

# SYSTEM DYNAMICS: SYSTEMS THINKING AND MODELING FOR A COMPLEX WORLD

IAP 2020 SESSION – JANUARY 13, 2020



James Paine  
System Dynamics Group  
MIT Sloan School of Management

# Plan for Today

## 01 Welcome!

- *Grab some food!*
- *Introduction to the SD Group at MIT*

## 02 Overview of Systems Thinking

- *What is 'System Dynamics'?*
- *What is 'Systems Thinking'?*
- *Tools of the trade and key concepts*

## 03 Hands on! Fishbanks Simulation

- *Teams of 4 (+/- 1)*
- *One laptop per team needed*

## 04 Debrief and wrapup

- *Fishbanks debrief*
- *Tying it into Systems Thinking*
- *Other SD resources at MIT*



# About Me



## James Paine

- MIT Sloan School of Management
- System Dynamics Group, emphasis on Behavioral Operations Management

## Background

- B.S. Chemical Engineering (UF)
- M.S. Mechanical Engineering (Ga Tech)
- MBA Operations Management and Marketing (WFU)
- Worked for  $\approx 10$  years in GE-Hitachi (nuclear engineering), Inmar (reverse logistics and continuous improvement), HanesBrands (product marketing)

## Research Interests

- Product development (and failure)
- Supply chain management and cost mitigation via behavioral modeling (BOM)
- Managerial decision making in non-optimal environments

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# System Dynamics Group at MIT

<https://mitsloan.mit.edu/faculty/academic-groups/system-dynamics/about-us>



John Sterman

Jay W. Forrester  
Professor of  
Management



Nelson Repenning

School of Management  
Distinguished Professor of  
System Dynamics and  
Organization Studies



Hazhir Rahmandad

Mitsubishi Career  
Development Professor  
and Associate Professor of  
System Dynamics



David Keith

Assistant Professor of  
System Dynamics

# System Dynamics Group at MIT

<https://mitsloan.mit.edu/phd/students/current-phd-students>



Mahdi Hashemian  
B.S. Electrical Engineering;  
M.S. Management



James Houghton  
S.B. Aeronautics and  
Astronautics



Tianyi Li  
B.S. Geophysics; B.S. Applied  
Mathematics; M.A.  
Geosciences



Tse-Yang Lim  
B.S. Biology; Master of  
Environmental Management



Jose Luis Lopez  
B.S. University of Costa Rica;  
INCAE Business School, M.B.A.



James Paine  
B.S. Chemical Engineering;  
M.S. Mechanical  
Engineering; M.B.A.



Jad Sassine  
M.S. Applied Mathematics

# System Dynamics Group at MIT

## A (very) brief history



"Everything I have ever done has converged to become system dynamics."

-Jay W. Forrester

*at the 1989 International meeting of the System Dynamics Society*

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## MIT-originated field

Created by Dr. Jay Forrester in the mid-1950's while at MIT

First formalized in 1958 with "Industrial Dynamics - A Major Breakthrough for Decision Makers"

## Origins in control theory

Dr. Forrester had background in EE and pioneer in early digital computers. Inventor of Random Access Memory while working on MIT's WHIRLWIND I general purpose digital computer

Came to understand that social systems are much harder to control than physical systems, and often source of difficulties faced in projects

First major application was stock-flow-feedback structure of GE appliance plant three-year employment cycle, refined ideas of System Dynamics

Broadened beyond corporate management throughout 60's and 70's, including resource management such as WORLD2 simulation for Club of Rome

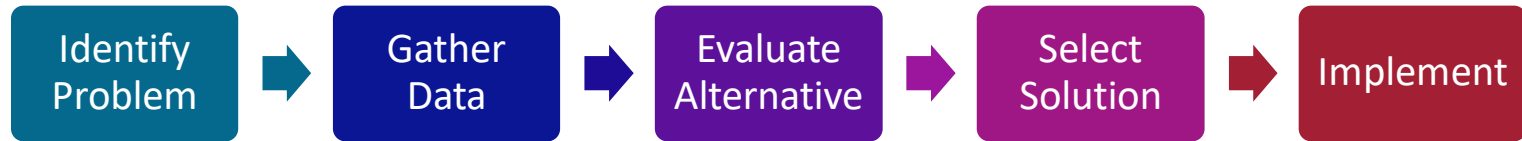
Evolved beyond methodology to thinking framework with applications in numerous fields



# OVERVIEW OF SYSTEM DYNAMICS AND SYSTEMS THINKING

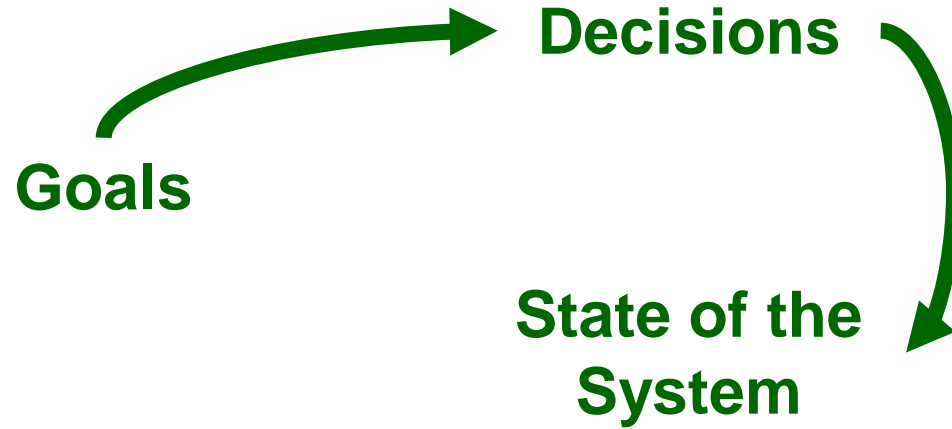
\*Portions of the following overview slides are modified from source material by Drs. John Sterman, Hazhir Rahmandad, and Robert Nachtrieb

# Open Loop Thinking

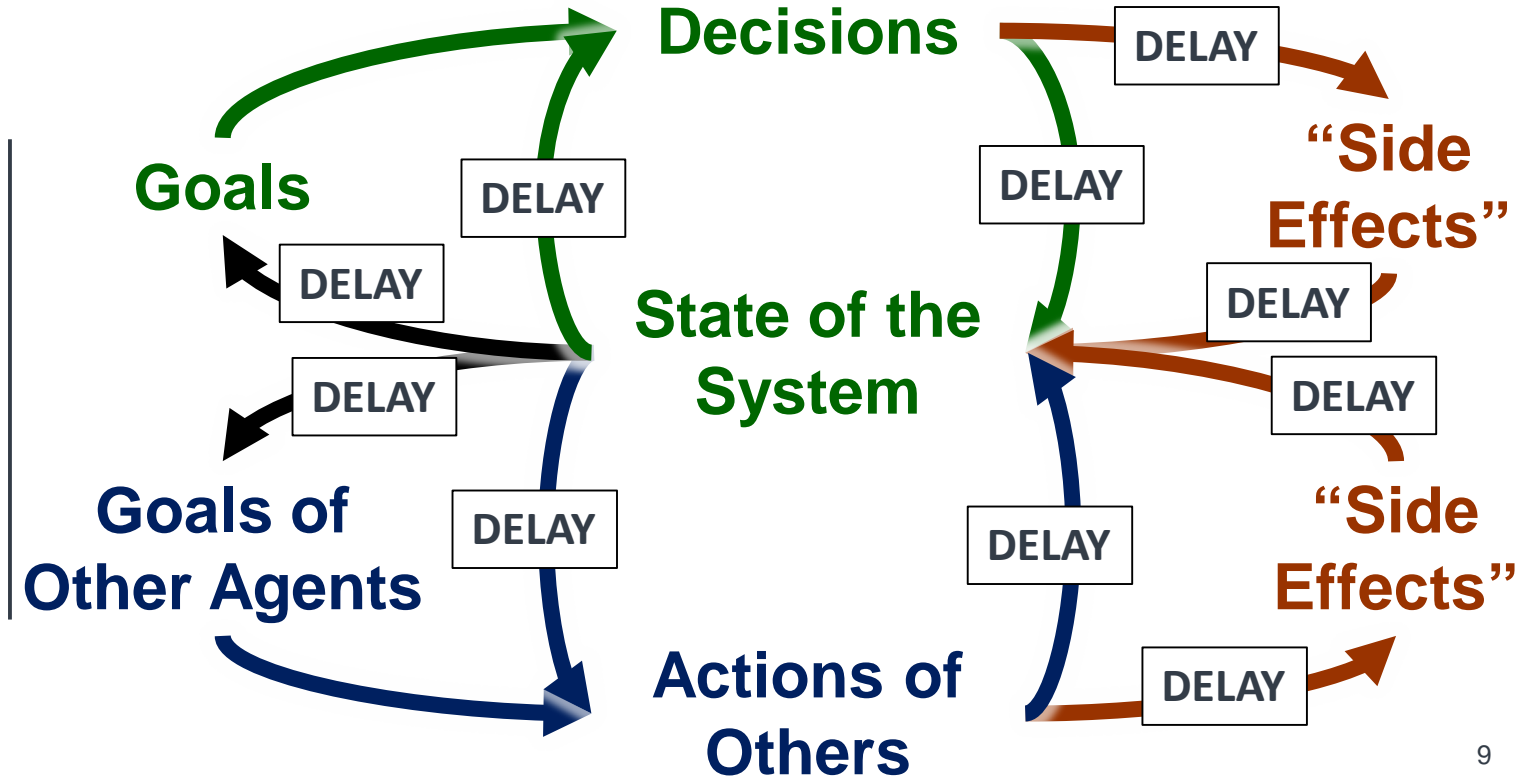




# Open Loop Thinking



# We are embedded in a larger system



# Systems Thinking Foundations

## What is a System?

A system is a set of interdependent parts sharing a common purpose.

The performance of the whole is affected by each and every one of its parts.

## Social and Economic Systems

Are highly complex systems:

- Dynamic
- Tightly coupled
- Governed by feedback
- Nonlinear
- Limited Information
- Ambiguity and delays in cause and effect

...and are typically more complex than human-made, physical systems.



# Systems Thinking and System Dynamics

...is not only tools and but rather framework to help 'close the loops' and:

Elicit and articulate mental models and impact of social and organizational structure

Expand mental models by explicitly accounting for feedback

Test and improve mental models and structure via simulation

Develop shared mental models and more effective organizations

The simulation's purpose is not to 'be right' but rather to help improve mental models and identify high leverage policy choices



# Systems Thinking Foundations

Structure Generates Behavior  
Dynamics emerge from the interaction of:

- Physics
- Information availability
- Decision rules

Mental Models Matter (a lot!)

It's not enough to change the physical structure, information, and incentives.

The Fundamental Attribution Error

Our first instinct is to blame the people in the system. Almost always this is a low-leverage response



# Breaking Away from the Fundamental Attribution Error

THE BASIC ASSUMPTION:  
We believe that everyone  
in this community is  
intelligent<sup>and</sup> capable, cares  
about doing their best,  
acts with integrity, and  
wants to learn.



# Structure Generates Behavior



**VISIBILITY**



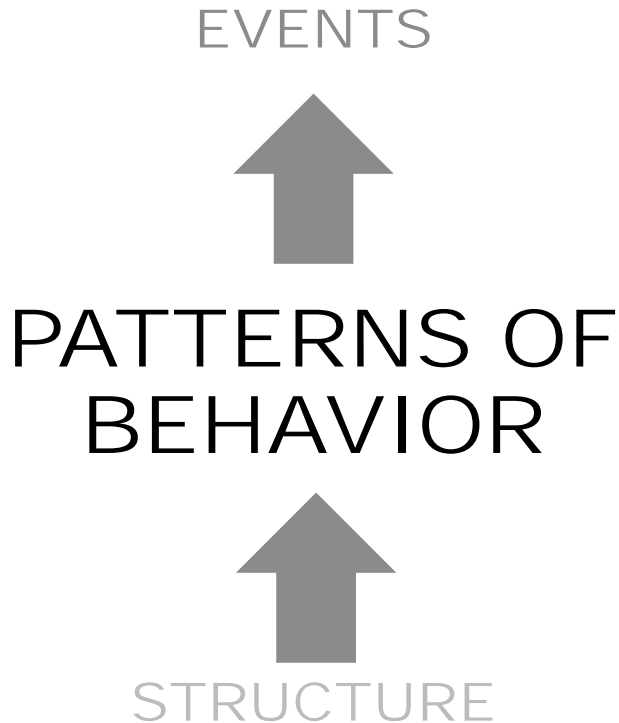
# Structure Generates Behavior



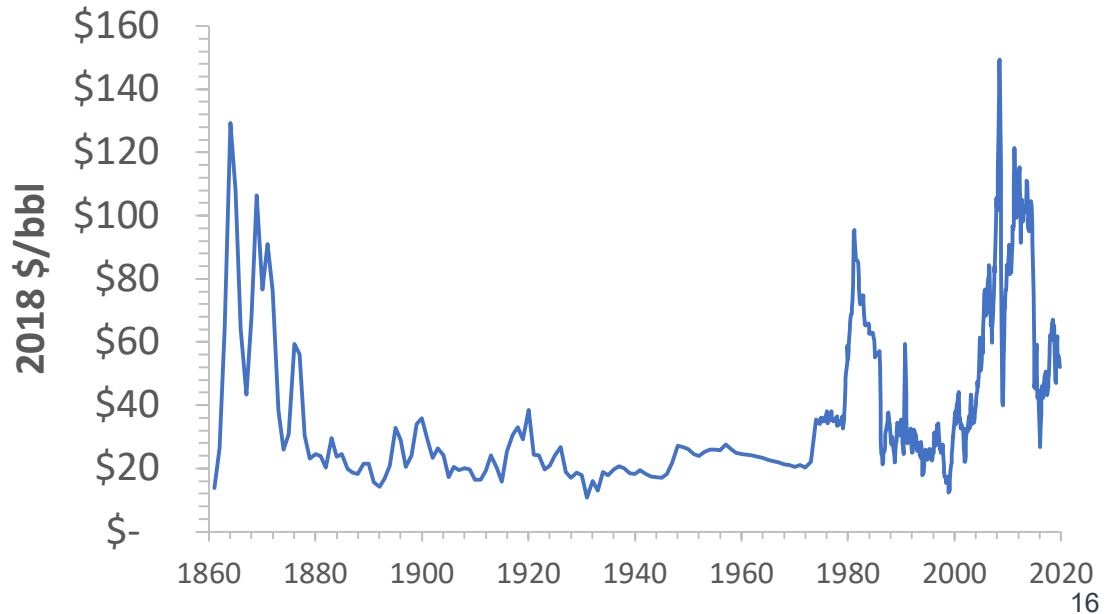
- “Drunk trader caused a spike in oil prices” (NY Post, 2012)
- “Oil prices keep falling — this is why” (Washington Post, 12/21/15)
- “OPEC Rumors Continue To Pull Oil Prices Higher” (Oil Price, Aug 2016)
- “Trump slams OPEC for high oil prices” (Fortune, 4/20/18)
- “Another Sign of Economic Worry: Tumbling Oil Prices” (NYT, 6/5/19)
- “Oil prices surge after tanker attack in Gulf of Oman” (CNN, 6/13/19)



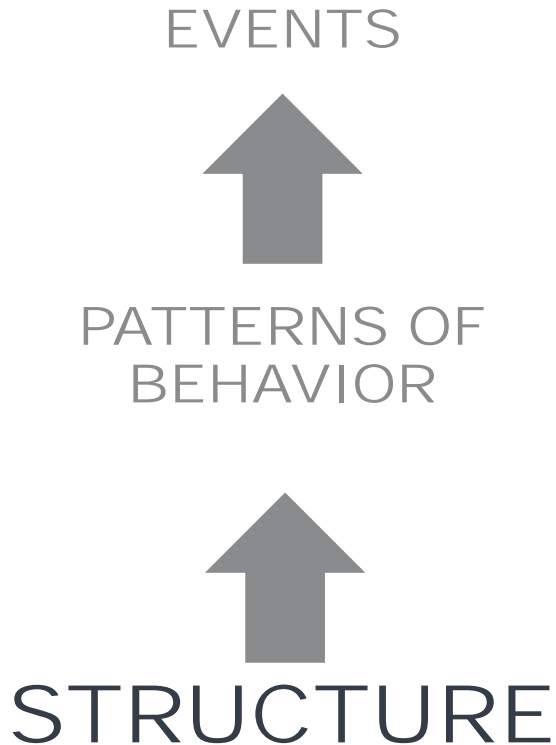
# Structure Generates Behavior



- **Chronic boom and bust cycles**
- **Real Prices rising on average**



# Structure Generates Behavior



- **Physical structure:**
  - Stocks and flows
  - Material delays
  - Feedback processes
- **Information availability**
  - Delays, biases, error, gaps
  - Access & transparency
- **Mental Models**
  - Actor goals and incentives
  - Time horizon, model boundary
  - Misperceptions of feedback

# (Some) Barriers to Learning in Dynamic Complexity

Dynamic Complexity

Limited Information

Confounding variables and Ambiguity

Bounded Rationality and Misperceptions of Feedback

Flawed Mental Models

Erroneous Inferences about Dynamics

Judgmental Errors and Biases

Defensive Routines and Interpersonal Impediments to Learning

Implementation Failure



'SYSTEM DYNAMICS' IS  
REALLY APPLIED 'SYSTEMS  
THINKING'





# (SOME) TOOLS OF SYSTEM DYNAMICS

# Tools and Methods

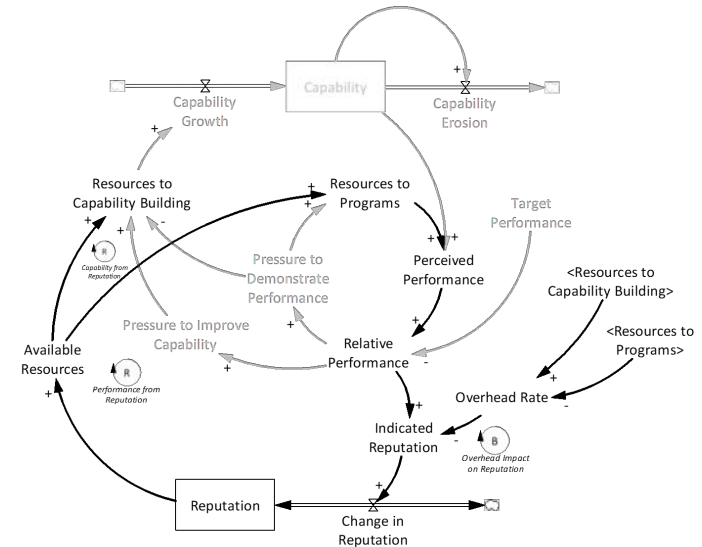
System Thinking and Modeling is Iterative

Spiral approach, and multiple tools available

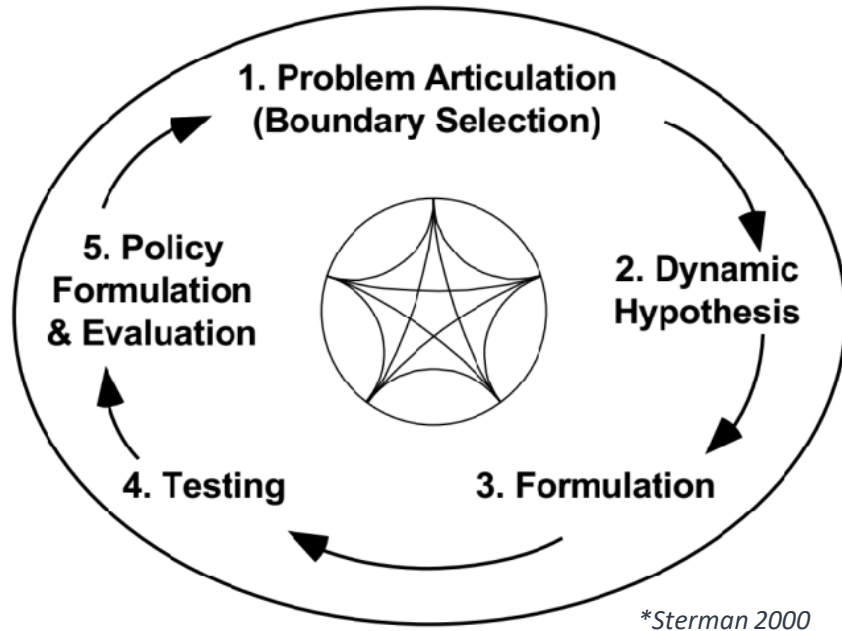
System Dynamics is NOT just compartmental models

System Dynamics practitioners use many modeling and simulation toolsets test the implications of hypothesized causal relationships

All Models are Wrong: But some models are useful!



# Tools in the Spiral Approach to Model Formulation

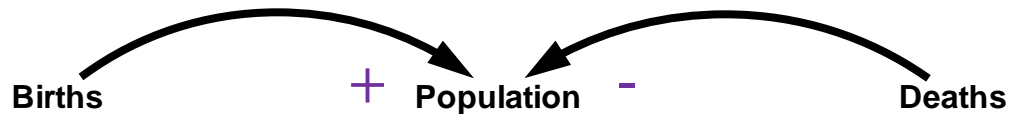
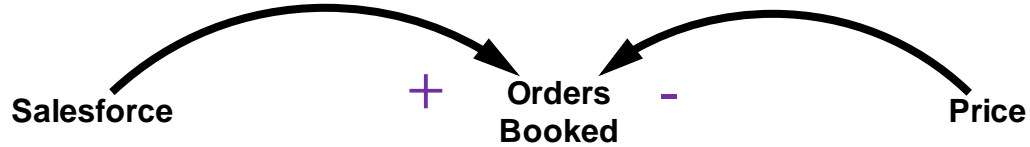
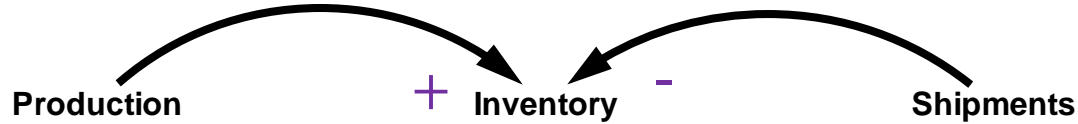


- Reference Modes
- Causal Loop Diagrams
- Stock and Flows
- Equation Formulation
- Dimensional Analysis
- Simulation
- Sensitive Analysis
- Policy Testing



Results of any step can yield insights affecting other steps 22

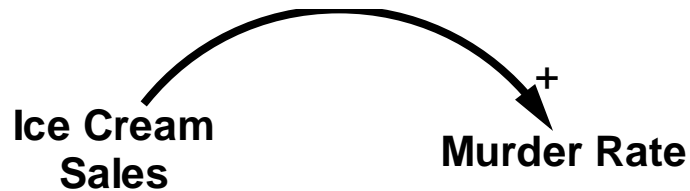
# Systems Thinking Tools: Causal Links



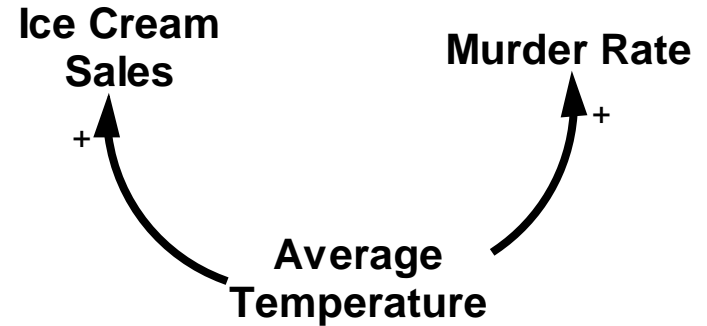


# Systems Thinking Tools: Causal Links

Incorrect!



Correct



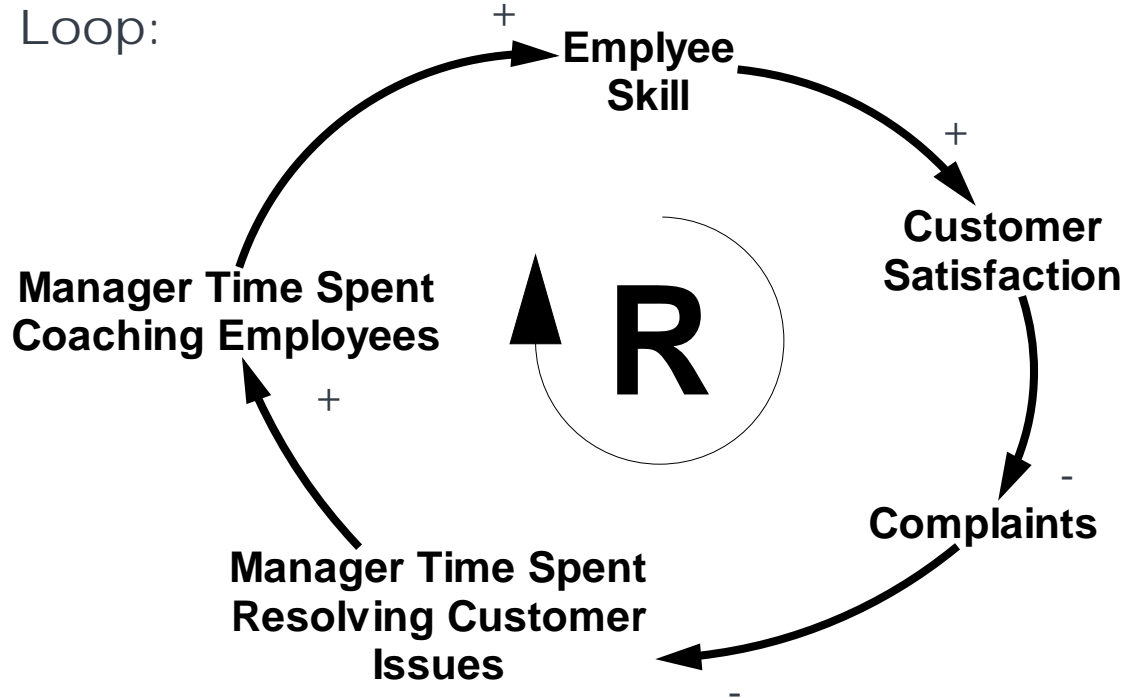
Just for fun:

<https://www.tylervigen.com/spurious-correlations>



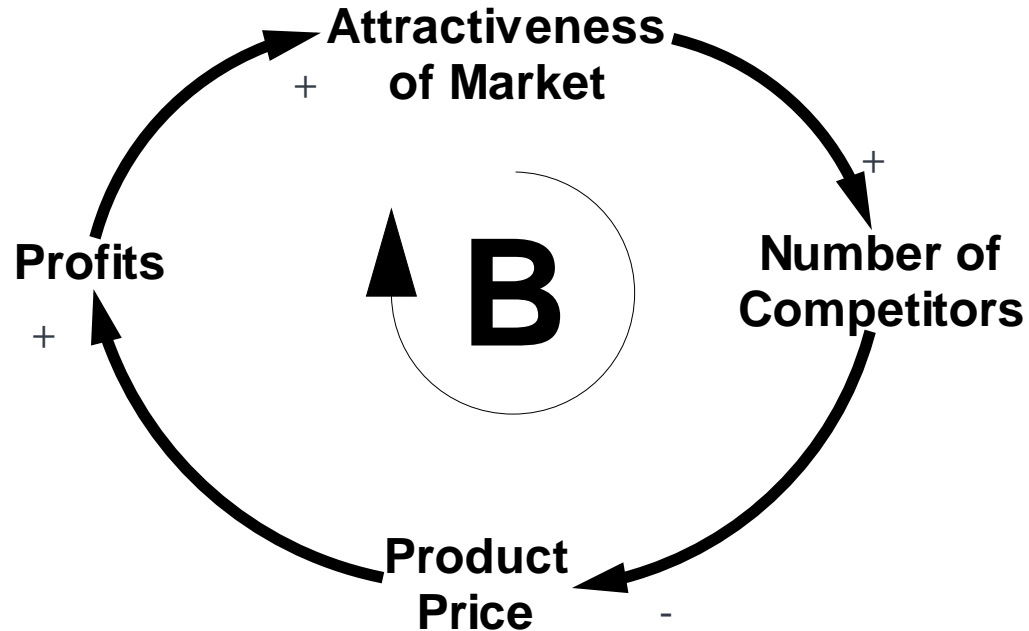
# Systems Thinking Tools: Loops

Reinforcing Loop:



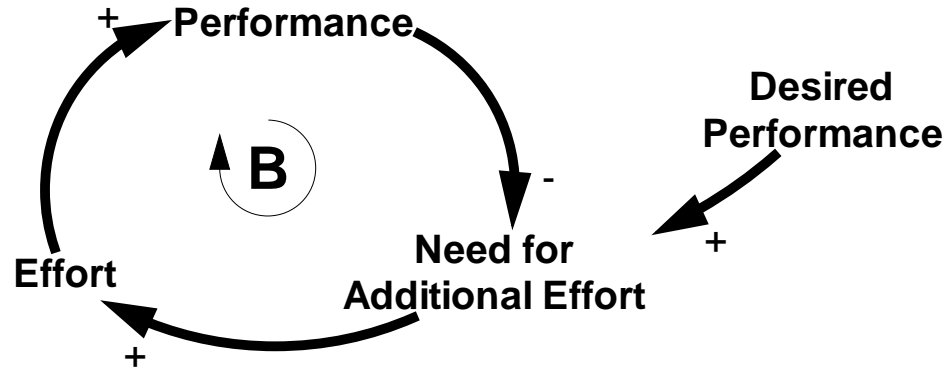
# Systems Thinking Tools: Loops

Balancing Loop:



# Systems Thinking Tools: Loops

Balancing Loops also called Goal Seeking Loops



Loop Polarity

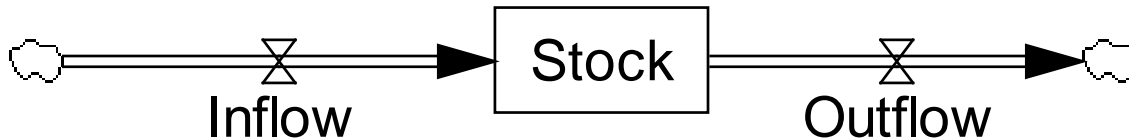
Right Way: Trace Effect of a Change Around the Loop

Quick Way: Count the '-' connections



# Systems Thinking Tools: Stock and Flows

Stock and Flow Diagram (Compartmental Model)



Integral Representation

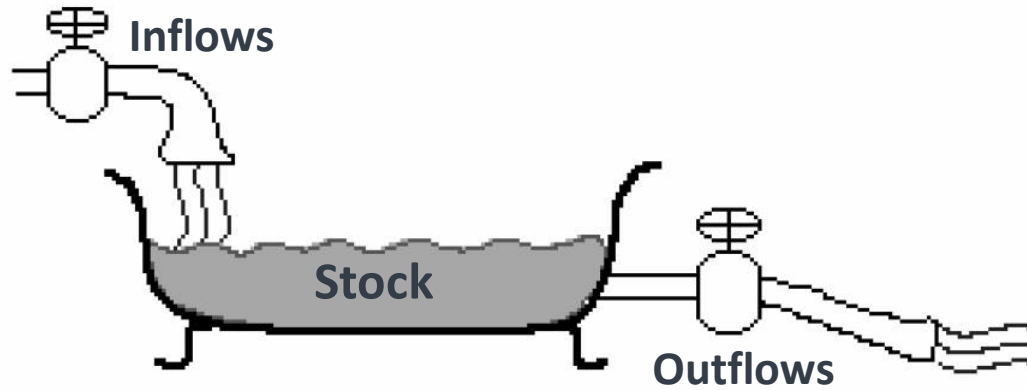
$$Stock(t) = \int_{t_0}^t [Inflow(s) - Outflow(s)] ds + Stock(t_0)$$

Differential Representation

$$\frac{d}{dt} Stock = Inflow(t) - Outflow(t) = Net\ Change\ in\ Stock(t)$$

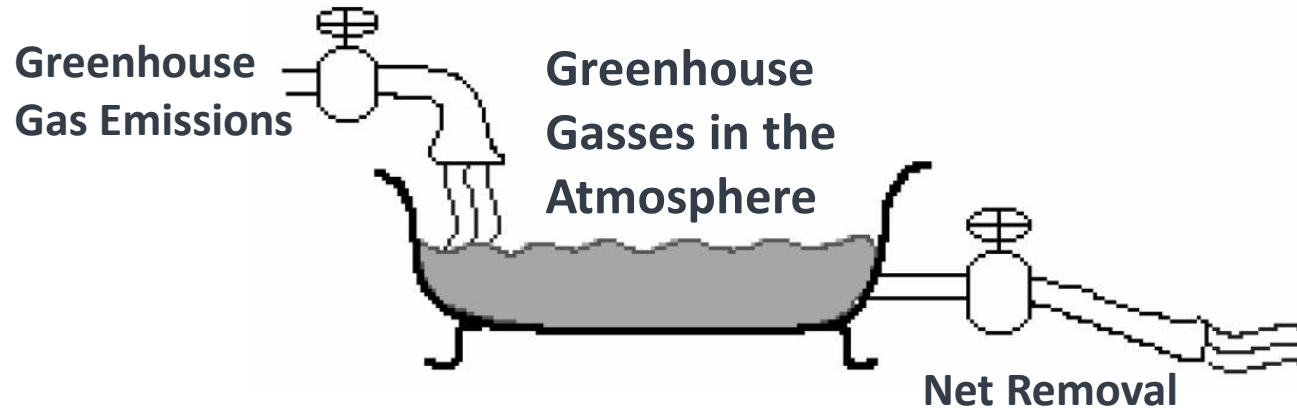
# Systems Thinking Tools: Stock and Flows

## Hydraulic Metaphor



# Systems Thinking Tools: Stock and Flows

## Hydraulic Metaphor



# Systems Thinking Tools: Stock and Flows

## Stocks

Balance Sheet

Wealth

Product preorders

Accounts Payable

CO<sub>2</sub> in Atmosphere

Integrals

Water in a bathtub

## Flows

Cash Flow Statement

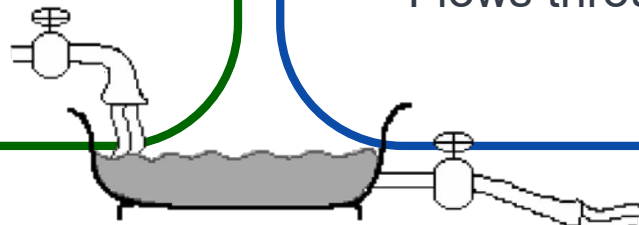
Income and Expenditures

CO<sub>2</sub> Emissions

Vehicle Production

Derivatives

Flows through faucet and drain





A black and white photograph of the MIT Sloan School of Management building. The building is a large, multi-story structure with many windows. In the foreground, there is a stone wall with the text "MIT SLOAN SCHOOL OF MANAGEMENT" engraved on it. A person is walking in the foreground, blurred. A large red rectangular overlay covers the right side of the image, containing the text "HANDS-ON MANAGEMENT FLIGHT SIMULATOR" in white capital letters.

# HANDS-ON MANAGEMENT FLIGHT SIMULATOR



# Fishbanks

James Paine

System Dynamics Group

MIT Sloan School of Management

*\*Briefing and debriefing borrowed heavily from Dr. Hazhir Rahmandad and Dr. John Sterman*

A black and white photograph of the MIT Sloan School of Management building. The building is a large, multi-story structure with a grid of windows. In the foreground, there is a stone wall with the text "MIT SLOAN SCHOOL OF MANAGEMENT" engraved on it. A person is walking past the wall, blurred due to motion. A large red semi-transparent rectangle is overlaid on the right side of the image, containing the text "OTHER SYSTEM DYNAMICS RESOURCES" in white capital letters.

# OTHER SYSTEM DYNAMICS RESOURCES



# Want more?

Classes at MIT

15.871- Introduction to System Dynamics

15.873 - System Dynamics for Business and Policy



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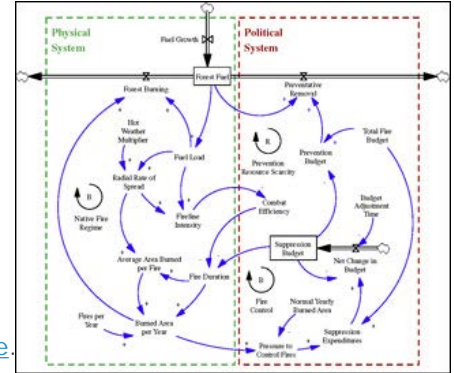
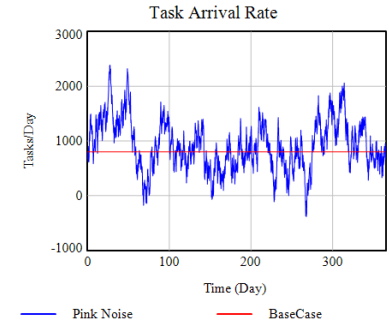
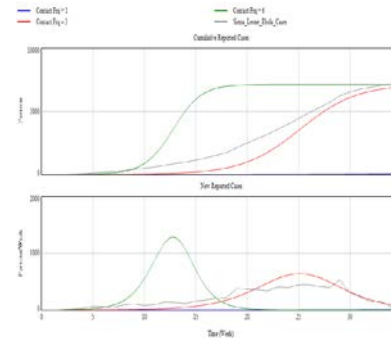
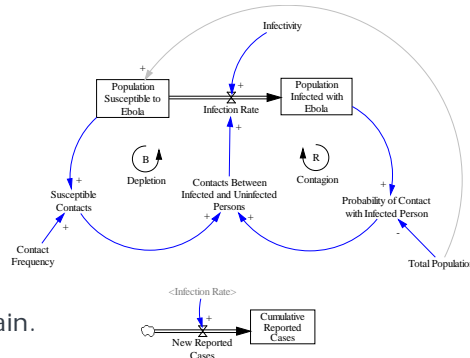
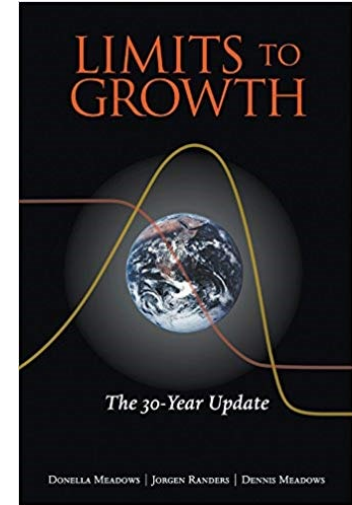
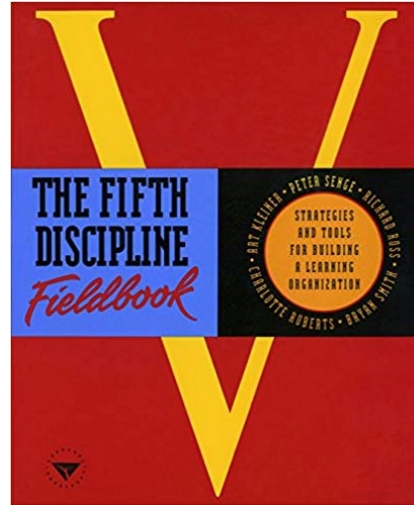
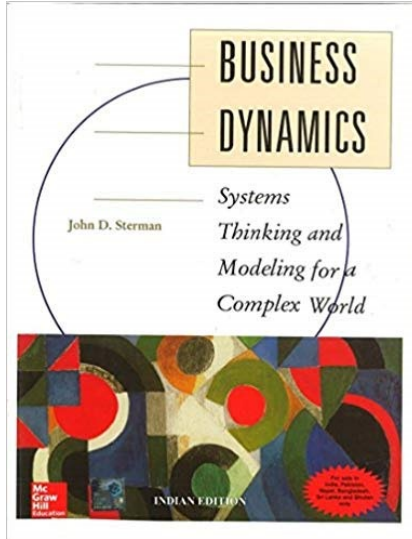


Image of the *Vasa* is in the public domain. Source: Wikimedia Commons.



# Want more?

## Books



- Sterman, J. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. McGraw-Hill / Irwin, 2000. ISBN: 9780072389159
- Senge, P. *The Fifth Discipline Fieldbook: Strategies and Tools for Building a Learning Organization*. New York, NY: Currency Publishers, 1994. ISBN: 0385472560
- Meadows, D., J. Randers, and D. Meadows. *Limits to Growth: The 30-Year Update*. Dennis Meadows, 2004. ISBN: 193149858X

**All are in the MIT Library!**

# Want more?

## Articles (personal favorites):

System Dynamics at Sixty: The Path Forward

Selling System Dynamics to (other) Social Scientists

Making the Numbers? “Short Termism” and the Puzzle of Only Occasional Disaster

Nobody ever gets credit for fixing problems that never happened: Creating and sustaining process improvement

Capability Traps and Self-Confirming Attribution Errors in the Dynamics of Process Improvement.

**All are free when accessing from MIT's network!**

<https://sdjournalclub.mit.edu/sites/default/files/documents/Sys%20Dyn%20Reading%20List.xls>

**INTRODUCTION**  
**System dynamics at sixty: the path forward**  
John D. Sterman

**The challenge**  
The field of system dynamics is going for the big one: Formos, in 2010. The 50th anniversary just this month commemorates the many important contributions made over the 50th anniversary, expanding the system dynamics network. Dynamics (Lanchester multiple times) (Ford, 2011) (McCardle, 2010) et al. of system dynamics and open systems, along with applications (eg. (Thames and Thompson, 2010) (Thames et al., 2010) (Garcia, 2010), and (eg. (Muller, 2010)).

Despite these advances, we in business circles. On the one hand, what used to drive some to be... (Continuation of the text is partially obscured)

**FIGURE 5. The Strategic Learning Loop**

g2g only because capability does not change immediately when the time dedicated to learning and improvement declines.

To illustrate these dynamics, Figure 6 shows two simulations of the model in which we show how a hypothetical process starts in working harder versus working smarter. Both simulations begin in the same equilibrium state. The first simulation shows the response to an increased emphasis on working harder. As more effort is dedicated to work, gross throughput immediately rises. Time spent improving falls immediately, but capability does not. Performance declines over time. The trade-off of working harder to however short-lived. With too little devoted to improvement, capability gradually erodes, eventually more than offsetting the increased time spent working. Working harder creates a "before-better" situation. Conversely, as seen in the second simulation, increasing the time spent on improvement reduces output in the short run. Eventually, however, capability rises more than enough to offset the drop in work effort and performance is permanently higher, a "worse-before-better" dynamic.

The interaction between the balancing (through long and the reinforcing (through short) loop creates a phenomenon we call the Capability Trap and helps explain why organizations often find themselves stuck in a vicious cycle of degrading capability. Managers and workers in need of an immediate performance

# Want more?

## Websites (personal favorites):

Creative Learning Exchange

<http://www.clexchange.org/>

Tom Fiddaman's MetaSD

<https://metasd.com/model-library/>

MIT OCW System Dynamics Self Study

<https://ocw.mit.edu/courses/sloan-school-of-management/15-988-system-dynamics-self-study-fall-1998-spring-1999/>

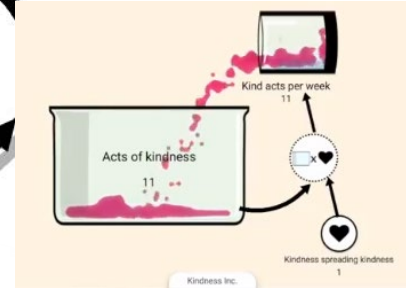
MIT System Dynamics Journal Club

<http://sdjournalclub.mit.edu/>

The System Dynamics Society

<https://www.systemdynamics.org/what-is-sd>

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### Model Library

This library contains replications of many classic models from system dynamics. Citations are provided. Unfortunately I don't know of online resources for classic SD publications are available through [Leverage Networks](#) and [Amazon](#).

Many of the models in this library were recreated from published works in MIT School's PhD Seminar in System Dynamics. Where credit is unclear, it goes to Scott Rockart, Nelson Repenning, Ed Anderson, Liz Krahnert, and others. For the arduous process of reconstructing these models from publications, most of these models are replications, it's possible that they contain errors.



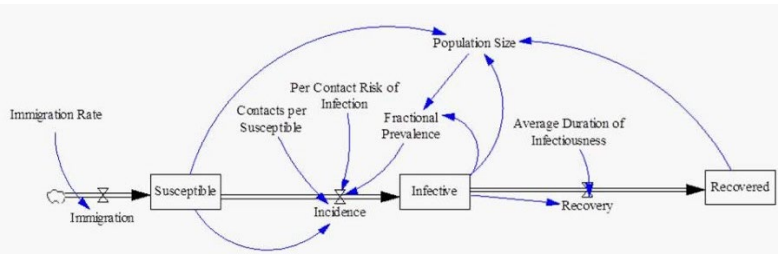
### System Dynamics Self Study

A screenshot of the MITSD System Dynamics Self Study website interface. It shows a navigation menu with links for "COURSE HOME", "SYLLABUS", "READINGS", "ASSIGNMENTS", and "DOWNLOAD COURSE MATERIALS". A central graph displays several curves representing different variables over time. The legend indicates: "Heroin stock" (orange), "Number of drug users" (green), "Prior" (purple), and "Revenue-making crime" (red). The graph shows a peak in revenue-making crime followed by a decline, and a corresponding increase in the number of drug users. The website is credited to "Instructor: Prof. Jay Foray" and "MIT Course 15.988". It also mentions "As Taught: Fall 1998 - Spring 1999" and "Level: Graduate".

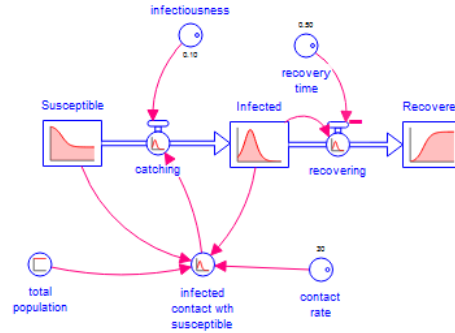


# (Some) Software

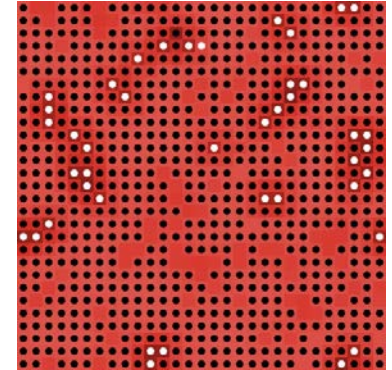
# Vensim



Vensim



Stella Architect



NetLogo



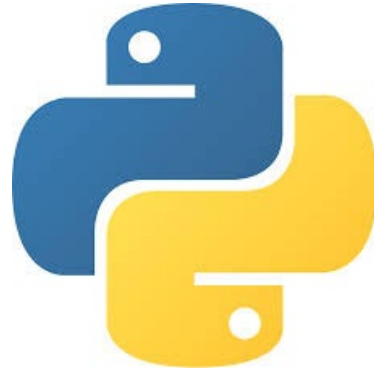
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# (Some more) Software



[R Language](#)



[Python](#)



[Mathematica](#)



**MATLAB**  
[MATLAB](#)



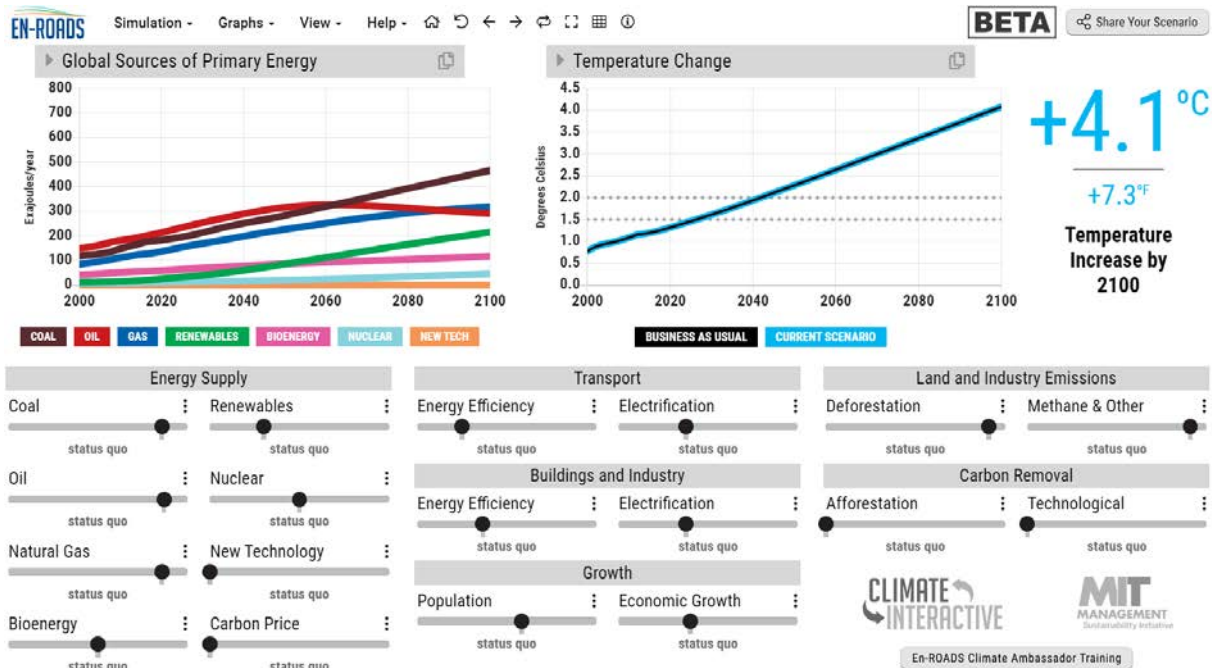
[TensorFlow](#)



# System Dynamics in Action

## En-Roads Climate Policy Simulator

<https://en-roads.climateinteractive.org/scenario.html?v=2.7.6>



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<https://ocw.mit.edu/>

Systems Thinking and Dynamic Modeling for a Complex World  
IAP 2020

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