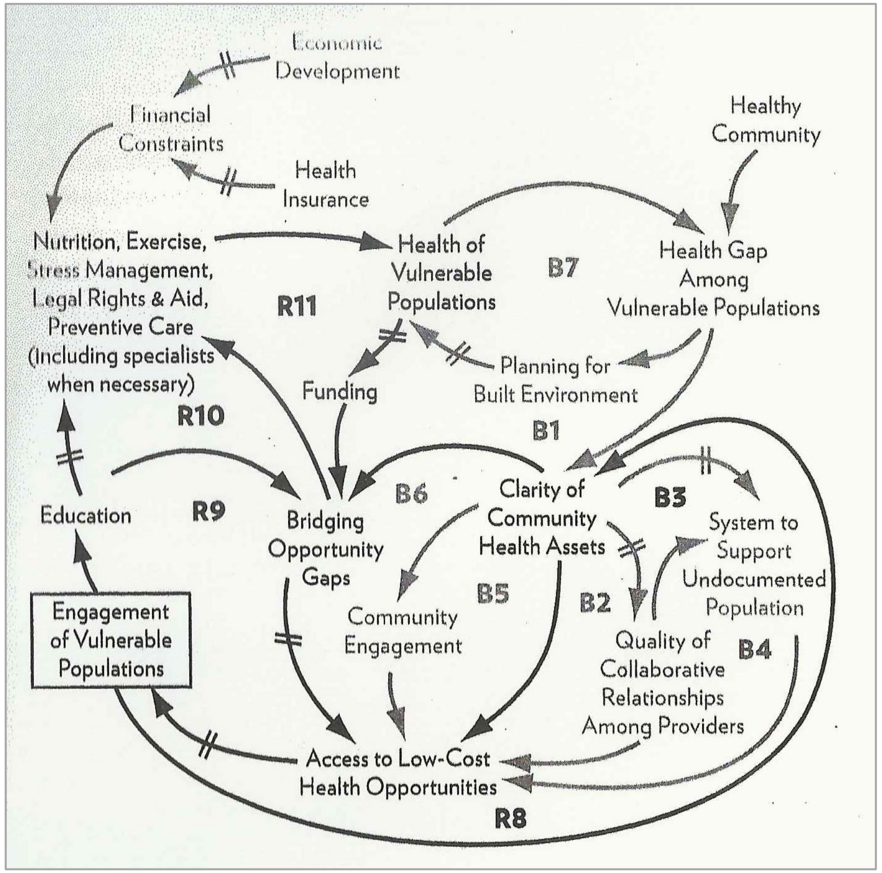


FIGURE 3.2 THE ICEBERG. The iceberg helps you to begin to distinguish a problem's symptoms from its root causes. Innovation Associates Organizational Learning

D.P. Stroh, *Systems Thinking for Social Change*, Chelsea Green Publishing, 2015

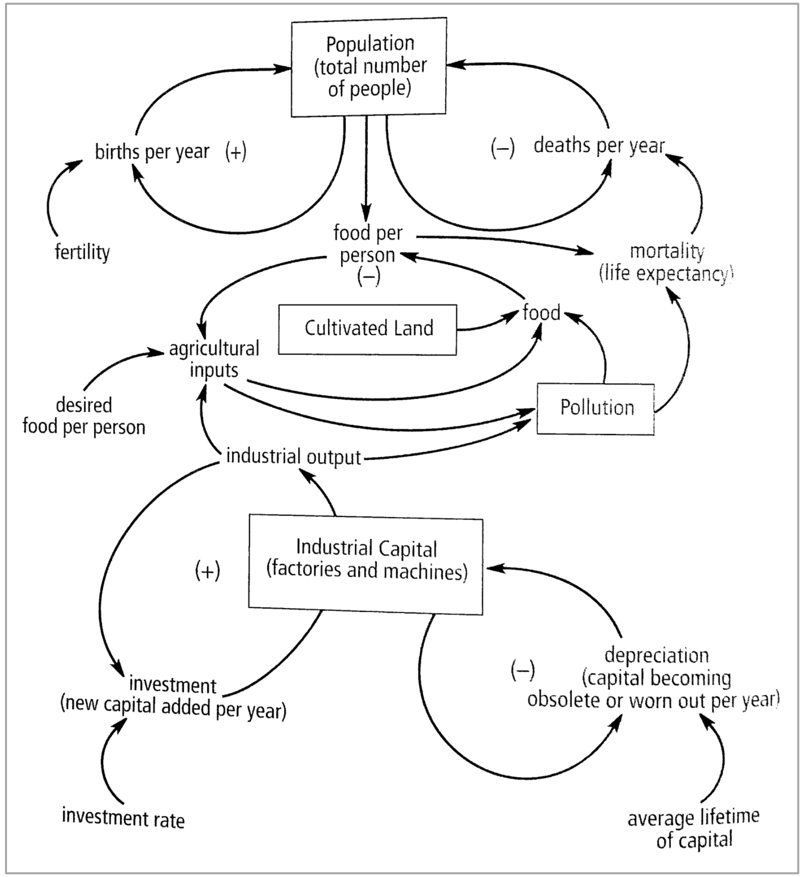
"A systems insight . . . can raise more questions!"
-- D.H. Meadows, *Thinking in Systems: A Primer*

Systems Thinking Diagrams



Reinforcing progress toward a healthy community

D.P. Stroh, *Systems Thinking for Social Change*, Chelsea Green Publishing, 2015



Feedback loops of population, capital, services, and resources

D. Meadows, J. Randers, and D. Meadows, *Limits to Growth: The 30-Year Update*, Chelsea Green Publishing, 2004

Common Concepts: Stocks and Flows

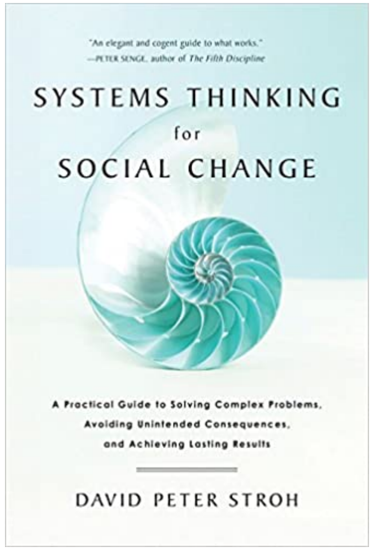
	Stocks	Flows
Business (e.g., R&D)	• Funds • Laboratory facilities • Intellectual property developed • R&D staff	• Funds transfer • Development of intellectual property • Hiring and departures of R&D staff
Social change (e.g., housing)	• Total low-cost housing • Open low-cost housing • Homeless population	• New builds • Houses becoming uninhabitable or being repurposed • People gaining homes • People becoming homeless
Ecosystem (e.g., climate change)	• CO_2 in atmosphere • Polar ice	• CO_2 emissions • CO_2 absorptions • Polar ice melt

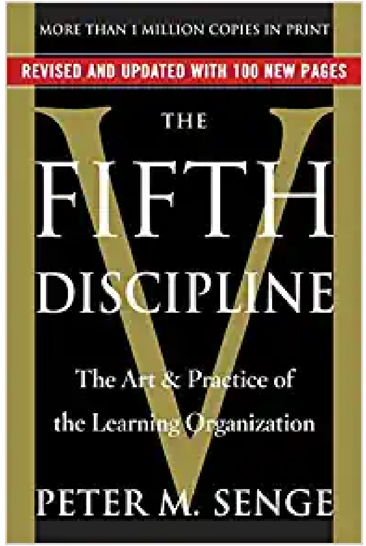
Operationalizing the Systems Perspective

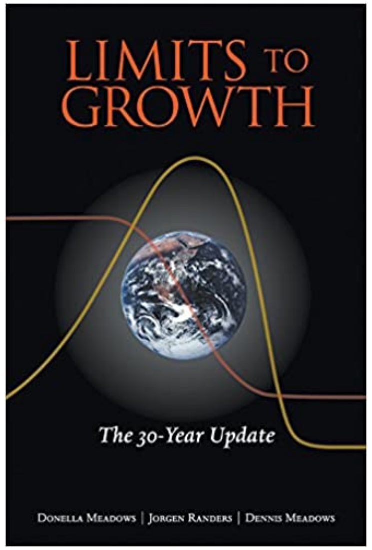
- A uniform language across all application domains and problems
- Common structures, archetypes, best practices, failure modes
- Separation of the system to be managed and the control or decision making needed to manage the system
- The concept of models, including mental models
- Separation of the "stuff" of interest and the information signals and processing involved in controlling the stuff – *feedback*

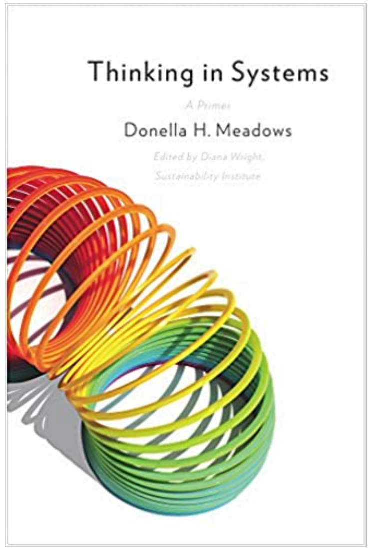
> Systems of information-feedback control are fundamental to all life and human endeavor, from the slow pace of biological evolution to the launching of the latest space satellite . . . Everything we do as individuals, as an industry, or as a society is done in the context of an information-feedback system.
> -- Jay Forrester, *Industrial Dynamics*, MIT Press, 1960

More on Systems Thinking . . .

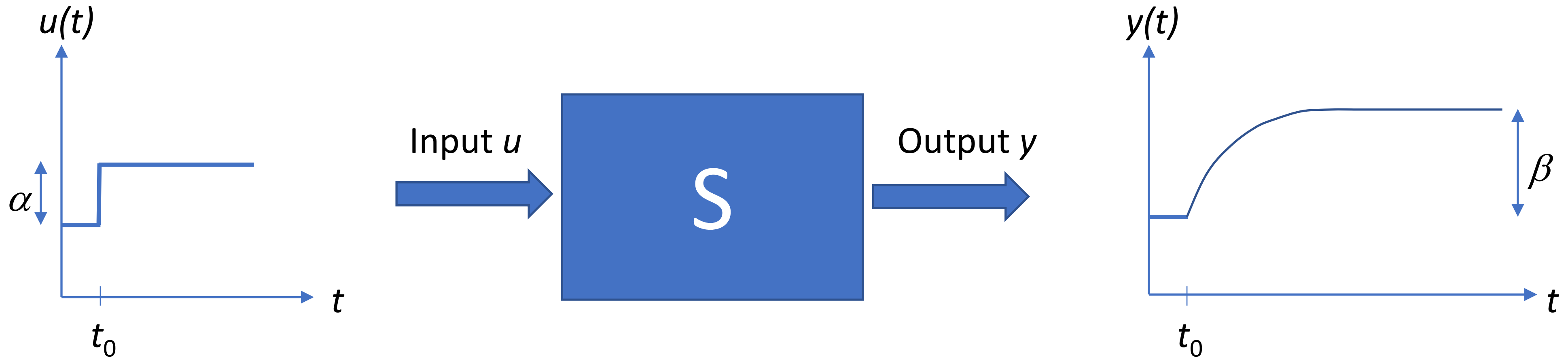








A Simple Dynamical System

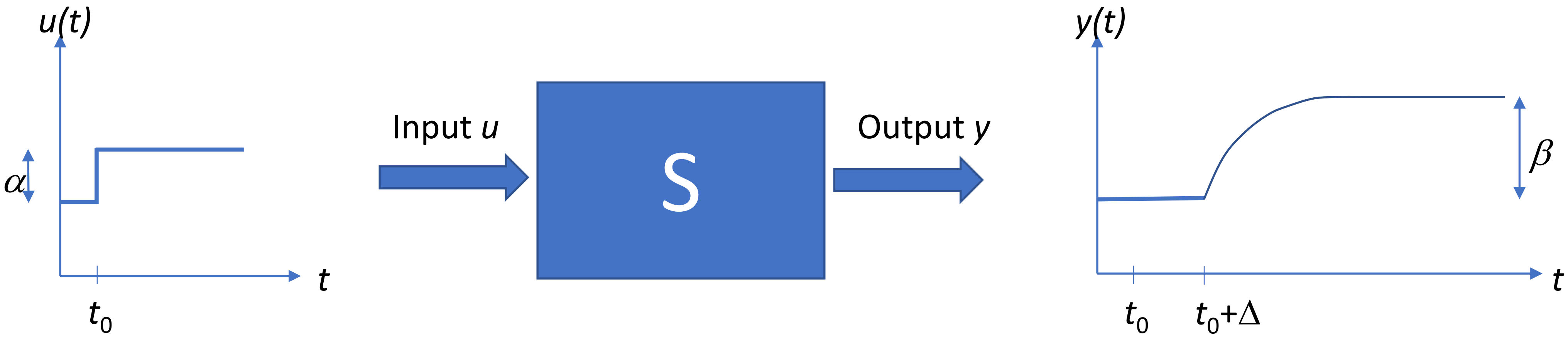


Physical example (S: room): The temperature *y* ultimately increases by β after you turn the heat *u* up by α

Management example (S: software development team): Increase # of coders *u* by α → lines of code produced (*y*) gradually increase until stabilizing at an increase of β

Example shown is a very simple dynamical system ("first-order, linear")

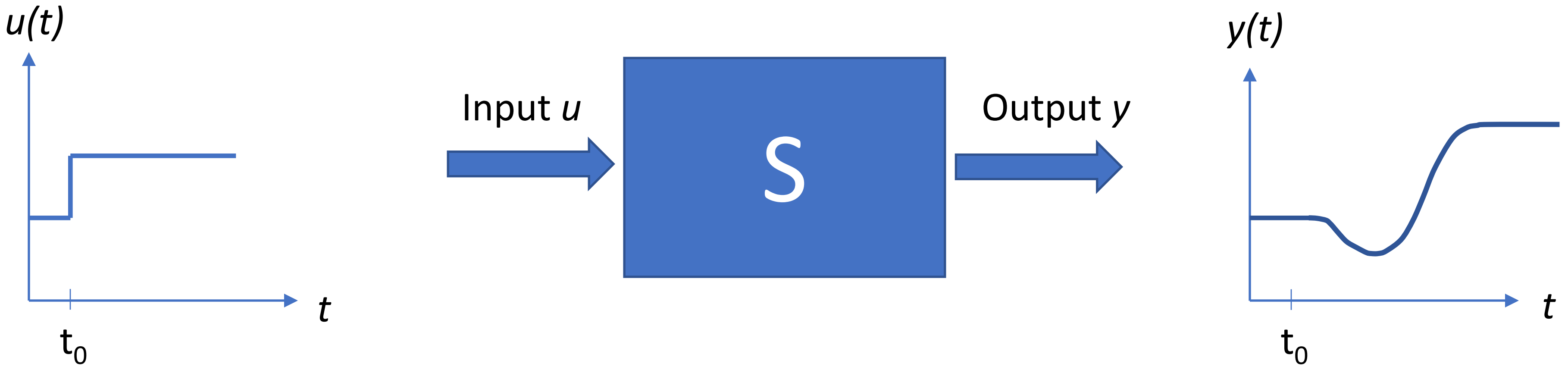
Simple Dynamical System with Delay



Example: Increase R&D at time t_0 → revenue starts to increase after a delay of time Δ (need time for new product introductions)

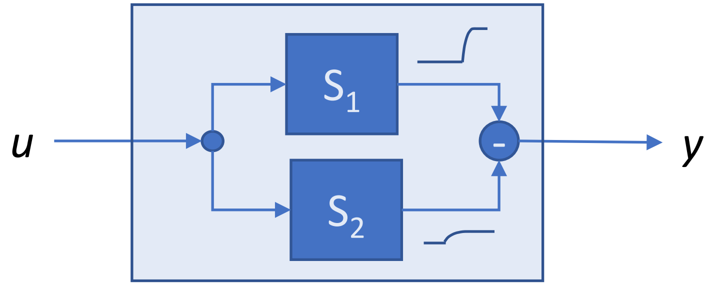
A simple dynamical system with delay ("first-order linear with delay")

Dynamical System with “Inverse Response”



Example: Increase R&D spend *u* at time t_0 → profit *y* initially decreases until new products start to roll out

Inverse response often results from two different subsystems acting in parallel



A System – "Black Box" View

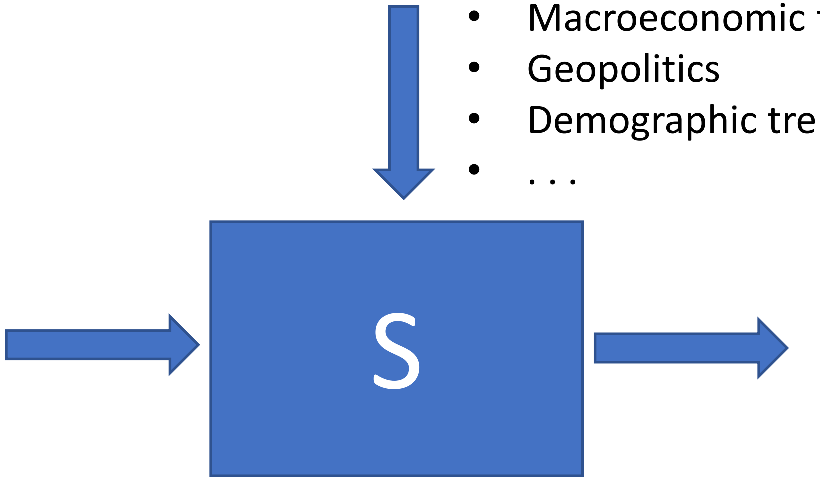
- Examples: Project management, portfolio management, new product introduction, service delivery, strategic planning, . . .
- What are the inputs, outputs, and disturbances
- What are the dynamics involved in the system
- How much do you understand about what goes on inside the black box?

<u>Disturbances *d*</u>

- Macroeconomic factors
- Geopolitics
- Demographic trends
- . . .

<u>Inputs *u*</u>

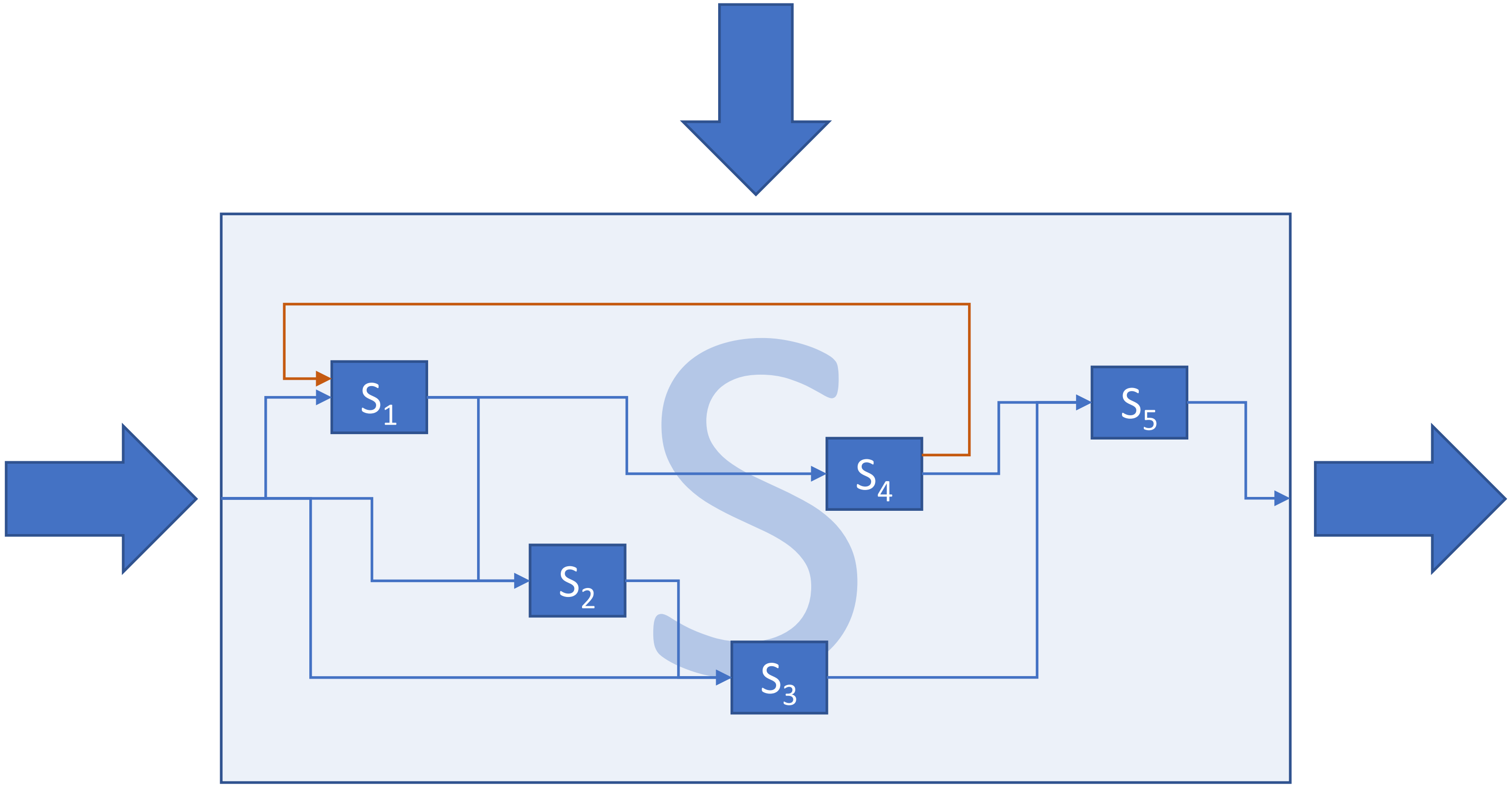
- Marketing spend
- R&D expenditures
- Financial management
- Real-estate
- Organizational design
- . . .



<u>Outputs *u*</u>

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

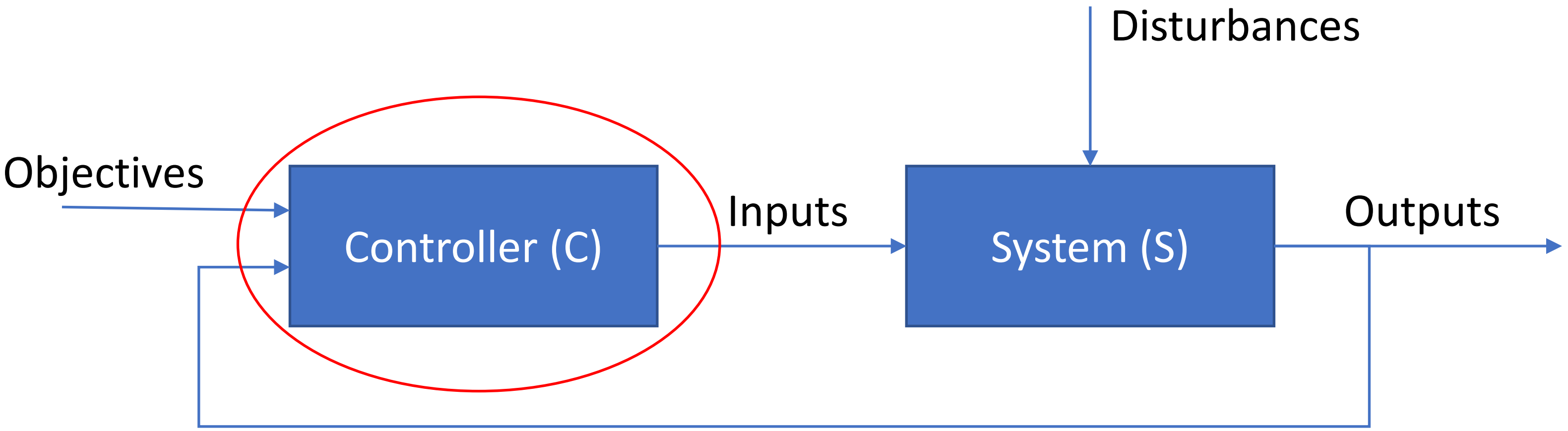
Systems have structure (including feedback)



Example: Functions within an enterprise

Feedback more pervasive in complex systems than shown here

Systems and Control



C: Controller or decision maker: relying on measurements of S to manage its operation

A successful controller will help achieve objectives for S, despite disturbances, etc.

(Sometimes we need to change S to make it easier to control)

Do we have examples of high-performance control of complex dynamical systems? **YES →**

Industrial Successes of Advanced Control

Plantwide control and optimization: 15-30 MPCs; $1.5-3M increase in production

Rubicon Water Pty: Precision irrigation using network control theory. Deployed in Australia, NZ, US, China, India

Kiva warehouse robots—control scientist's startup acquired by Amazon for $775M

Automated Transfer Vehicle for ISS: With robust control, docking accuracy improved from 8 cm to 2 cm

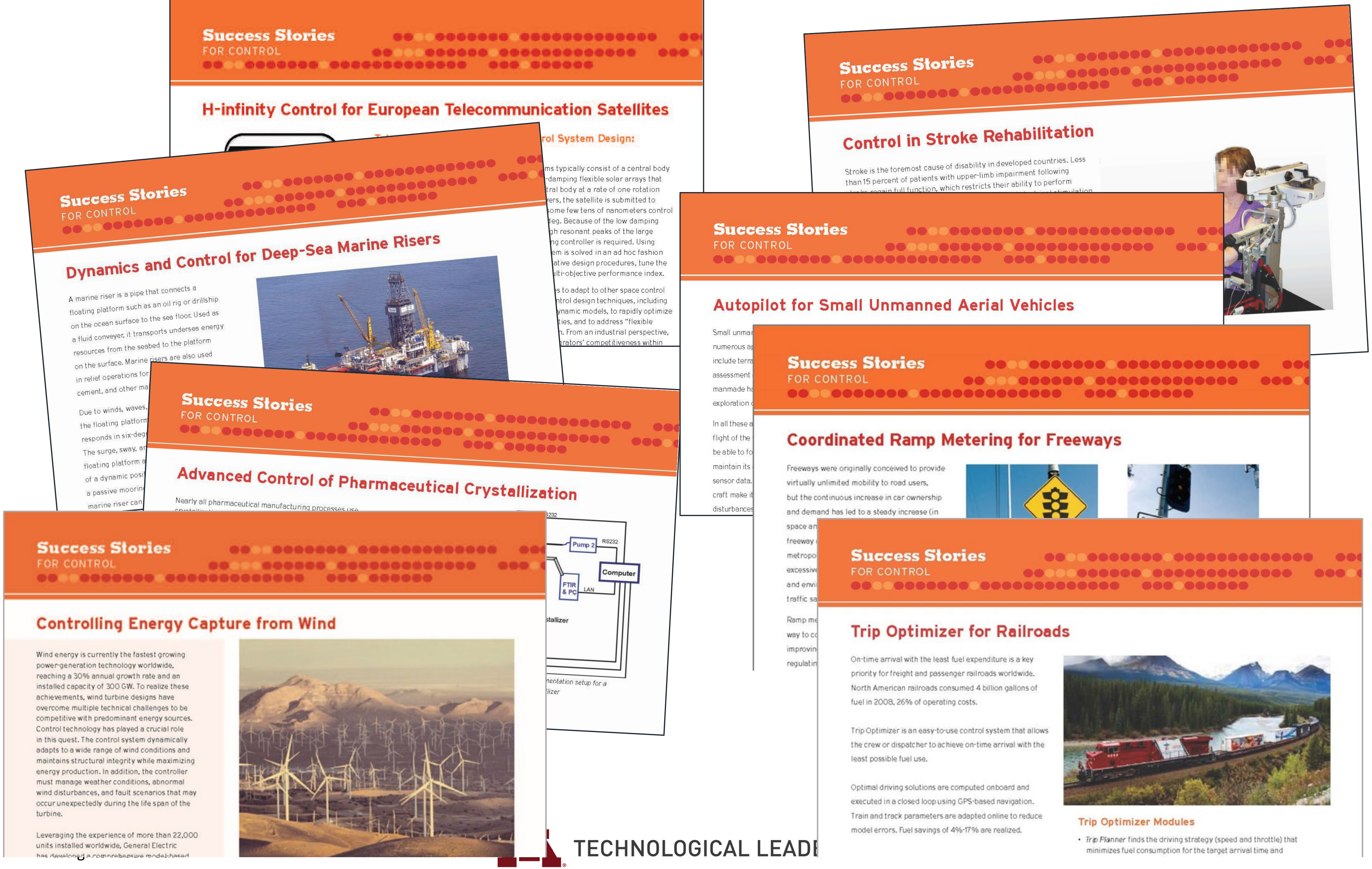
Airbus A350: Robust-control-based fault detection; benefits of reduced weight and fuel consumption

13 billion mobile phones worldwide; each has 6+ critical control loops!

Seagate disk drives: Billions shipped that use μ-synthesis-based feedback control

Medtronic MiniMed: Automatic control of insulin; implanted in >200K patients; revenues in $Bs

T. Samad, M. Bauer and S. Bortoff, et al., "Industry engagement with control research: Perspective and messages," *Annual Reviews in Control*, vol. 49, pp. 1-14, 2020, https://doi.org/10.1016/j.arcontrol.2020.03.002 (open access)



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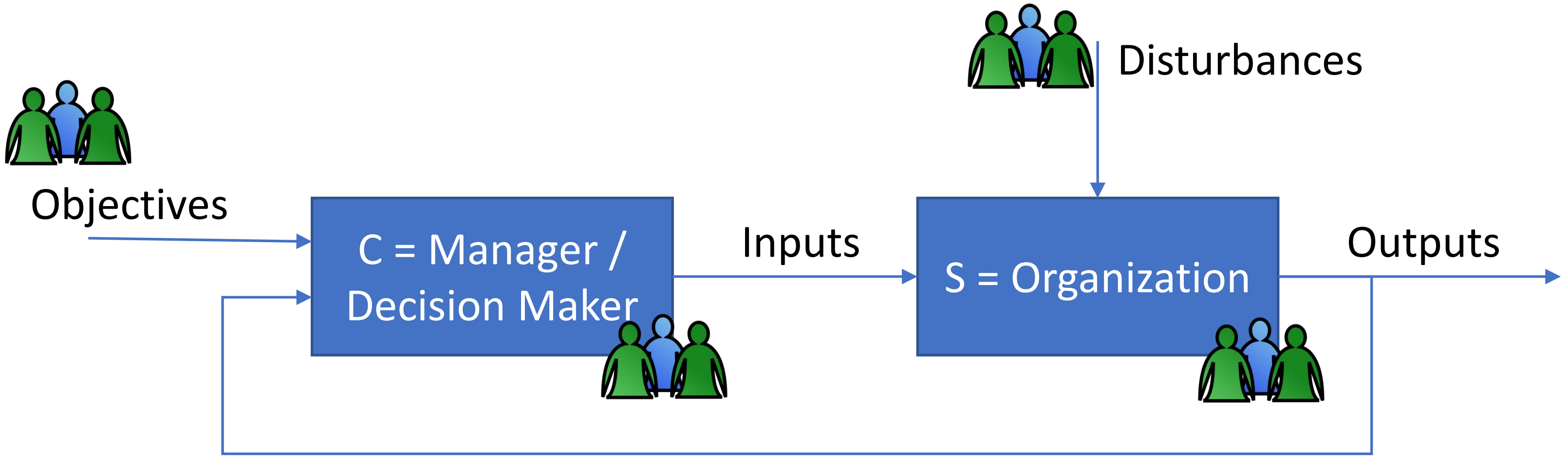
The Impact of Advanced Control, 2nd ed., T. Samad & A. Annaswamy (eds.), IEEE Control Systems Society, 2014; www.ieeecss.org

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

Control Systems for Technology Management



Control Science: Insights for Managerial Decision Making

Program and project management

Technology research and development

Portfolio management

New product introduction

Innovation processes

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

Key Concepts

Stocks and Flows

Dynamics

Systems

Inputs and Outputs

Time delays

Feedback

Uncertainty

Feedforward

Models

Disturbances

Optimization

Estimation

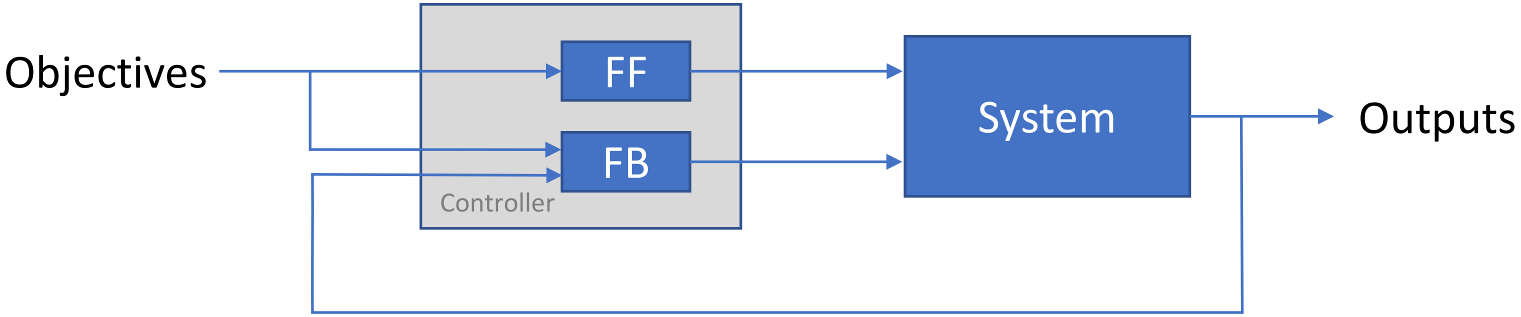
Stability

Actuators

Sensors

. . . and others

Feedback and Feedforward



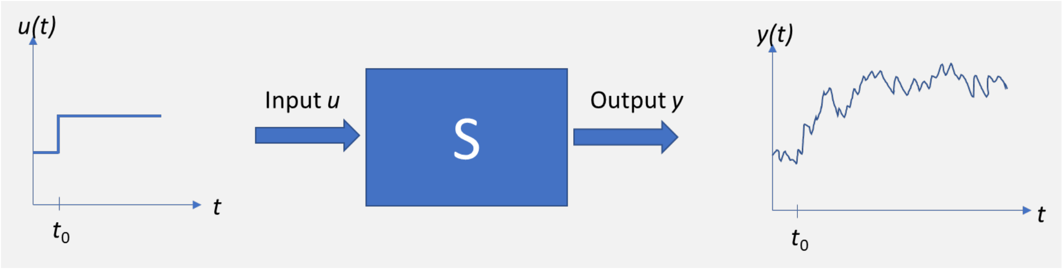
Feedforward (FF) allows fast responses; feedback (FB) takes time to work—but is essential for mitigating uncertainty

Both feedback and feedforward control should be applied for fast yet reliable decision making

- Exploit the understanding we have of the system for feedforward commands
- Rely on feedback for overcoming the limitations of our understanding and other uncertainties

Noise and Disturbances

Noise

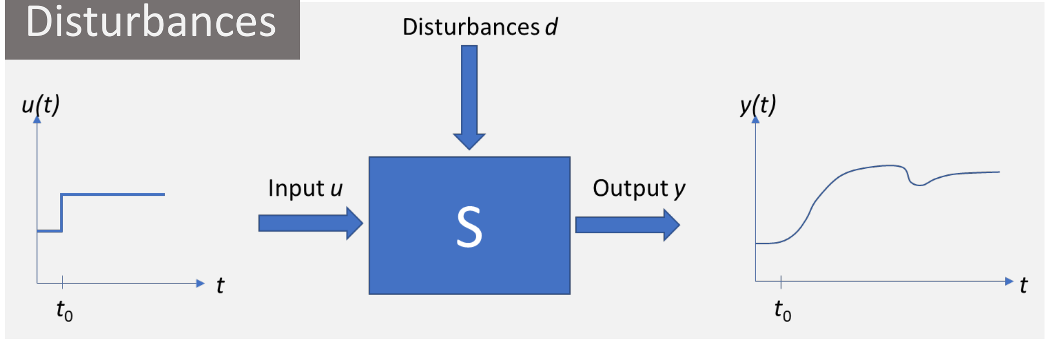


The system and its measurements are never as “clean” as we would like; random noise is pervasive in real systems

Example: Your revenue may depend on the weather, which has a significant random component

Noise may not always be “Gaussian” or “normal”

Disturbances



Disturbances: External adverse influences not under our control, and sometimes not measurable either; disturbances may be short-lived or of extended duration

Examples: New tariffs get imposed, consumer confidence drops, a hurricane impacts operations, a pandemic hits

We would like to minimize the effect of disturbances as much as possible (“disturbance rejection”)

An important but often overlooked distinction

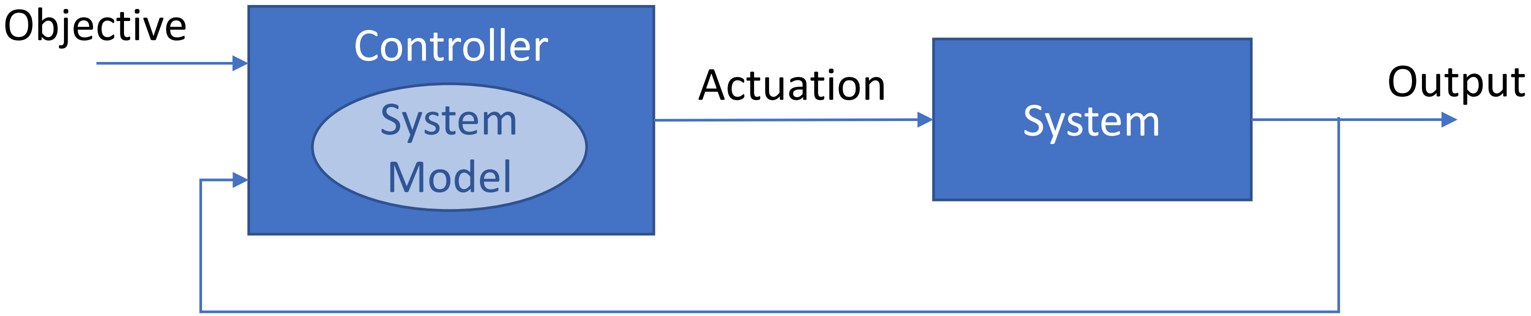
Uncertainty – the need for rigor in terminology!

- In 1948, Yugoslavia broke from the Soviet Union, raising fears the Soviets would invade
- In March 1950, a US national intelligence report was published, stating, "Although it is impossible to determine which course of action the Kremlin is likely to adopt, we believe the extent of [Eastern European] military and propaganda preparations indicates that an attack on Yugoslavia in 1951 should be considered a serious possibility."
- Sherman Kent (CIA,"the father of intelligence analysis") subsequently asked each person on the team that wrote the report what they meant by "a serious possibility." Everyone had approved the report.
- Responses ranged from odds of [80 to 20] to odds of [20 to 80]!
- What do we mean when we say "quite likely" or "it's possible" or "there's a good chance"? And what do we think others understand when we use such phrases?

Philip Tetlock and Dan Gardner, *Superforecasting: The Art and Science of Prediction*, Crown, 2015

Models (and Mental Models)

Virtually all advanced control for engineered systems is model-based . . . Models are essential to the design and/or operation of the controller



Models (and Mental Models)

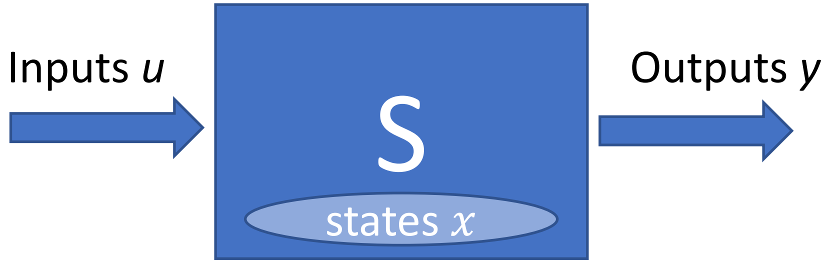
What do models in control engineering have to do with managerial decision making?!

→ Human decision-making is "model-based" too!

- **Conceptually identical to model-based control, except that the models are in the minds of the decision makers!**
- **Managers make decisions based on their knowledge or belief (their "mental models") about their organization (resources, capabilities, etc.), the business environment, etc.**

> "Remember, always, that everything you know, and everything anyone knows, is only a model. . . .
>
> "Getting models out into the light of day, making them as rigorous as possible, testing them against the evidence, and being willing to scuttle them if they are no longer supported is nothing more than practicing the scientific method—something that is done too seldom in science, and is done hardly at all in social science, management, or the government."
>
> –D.H. Meadows, *Thinking in Systems: A Primer*

“States” versus “outputs”



The measured outputs will usually not tell us what’s really going on in the system

The “states” of a system characterize its status—these must often be estimated from the outputs and other information (in particular, the model)

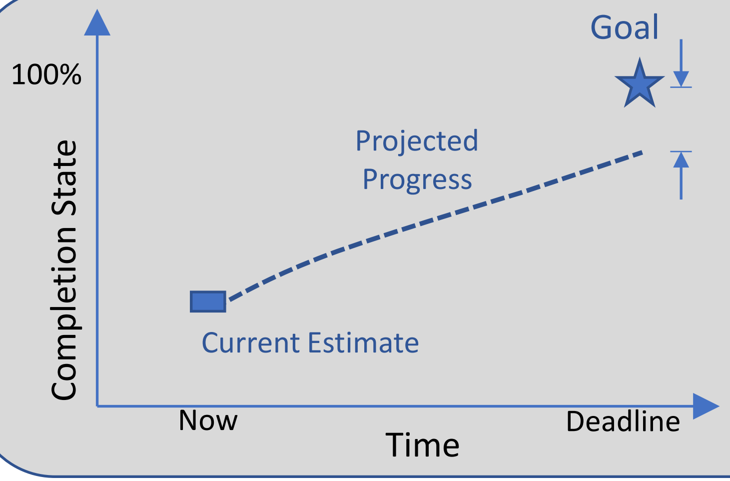
Decision making should be based on state estimates $\hat{x}$ and not just the outputs (or easy-to-measure KPIs)!

Technology management example:

- You’re leading a software development program. Your dashboard indicates the lines of code each team is producing each day. How does this measurement relate to how well the program is going relative to plan?

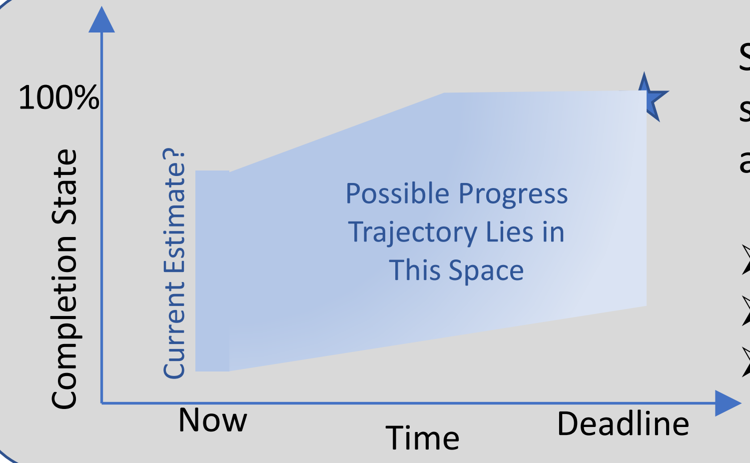
Importance of State Estimation and Modeling (Illustration)

Objective: Ensure product development is completed by the deadline



Additional funding needed to ensure this gap is covered

A “highly confident” prediction if the current state of development is known and progress with current resources can be well predicted



Substantial uncertainty in estimate of current state and progress trajectory—how much additional funding should be requested?

- Less predictable outcome
- Higher likelihood of not making plan
- Higher likelihood of wasted resources

In reality, managers will encounter situations between these extremes. In all cases, the confidence with which a decision can be made, and the reliability of the projected outcome, depend on the accuracy of the state estimate and the decision maker’s mental model

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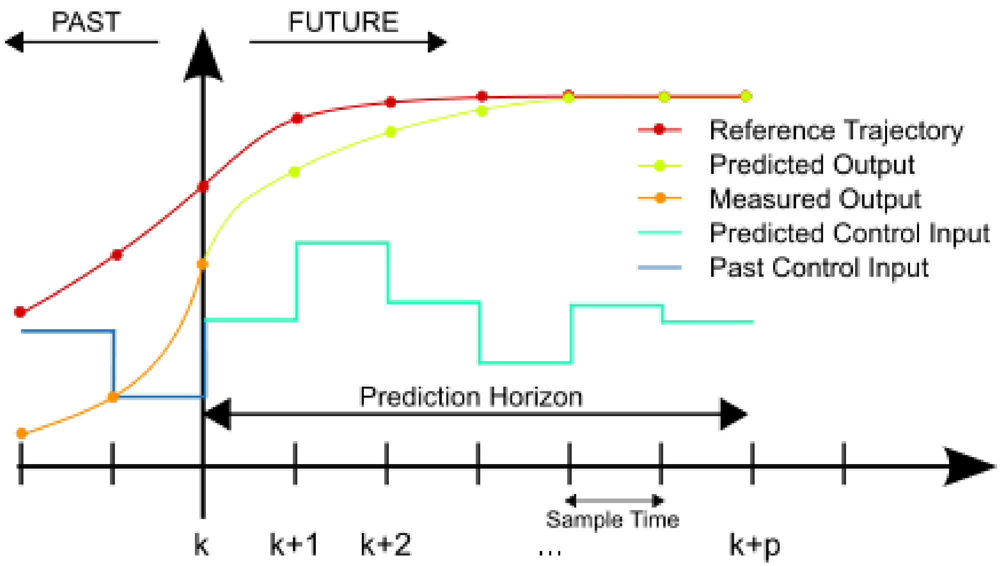
Model Predictive Control (MPC)*



Source: Martin Behrendt [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)]

Current time: *k*

1. Gather information about the state of the system at time *k* – *feedback*

2. Estimate how the system will respond to possible current and future decisions – *mental model*

3. The input action sequence that results in the best performance (given the objectives & constraints) can then be your plan of action – *optimization*

4. Take the first step in the plan – the action at time *k*

5. $k \leftarrow k + 1$ (time advances)

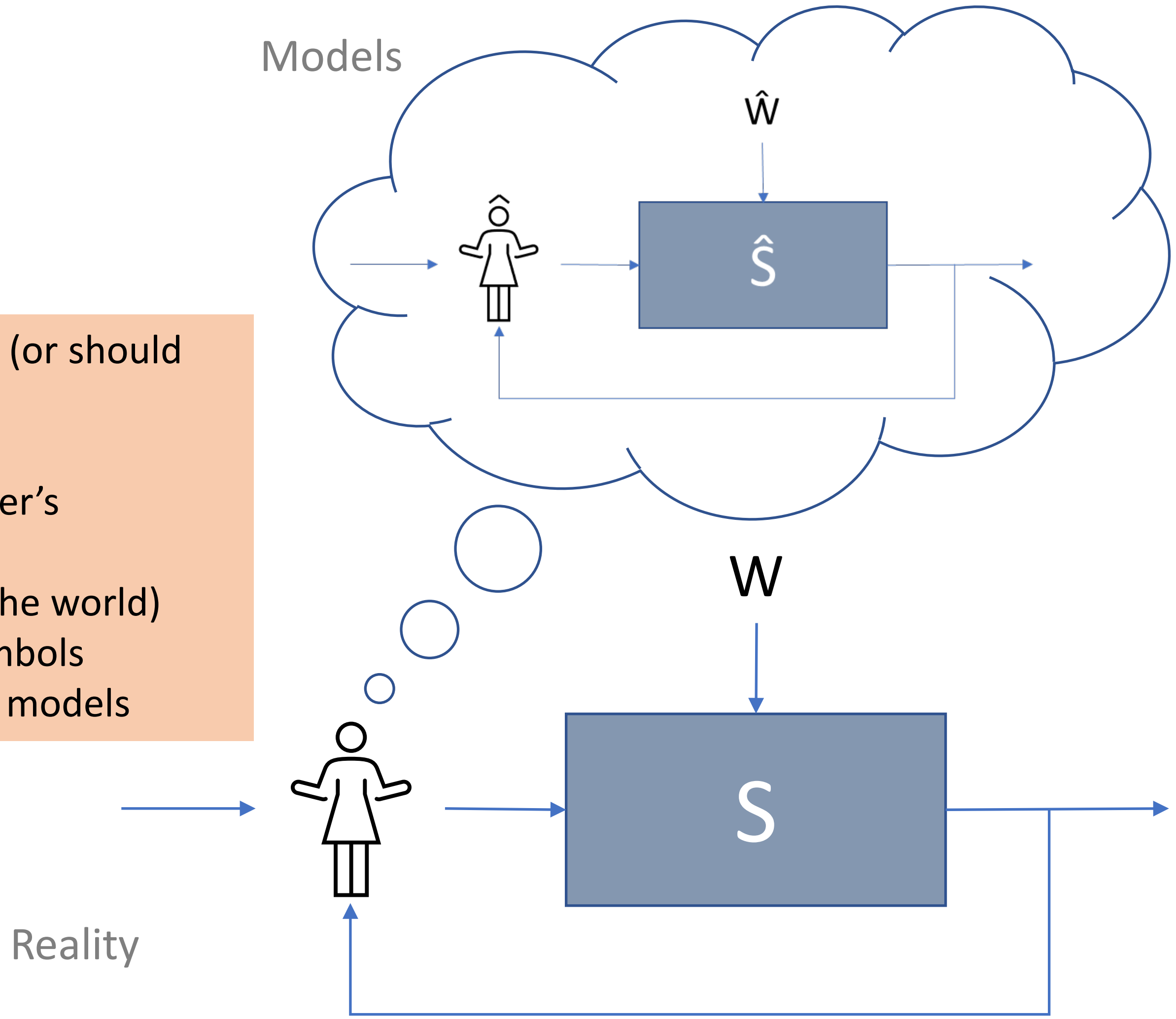
6. Go to Step 1 and continue

*MPC is the most successful advanced control technology in industry (T. Samad, et al., "Industry engagement with control research: Perspective and messages," *Annual Reviews in Control*, 2021, https://doi.org/10.1016/j.arcontrol.2020.03.002)

Decision Making in Management

How managers make (or should make) decisions

- S: system (manager's organization)
- W: disturbance (the world)
- The "hats" on symbols represent mental models



The quality of decision making depends substantially on the decision maker's model of reality

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"

Time Delays Make Control Harder

"... one of the lessons of balancing loops with delays: that aggressive action often produces exactly the opposite of what is intended. It produces instability and oscillation, instead of moving you more quickly toward your goal."
–Peter Senge, *The Fifth Discipline: The Art and Practice of the Learning Organization*

Time delays are especially important for managerial decision making—the effects of an action may not be known for weeks, months, years, or decades. Delays can arise from:

- Communications
- Policy implementation and uptake
- Time needed for decisions to have an effect
- Time needed for measurement and observation of effects

"One of the highest leverage points for improving system performance is the minimization of system delays."
–Ray Stata (CEO, Analog Devices)

Make sure you understand the delays in the system you're managing

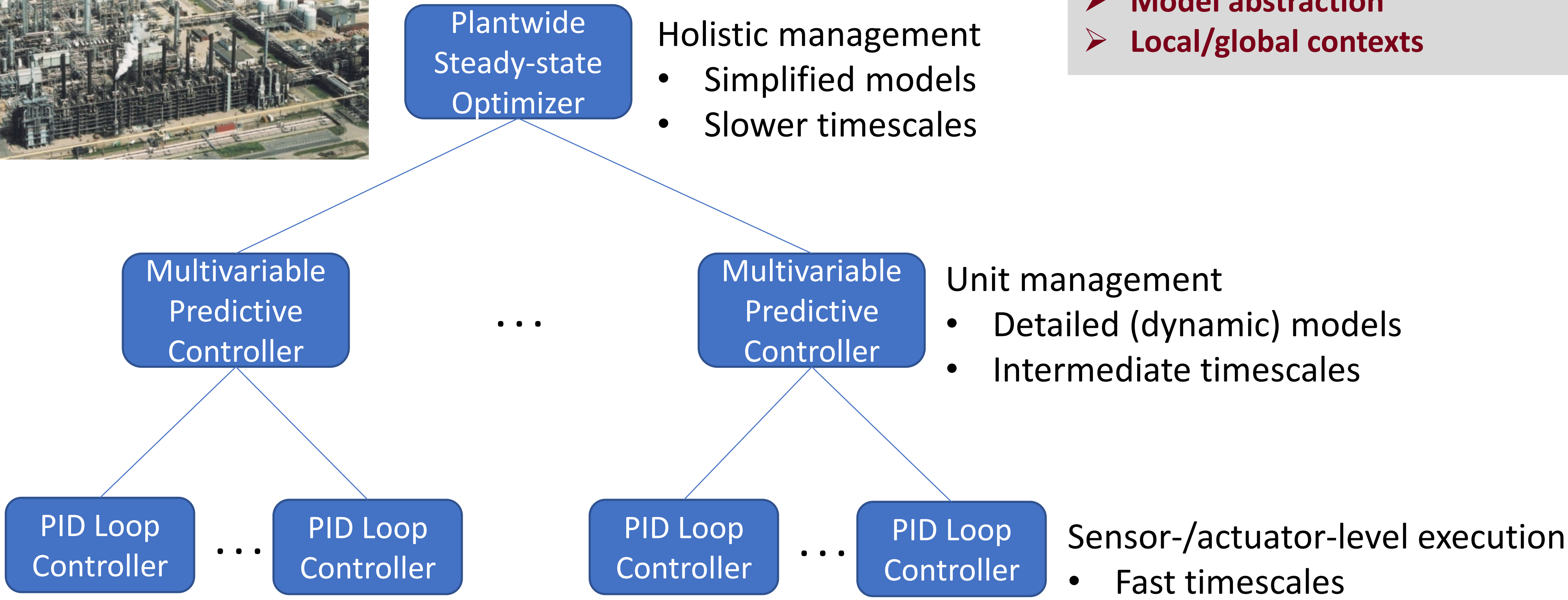
To improve performance, take action to reduce delays.

Insights from Control Science for Decision Making

- *Feedback* and *feedforward*—counteracting uncertainty and improving response time
- *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
- Distinctions—and tradeoffs—between *performance* / *robustness* / *adaptation*
- *Exploration* versus *exploitation*—there's no free lunch
- Control loops and *stability*: Well-designed feedback control can stabilize an unstable system; poor control can destabilize a stable system
- *Time delays* make high-performance control difficult to achieve
- *Sampling rates* should be sensitive to system dynamics—over-sampling can result in over-reaction, waste resources
- Effective decision-making requires *state estimation*, not just measuring outputs
- Hierarchical and multi-level control—theory extends to *systems of systems*

Control and Managerial Hierarchies

Lessons from enterprisewide optimization and control:
- ➢ **Timescale separation**
- ➢ **Model abstraction**
- ➢ **Local/global contexts**

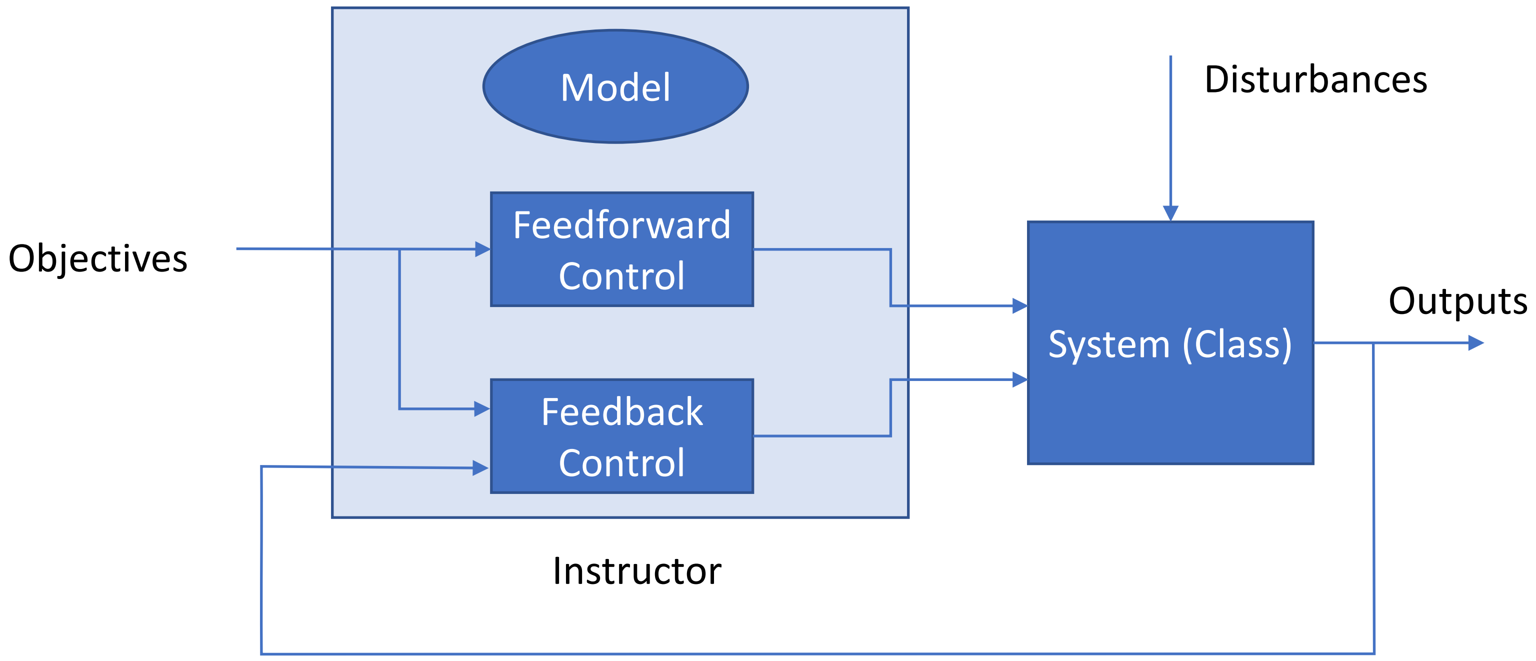


[Process optimization and control hierarchy]

Summary

- Control science and engineering is an essential discipline for complex engineered systems
- But at its core control isn't the combination of its mathematical tools; it is its rigorous, systems-oriented mindset
- The relevance of control goes beyond engineered systems to decision making in all complex dynamical systems—including business organizations, societies, and the planetary ecosystem!
- Control science provides key insights for managing such systems that are based on rigorously founded principles and theory
- A few insights have been suggested in this presentation; many more remain to be developed

Examples from my world – teaching a course



Objectives: Make students learn about the topic , enhance their interest in the topic, get high evaluations, . . .

Feedforward actions: Syllabus, pre-course messages

Feedback actions: Lectures, assignment grades/ comments, responses to individuals and groups

Outputs: Submitted assignments, class observations, student comments

States: Students' understanding of the material (instructor must estimate from outputs)

Disturbances: Snow day? Instructor misses class? Pandemic disruption?

Mental Model(s):
- Students' backgrounds and abilities
- Instructor's self-awareness of his abilities

An instructor’s decision-making process

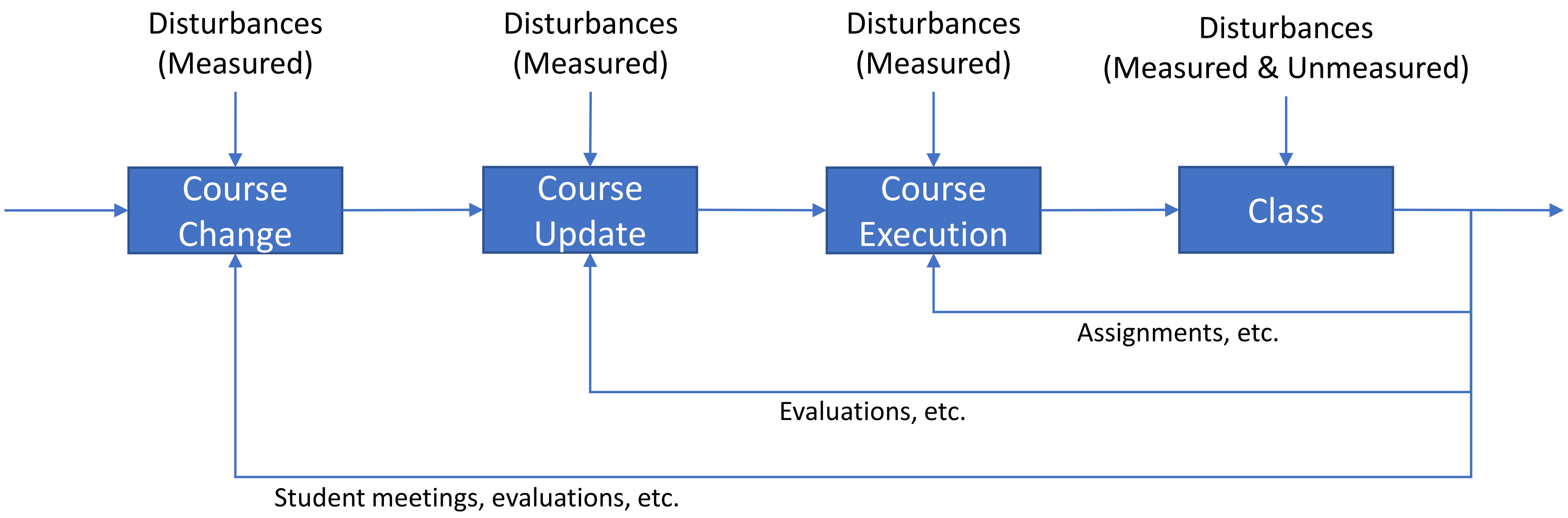
It’s interesting to consider how an instructor might go about his decision-making. In preparing his lecture he has to think about what he knows/believes about the class (his models of them), his effectiveness as a teacher, instructional options available, and, based on this and more, decide what and how to teach.

As he gains more feedback during the course, he will update his models… he’ll understand better what the students’ backgrounds/capabilities/interests/etc. are. As a result, if his model updates and lecture preparation approach are appropriate, the effectiveness of his teaching should improve.

But the converse is also possible… the instructor may misjudge the class and/or misinterpret their feedback. If he is led to believe that the class has more (less) background than it has, his lectures could be too advanced (respectively, too simple).

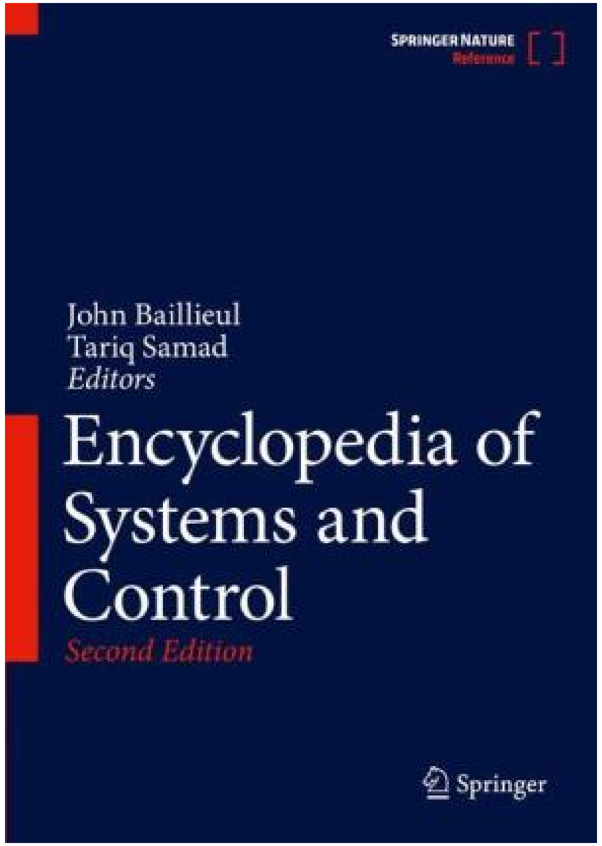
Instructors also have to think about reacting to disturbances, and potential disturbances: One approach would be to increase the “slack” in the course schedule, so that “make-up” time is available. Of course, there is a negative side to this too, in that the schedule would involve covering less material. This is an example of the “robustness versus performance” opposition—which side of the opposition to emphasize would depend (among other things) on the likelihood of disturbances. In any case, not all disturbances are predictable (cf. the pandemic).

Examples from my world – directing a program



A more functional view . . . Note time-scale separation

Control Systems: A Comprehensive Resource (3 vols.)

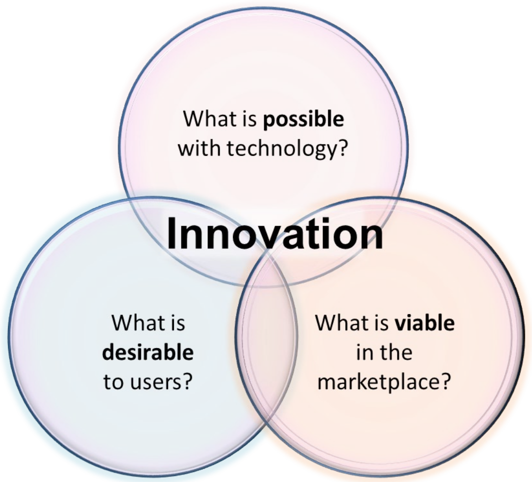


Technological Leadership Institute

https://cse.umn.edu/tli

- TLI was established in 1987 with an endowment from the Honeywell Foundation
- Part of the College of Science & Engineering at UMN
- Mission: To develop local and global leaders for technology-intensive companies
- M.S. in the Management of Technology – the first MOT program in a public university, second in the nation
- Professional education and thought leadership – innovation, emerging technologies, societal imperatives

M.S. in the Management of Technology (MOT)



How will we translate technical ideas into customer solutions that generate societal and economic value?

"The University of Minnesota's MOT program has provided a roadmap to success in the modern business environment, which has become infused with technology. The last two years have been an incredible journey, providing lifetimes of knowledge directly from people who experienced it, including brilliant professors from diverse backgrounds, world-class guest speakers, on-site experiences with lead executives at their businesses, and a cohort of amazing professionals." (MOT-20 graduate)

MOT highlights . . .

- Innovation in products, systems, solutions, and services across diverse markets and sectors
- Tools and processes for managing technology, business, and policy
- Students undertake capstone projects that provide immediate return on investment
- International residency (two weeks)

Sign up for an info session!
https://cse.umn.edu/tli/ms-management-technology

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