System Dynamics (SD) and its Applications

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What is System Dynamics?

- An approach to understanding how systems can generate their own problems
  - An art
  - A set of techniques and tools
  - A set of computer simulation methods
  - A language

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Why system Dynamics?

"In the long history of evolution it has not been necessary until very recent historical times for people to understand complex feedback systems. Evolutionary processes have not given us the mental ability to interpret properly the dynamic behavior of those complex systems in which we are now embedded." *Forrester, 1973*

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Complex systems

"when you are confronted by any complex system, such as an urban center or a hamster, with things about it you are dissatisfied with and anxious to fix, you cannot just step in and set about fixing with much hope of helping. This realization is one of the sore discouragements of this century … You cannot meddle with one part of a complex system from the outside without the almost certain risk of setting off disastrous events that you hadn't counted on in other remote parts. If you want to fix something you are obliged to first understand … the whole system."

Lewis Thomas, 1974

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Policy Resistance

- Counter intuitive behaviour of social systems

  - Jay Forrester

- The best-laid schemes o' mice an' men

  gang aft a-gley -Burns

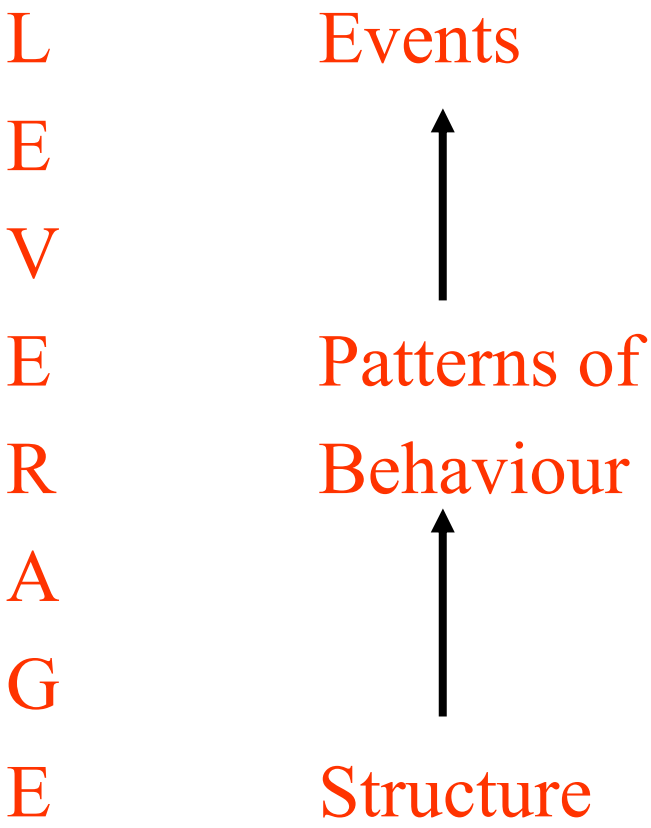
- And it will fall out as in a complication of diseases, that by applying a remedy to one sore, you will provoke another; and that which removes one ill symptom produces another

  -Sir Thomas More

Lessons

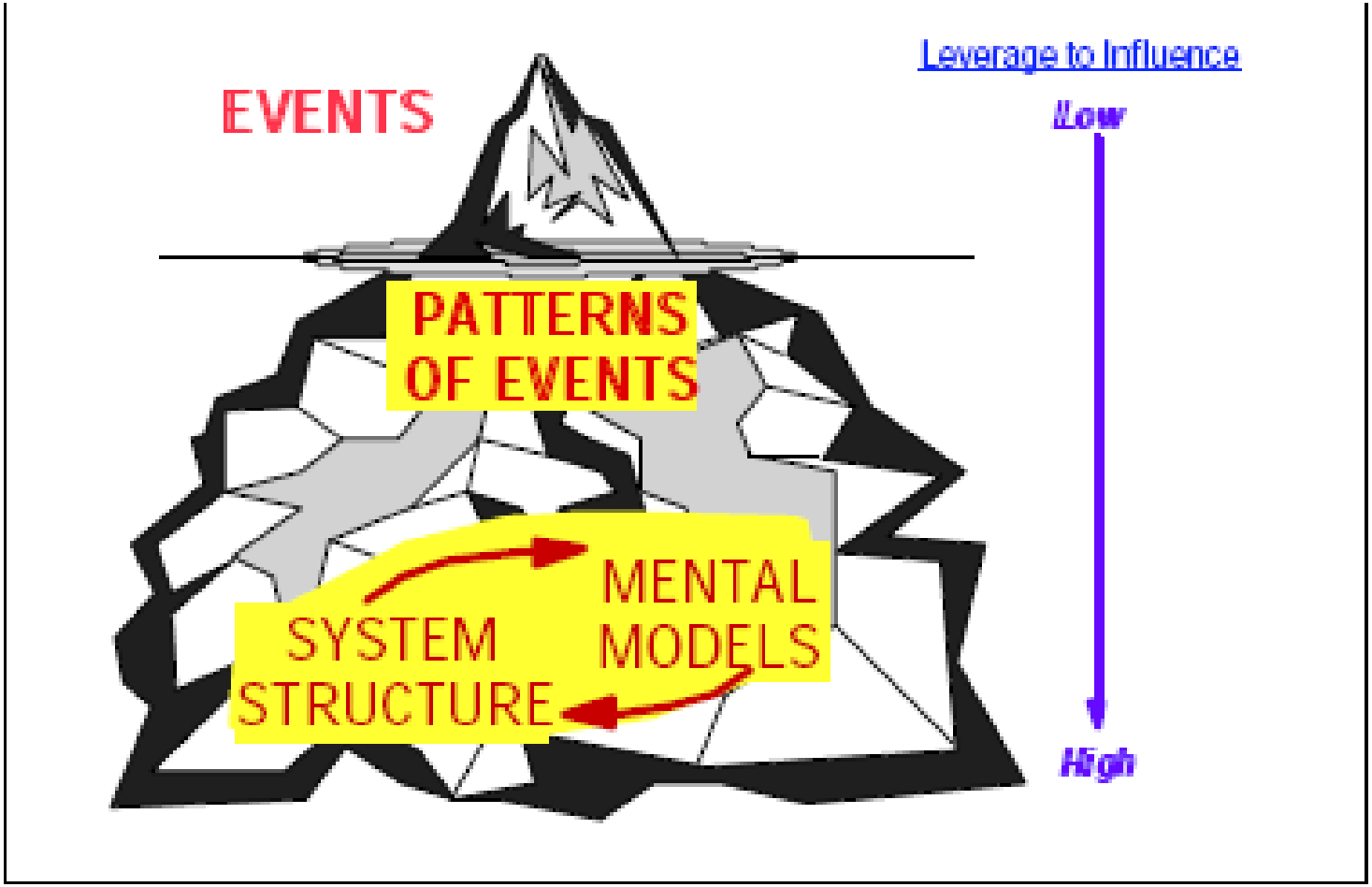
- Structure creates behaviour
- Greatest leverage comes from changing structure.
- Systems thinking helps in structure redesign.
- Cause of problem distant in time and space from symptoms

The Nature of Explanation



Feedback structures generate “Patterns of behaviour”

The Nature of Explanation



Structure

- Interdependent systems (of resources and other pertinent variables)
- Interdependence arise from the feedbacks
- Performance dynamics depends on this interdependence

Archetypes of systems

- Certain patterns of structure recur. These generic structures are "systems archetypes".
  - Archetype systems are sets of reinforcing and balancing feedbacks and delays that are interconnected.
- A relatively small number of these archetypes are common to a large variety of situations.
- The SD approach studies system behavior taking into account the architecture of feedbacks and time delays.
- The environment, represented as a set of stocks (or resources) and activities linked by flows of information and flows of material, submitted to time delays, is a classic object for System Dynamics analysis.

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Why Systems?

- Need for integrative thinking for complex problems in policy and management
- Definition: Collection of individuals or parts that interact with each other to form a whole.
- System behavior may not be predicted by behavior of the individual parts
- System stability: Collection of small systems likely to be more stable than a single large unit

Characteristics of Complex Systems

- **Dynamic** (over many different time scales)
- **Tightly coupled** (actors in system interact strongly)
- **Governed by feedback** (decisions affect state of world)
- **Nonlinear** (basic physics, multiple factors in decisions)
- **History-dependent** (many actions irreversible)
- **Adaptive** (natural selection, learning)
- **Counterintuitive** (cause and effect distant)
- **Policy resistant** (obvious solutions often ineffective)
- **Exhibit tradeoffs** (different LR v SR response)

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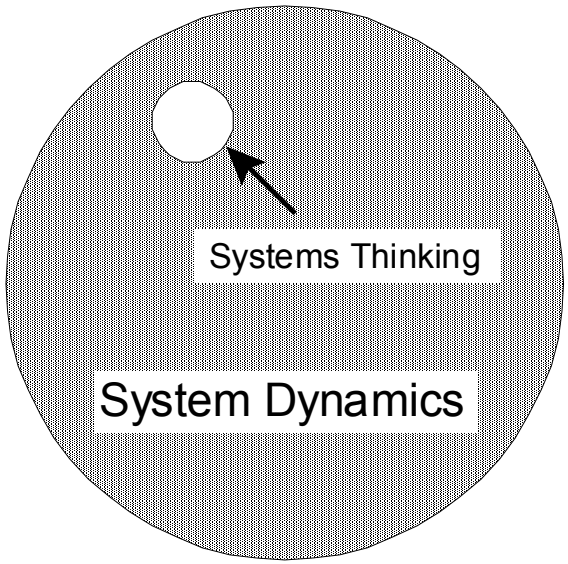
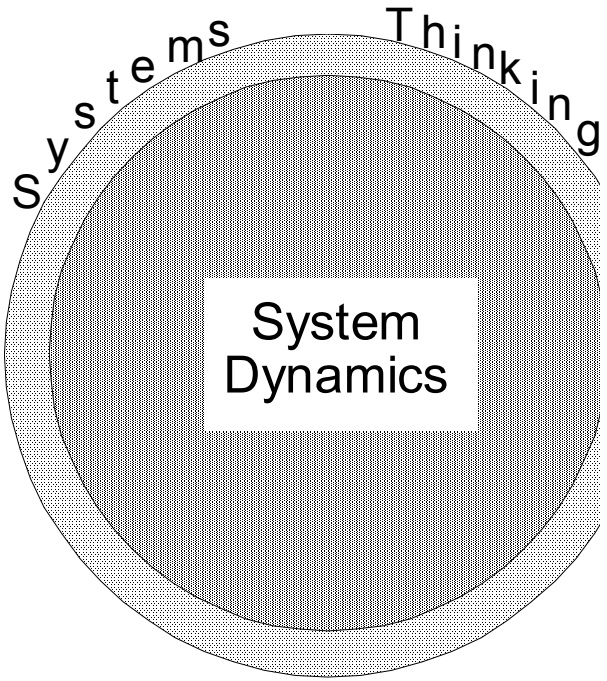
Systems Thinking
vs System Dynamics



Forrester's View of the Relation between System Dynamics and Systems Thinking



Richmond's View of the Relation be System Dynamics and Systems Thi

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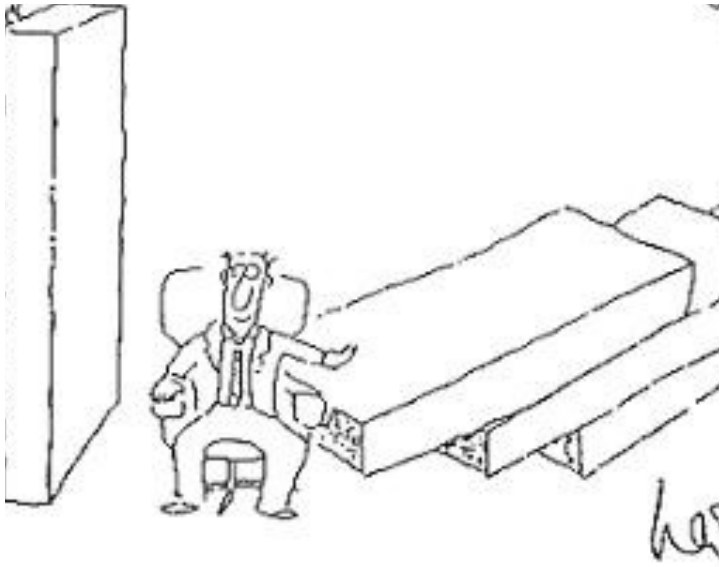
Common Themes?

- Feedback is fundamental to all systems approaches
- Feedback structure often hidden in peculiar notation
- Roots of feedback thinking:
  - **Biological-mathematical Models (Verhulst, Volterra)**
  - **Econometrics (Tinbergen, Samuelson, Hicks)**
  - **Engineering (Watt, Maxwell, Lyapunov)**
  - **Social Sciences (Smith, Ricardo, Hegel, Marx, Keynes)**
  - **Logic (Epimenides, Boole, Cantor, Russell, Whitehead)**

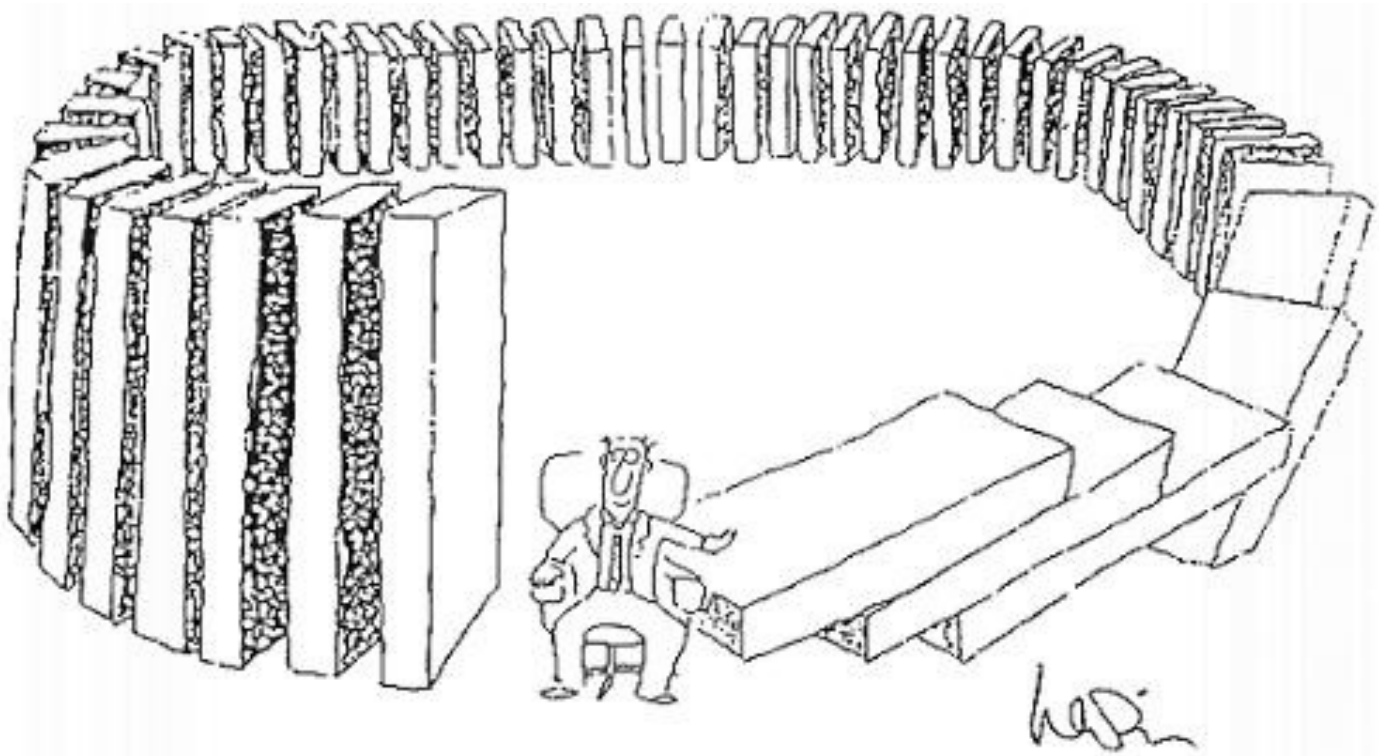
Decision Making



Ignoring (Long Run) Feedback Can Lead to Unintended Consequences

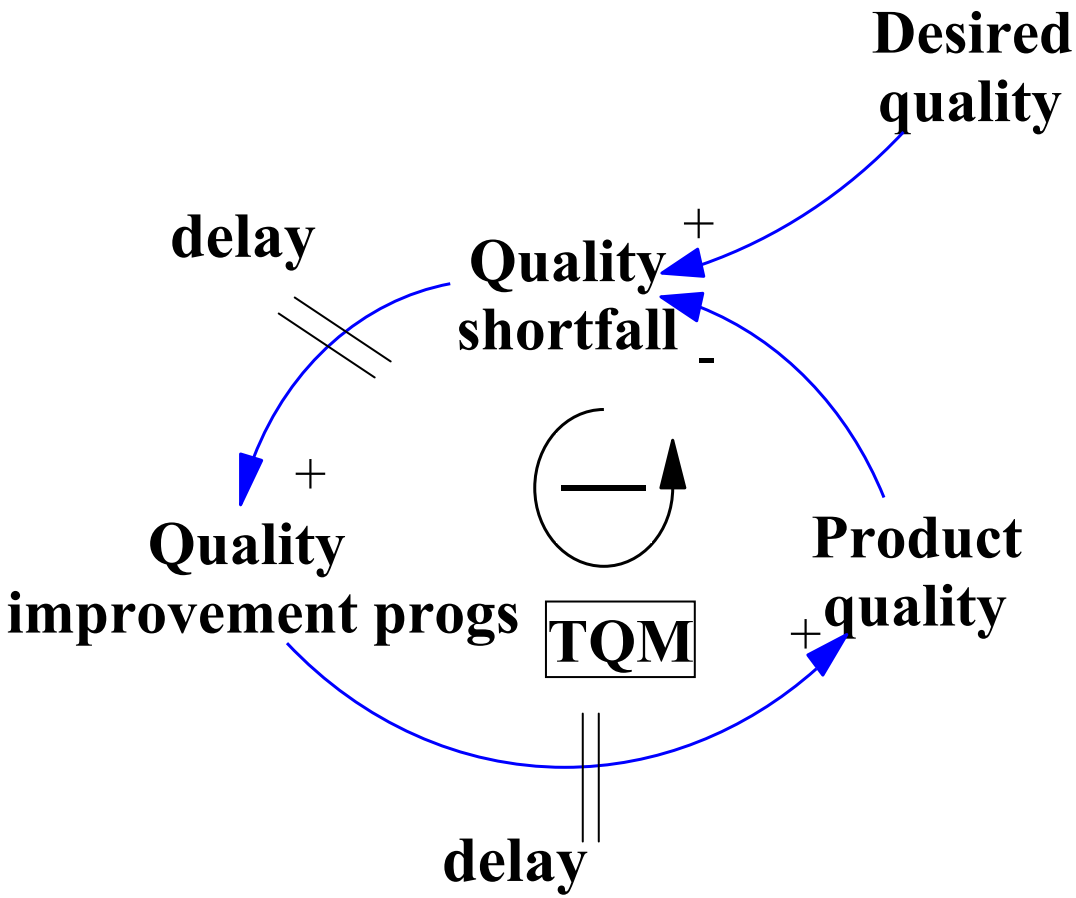
Decisions and Policy Resistance Due to Feedback

Feedback is fundamental to systems approaches



Ignoring (Long Run) Feedback Can Lead to Unintended Consequences

Causal Loop Diagram (CLD) Basics



Draw CLD

Specify causal relations

Specify loop polarity and name loop

Make goals explicit

Make delays explicit

Modeling Process

- Problem Articulation (boundary selection)
  - Problem statement
  - Identify the beneficiary (whose mental model needs to change?)
  - Choose or identify the time horizon
  - Choose key variables (consider all!)
  - Reference or Fundamental Modes
- Mapping (dynamic hypothesis) and feedback loop
- Model Formulation and Construction, levels and rates
- Testing and Validation
- Policy Formulation and Evaluation

Steps in Modelling

- Theme Selection: What is the problem? Why is it a problem?

- Key variables: What are the key variables and concepts we need consider? Agencies? Their actions?

- Dynamic problem definition: What is the historical behaviour of key concepts/variables? What might their behaviour be in future – their trajectories

- Endogenous focus: Try and explain the dynamics as the endogenous consequences of the feedback structure

- Develop maps of causal structure based on hypothesis and key variables.

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Patterns of Behaviour

- **How many “pure”patterns of behaviour are there?**
- **If only a few, then possibly a small number of structures can help us understand a lot.**

Exponential Growth / Collapse

Goal Seeking or Exponential Adjustment

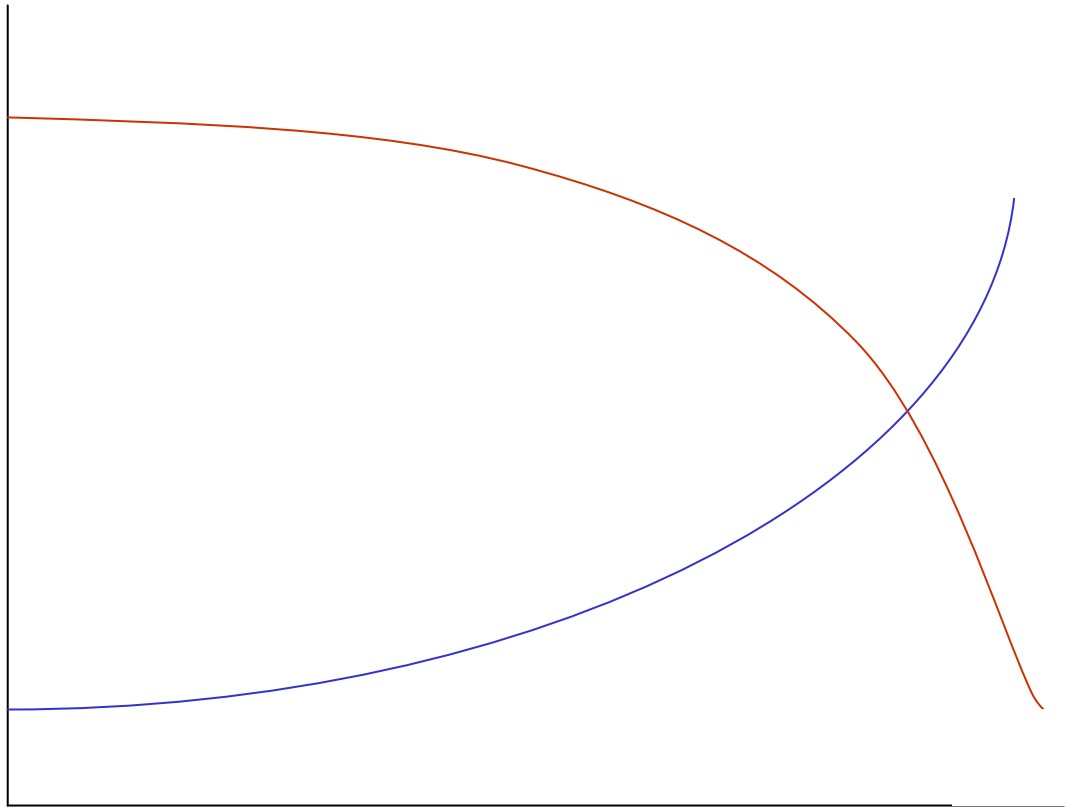
Oscillations

S-Shaped Growth

S-Shaped Growth with overshoot

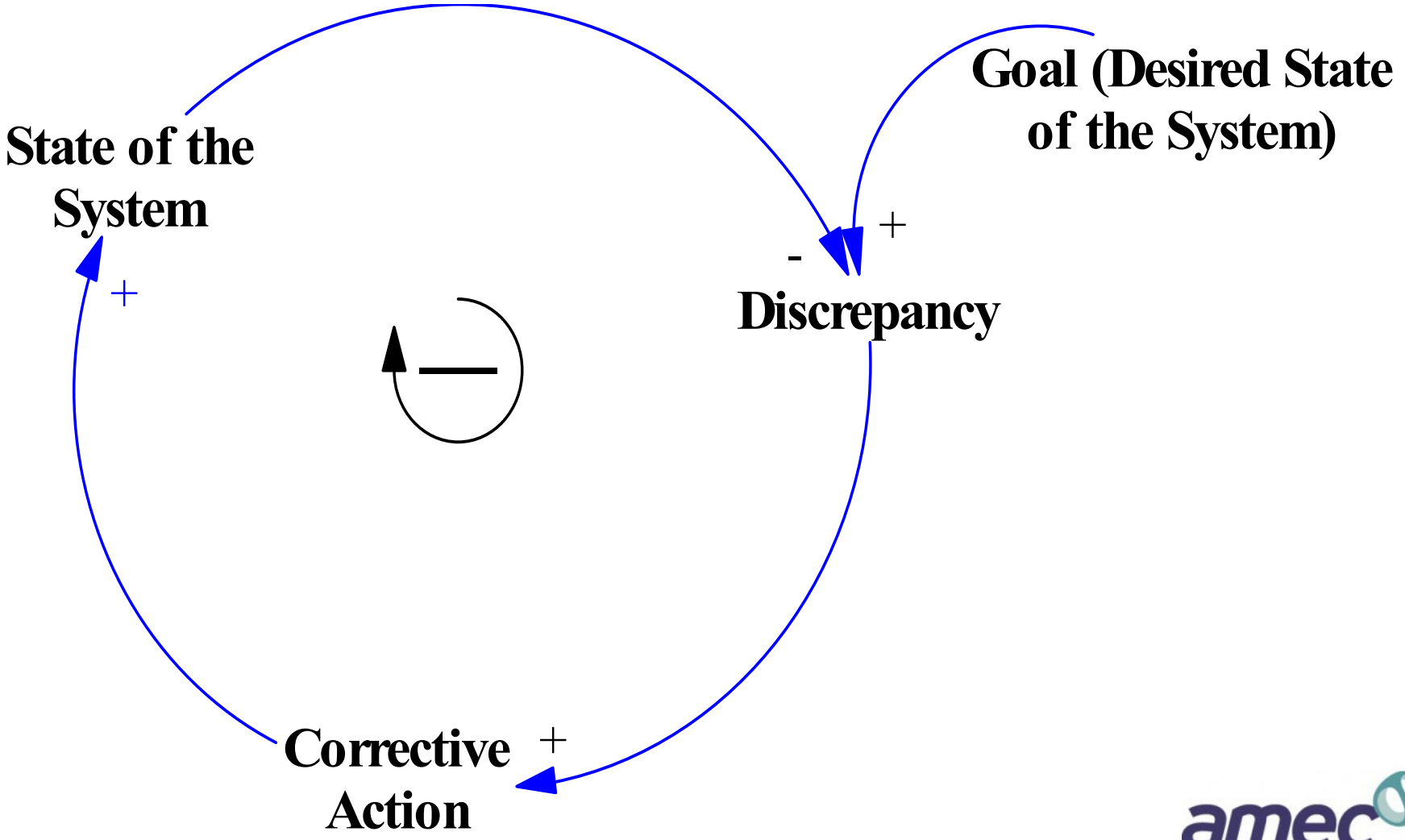
Overshoot and Collapse

Exponential Growth / Collapse

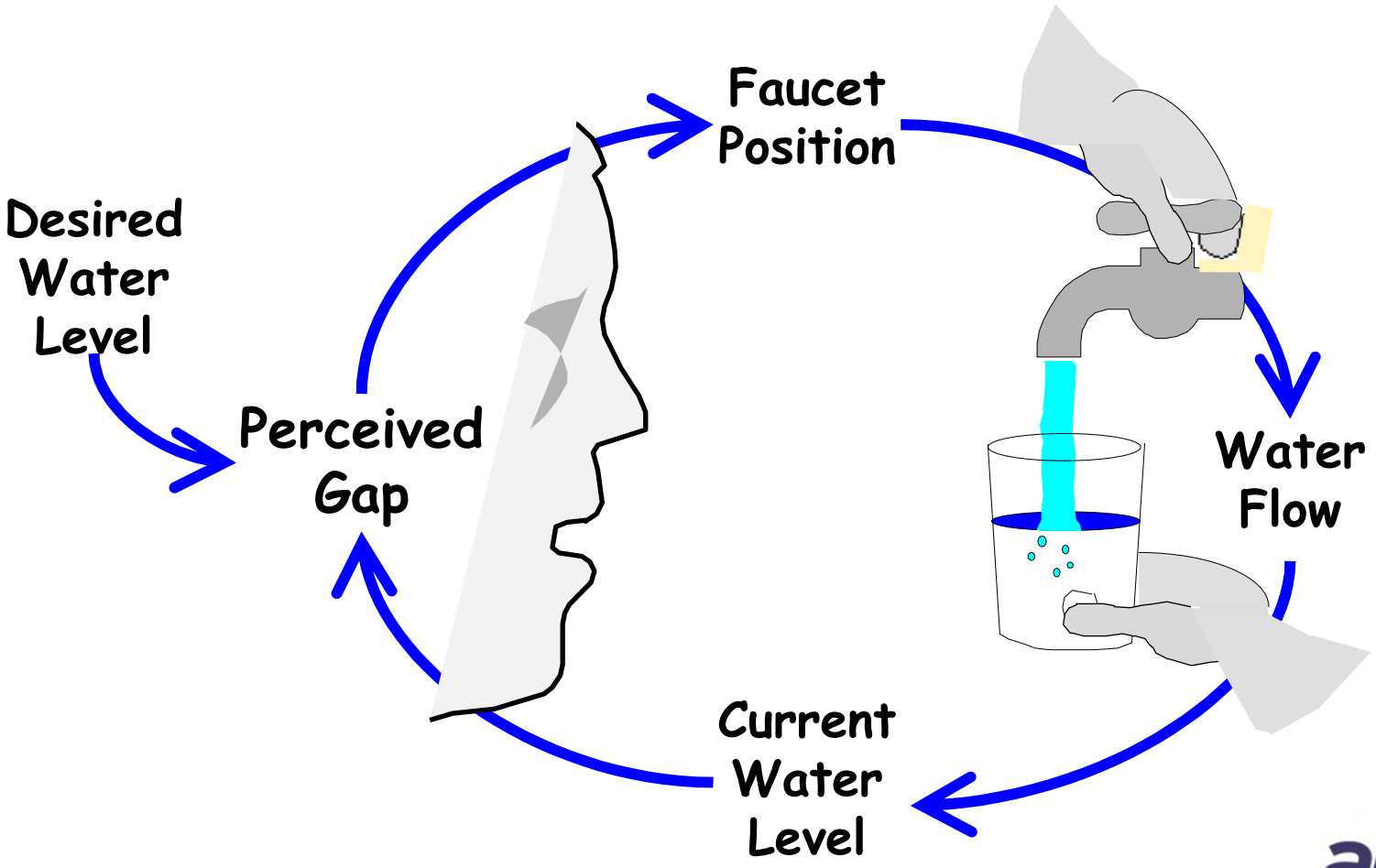


time

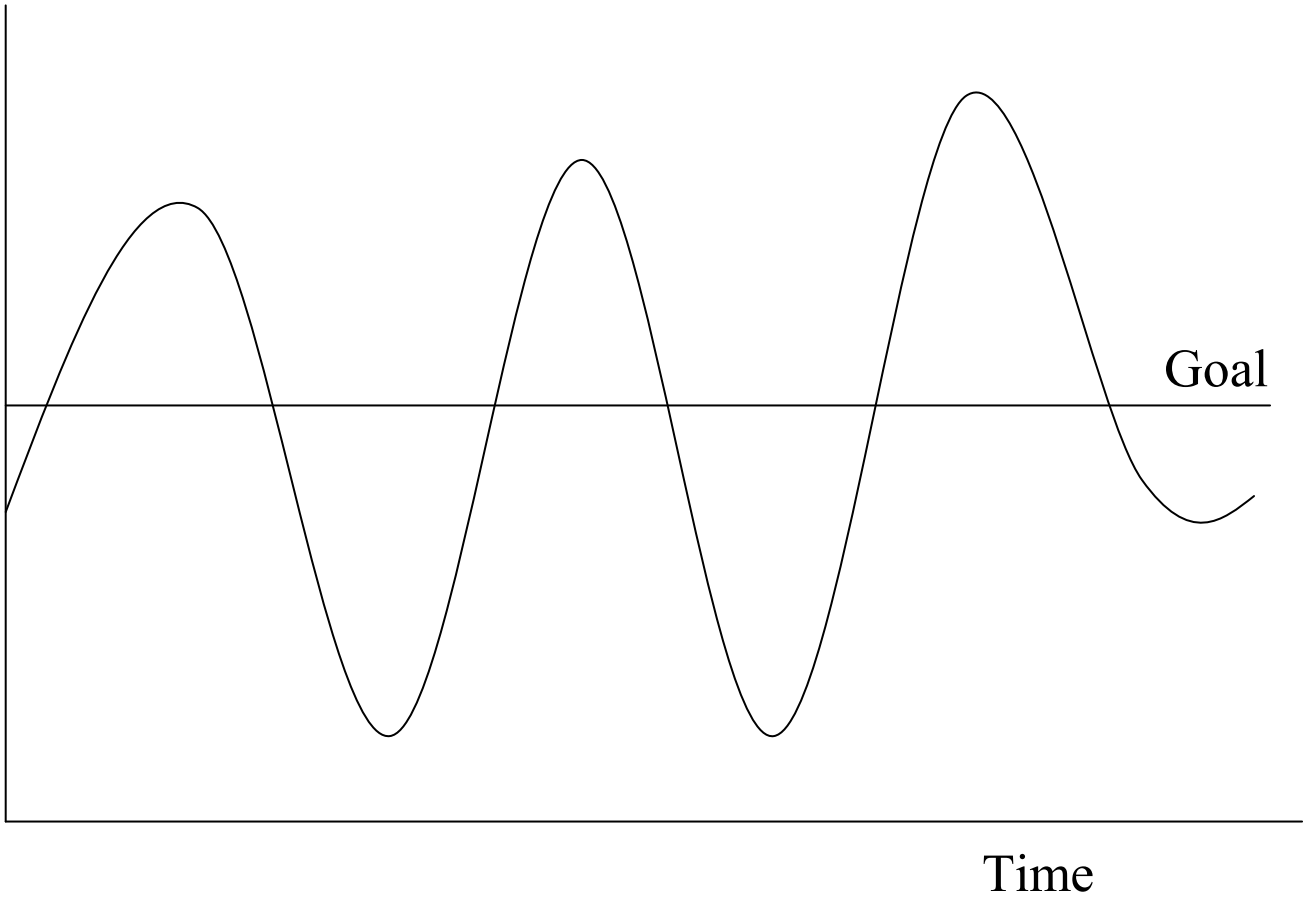
Goal Seeking : Structure



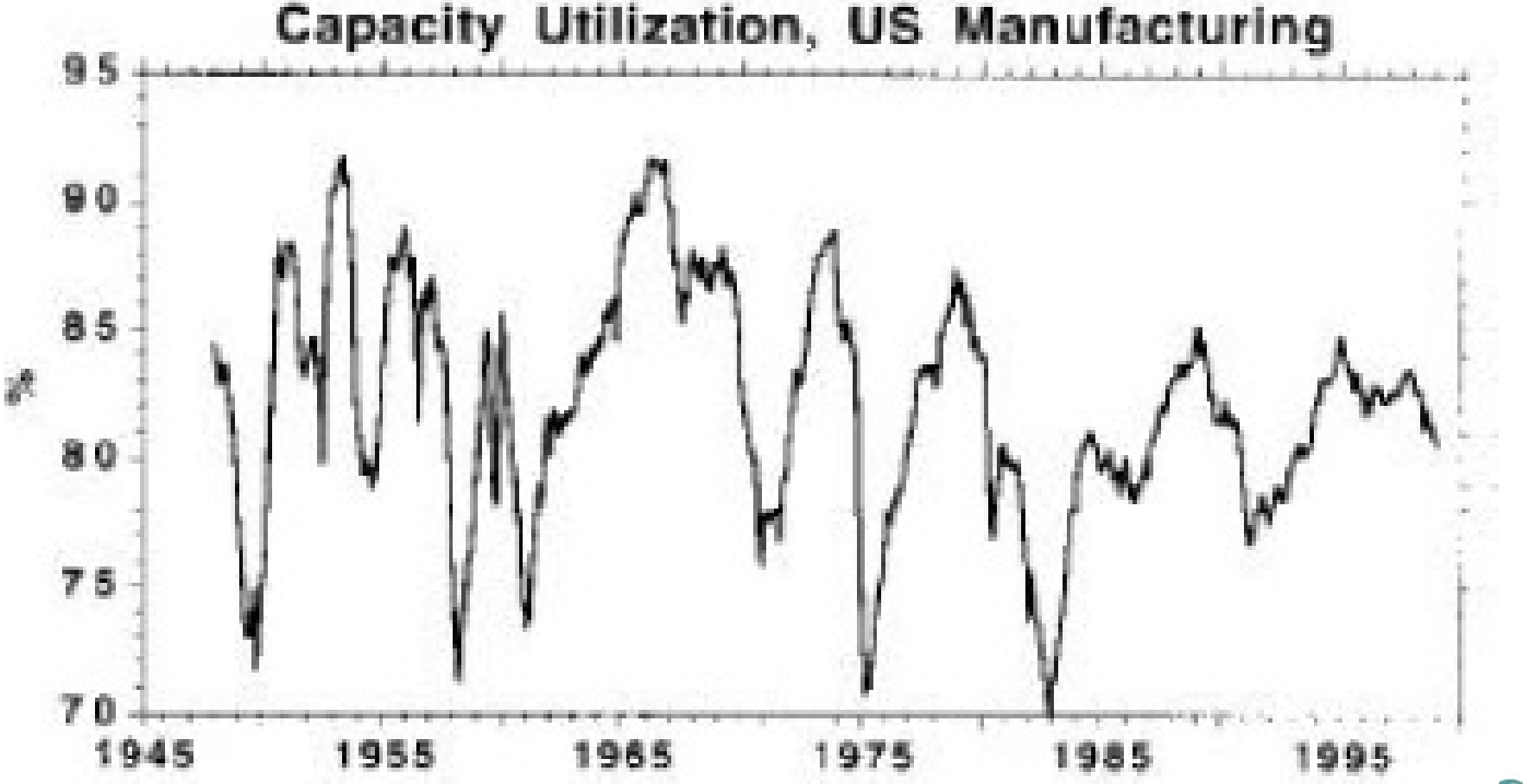
Filling a cup of water



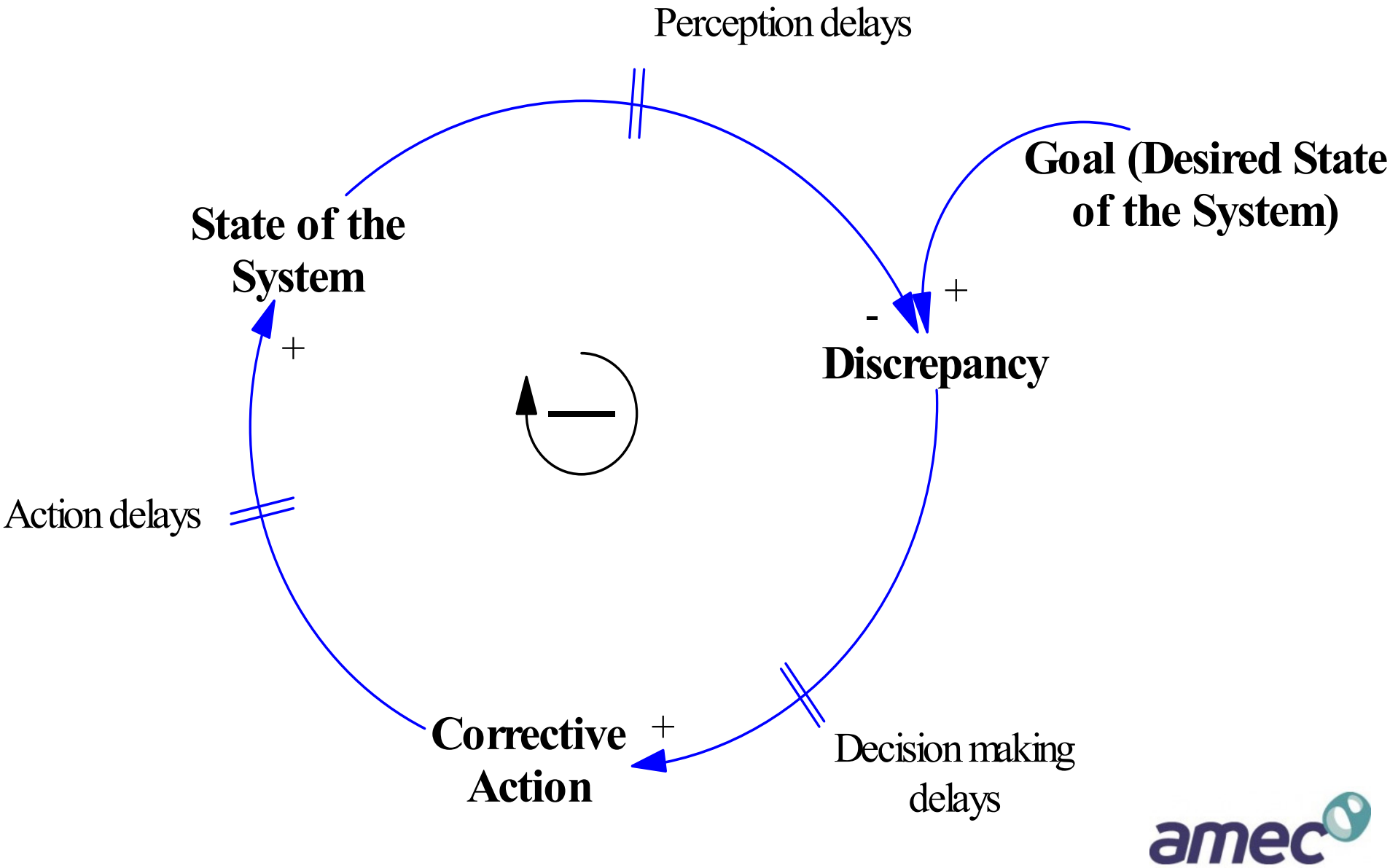
Oscillations



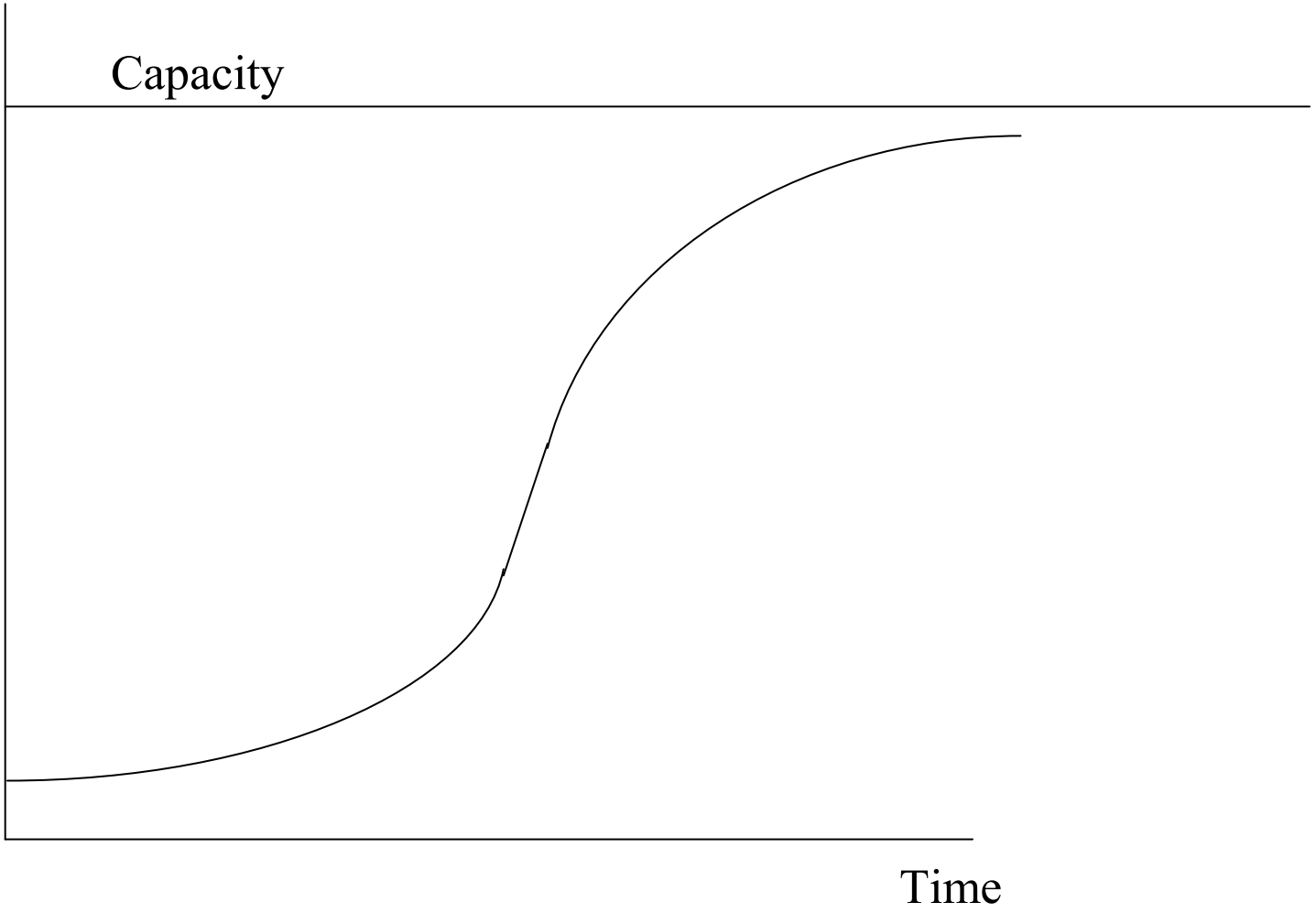
Balancing Loop Oscillation: U.S. Mfg'g Capacity Utilization



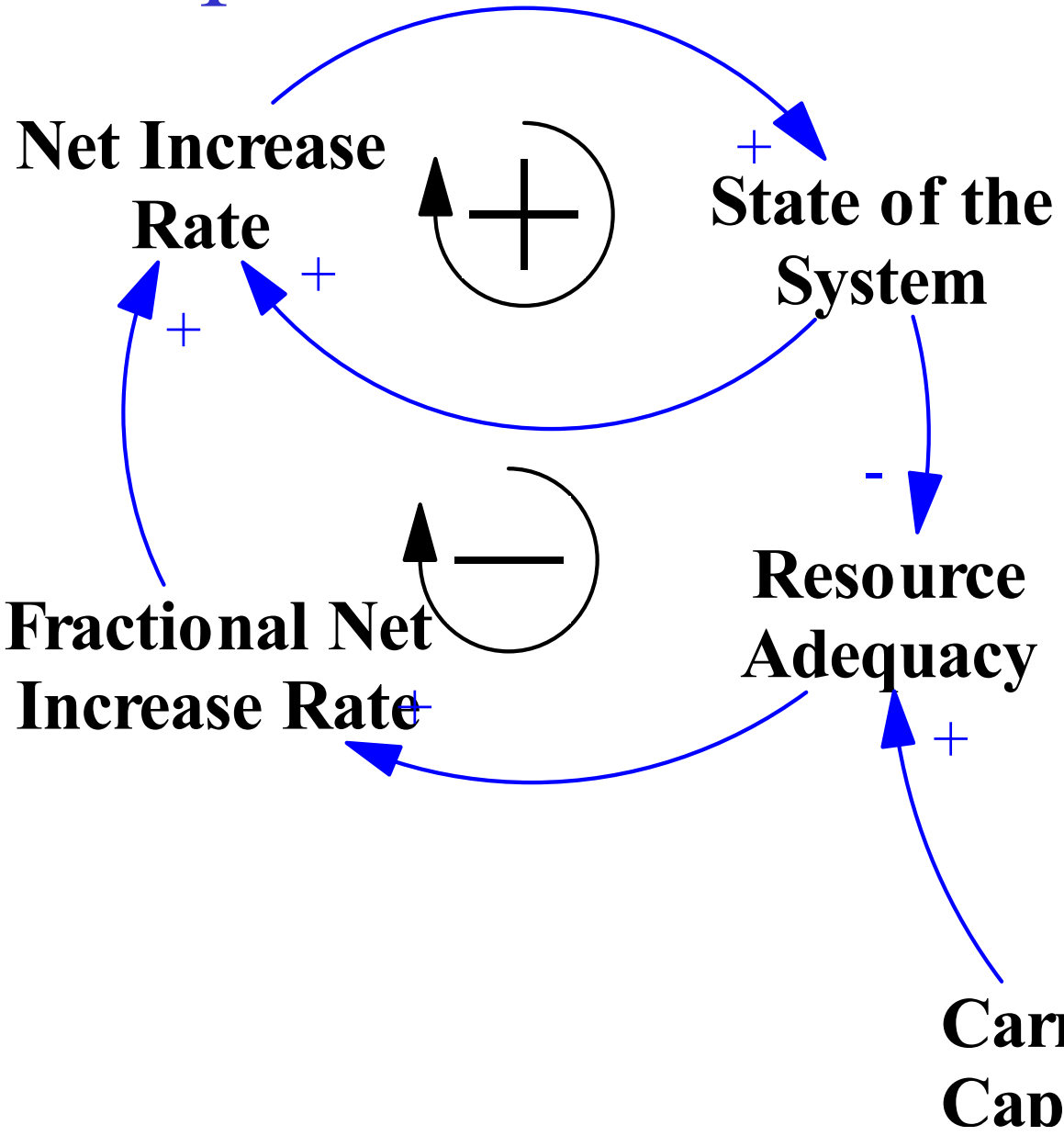
Oscillation: Structure



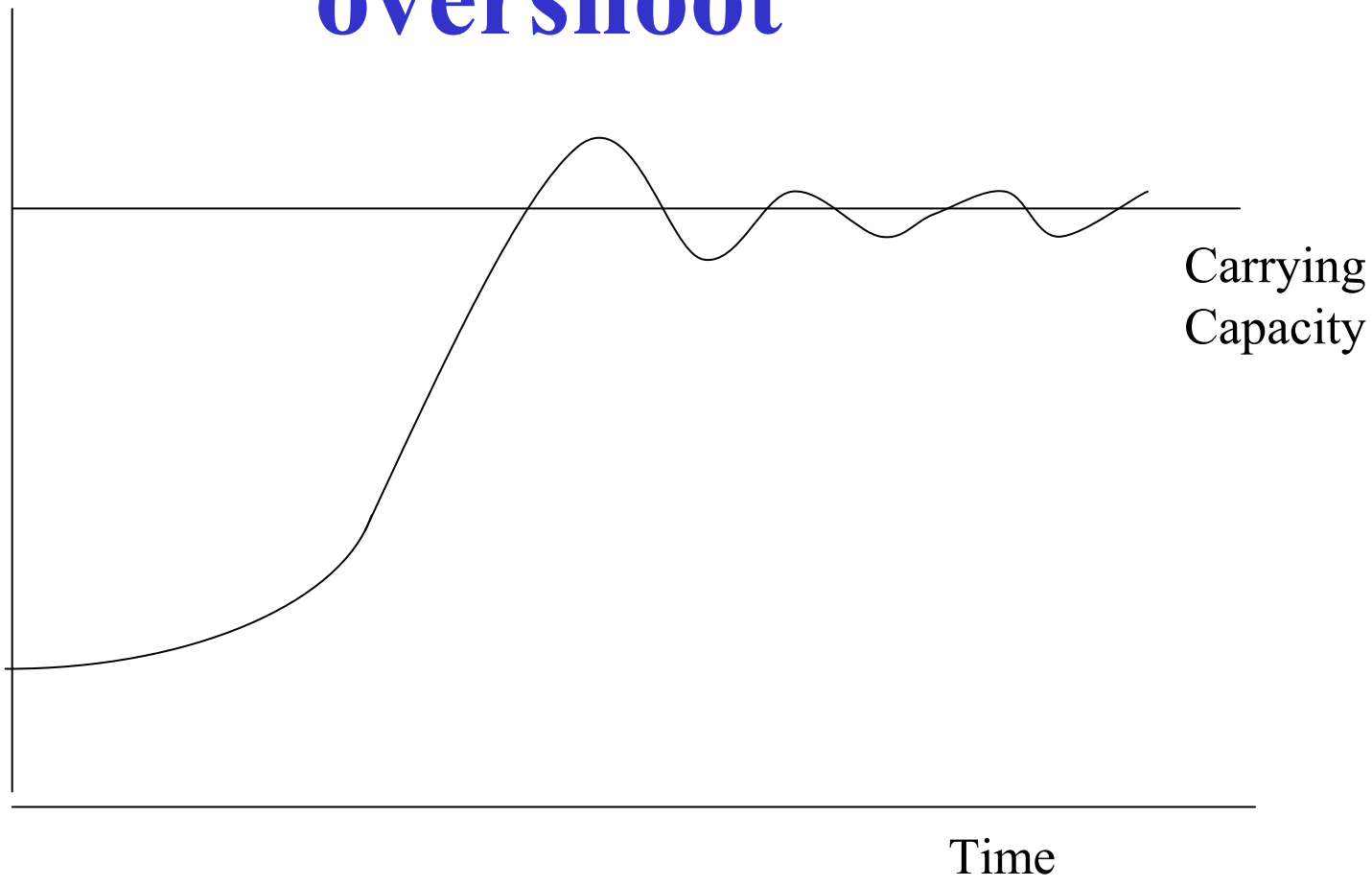
S-Shaped Growth



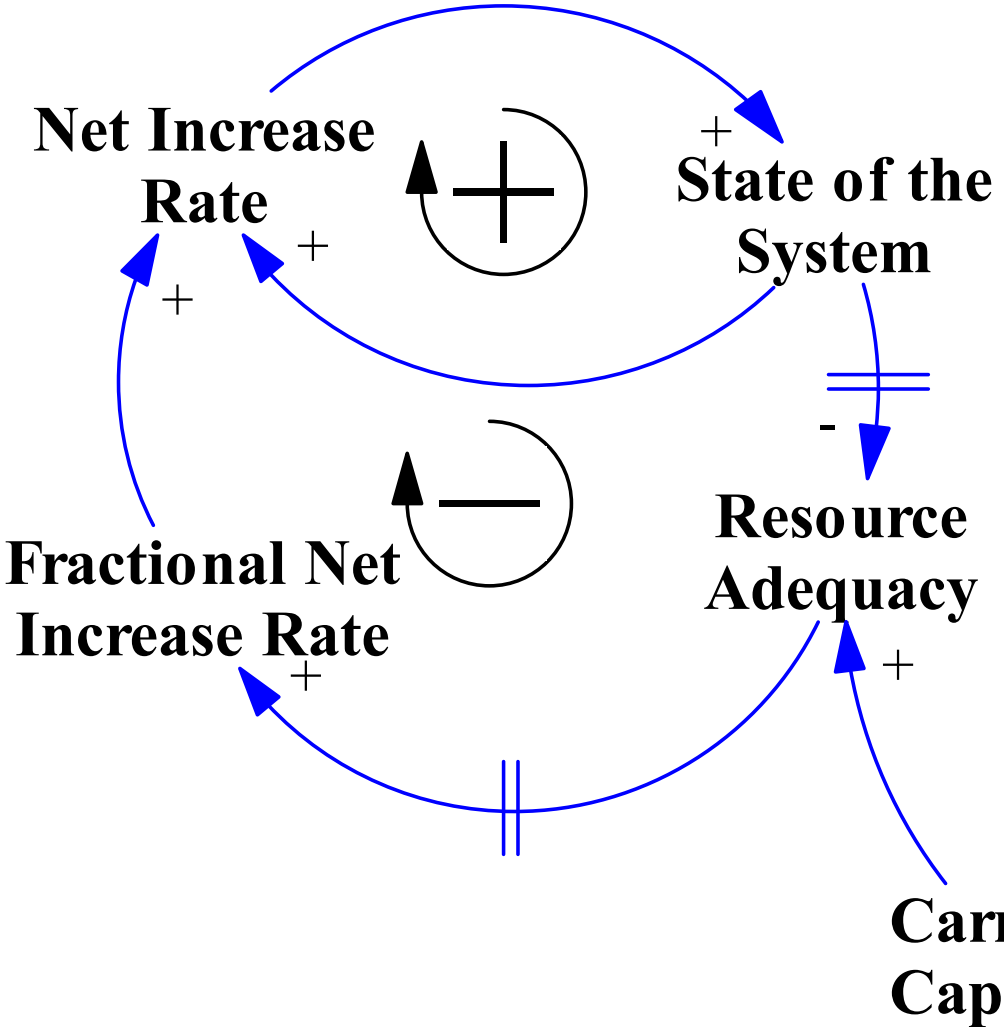
S-shaped Growth: Structure



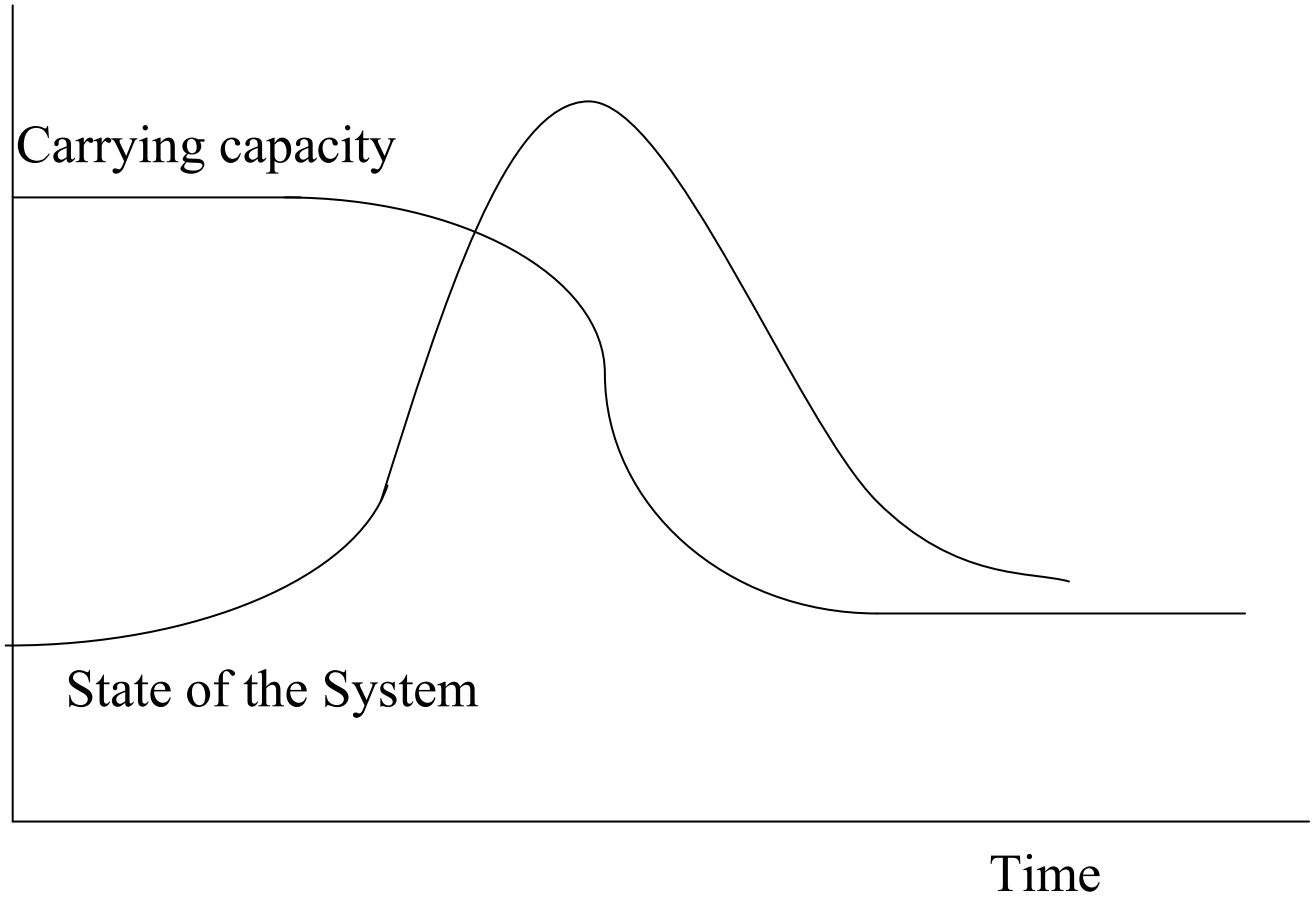
S-Shaped Growth with overshoot



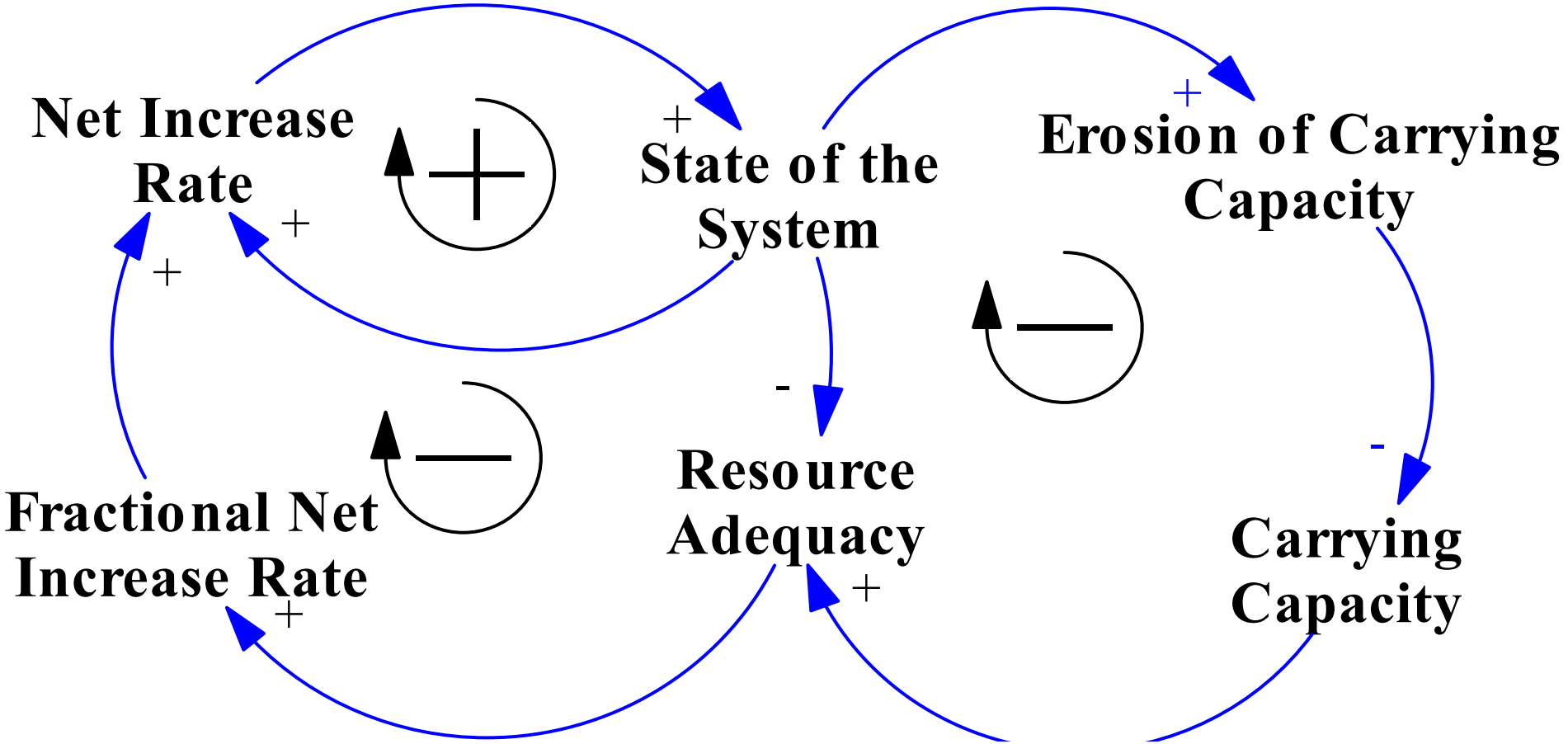
S-Shaped Growth with Overshoot: Structure



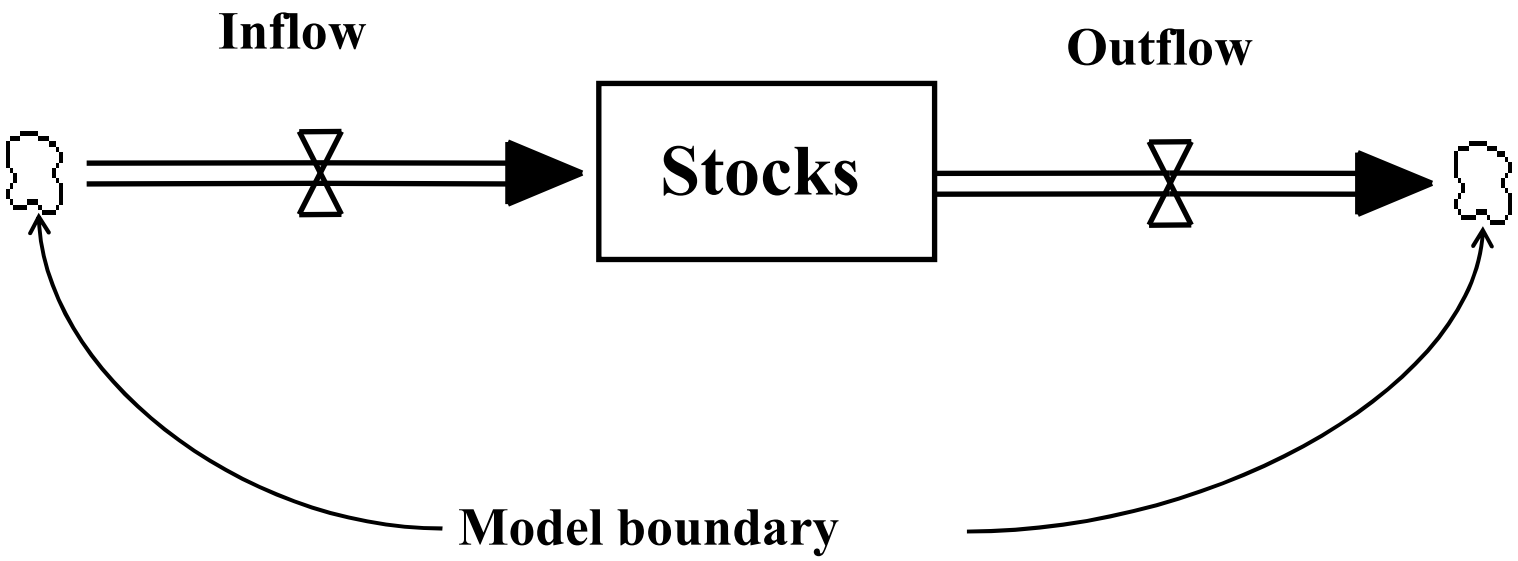
Overshoot and Collapse



Overshoot and Collapse: Structure



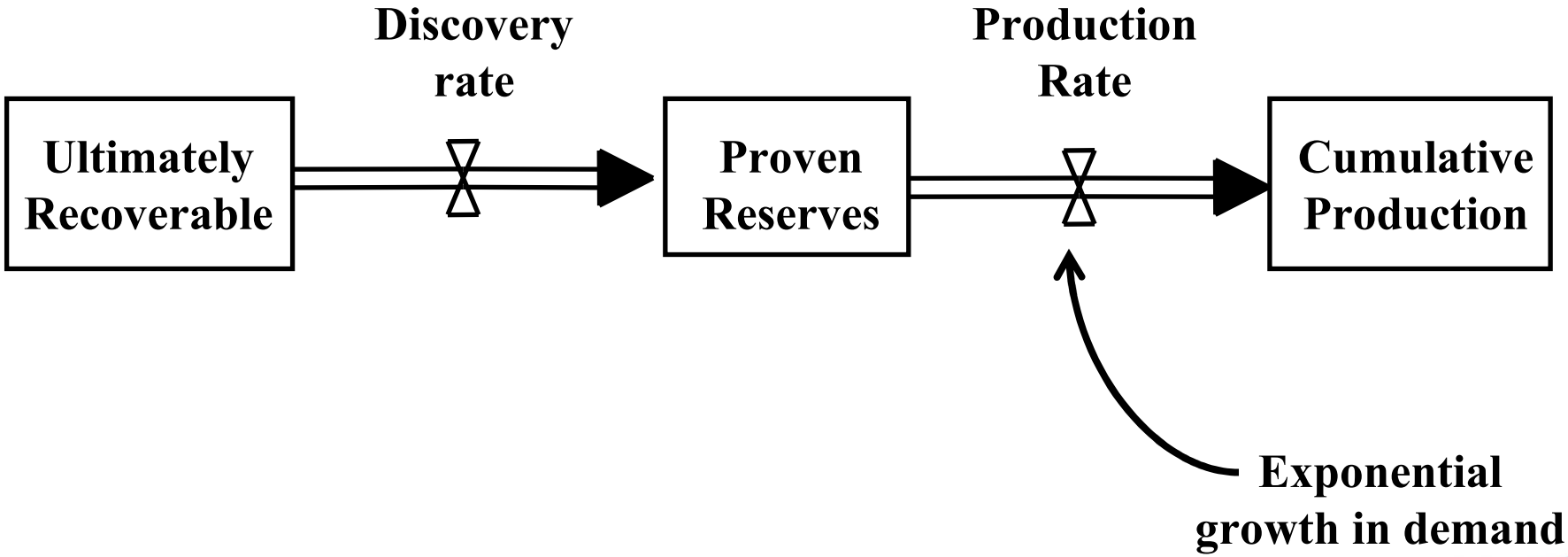
Modelling Stocks and Flows



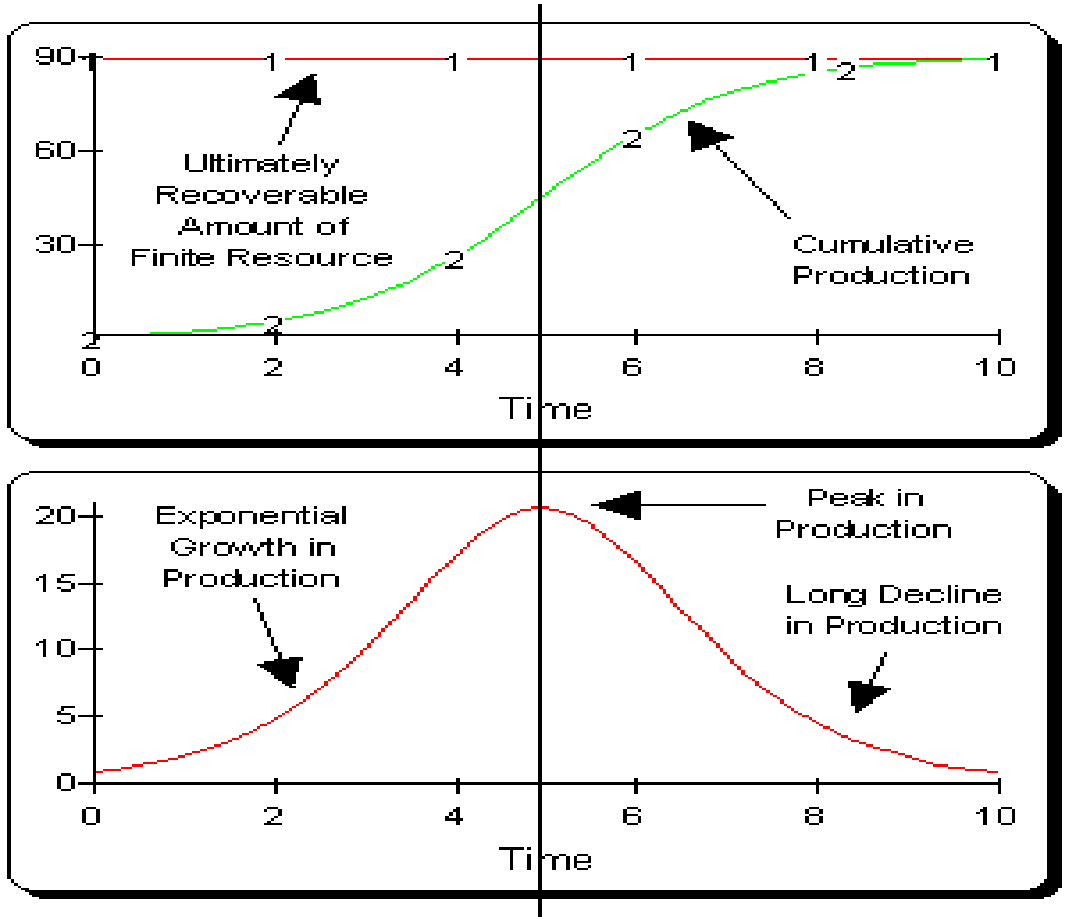
Stocks and Flows

- **Dynamic behaviour arises when flows accumulate in stocks**
- **Characteristics of stocks:**
  - **Have memory**
  - **Change the time shape of flows**
  - **Decouple flows (inflows ≠ outflows)**
  - **Create delays**

Hubbert's View of Oil & Gas Discovery and Production



Hubbert's Life Cycle Theory of Discovery and Production

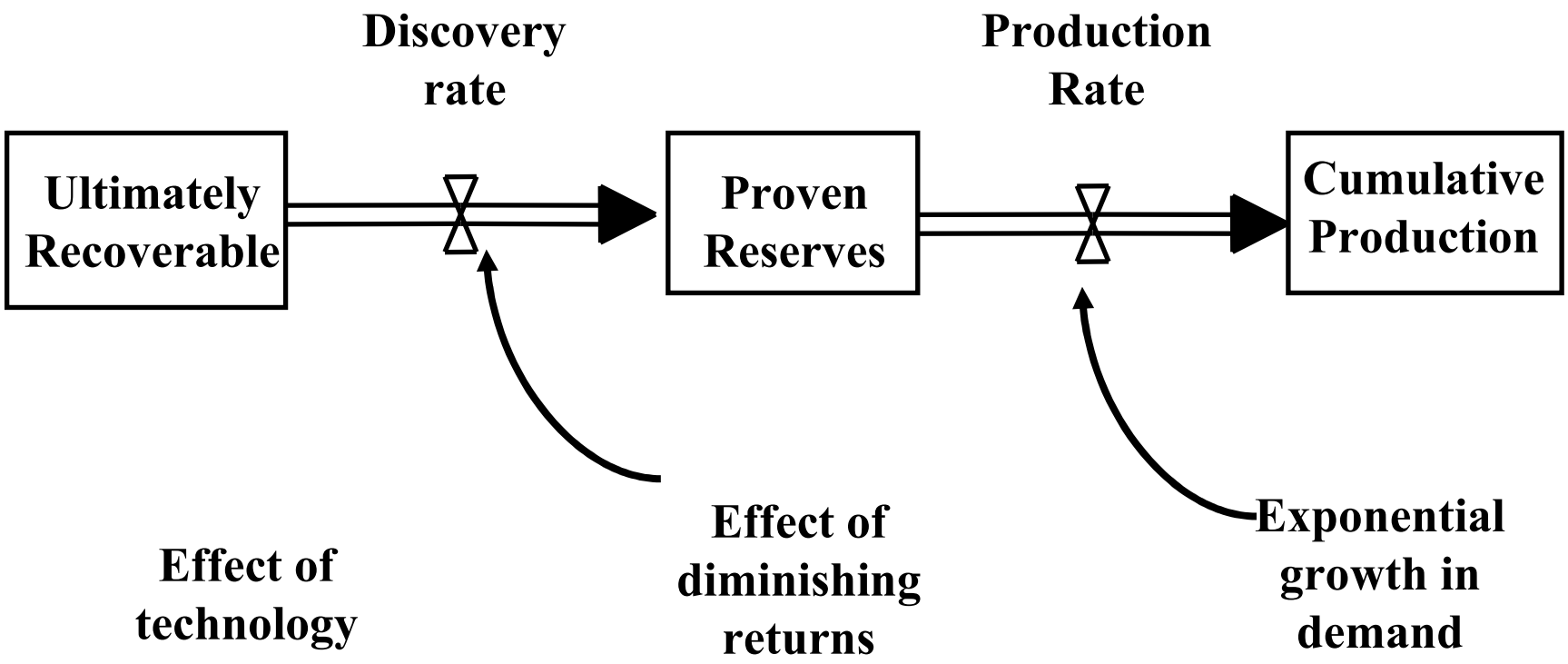


Adelman on Oil Resources

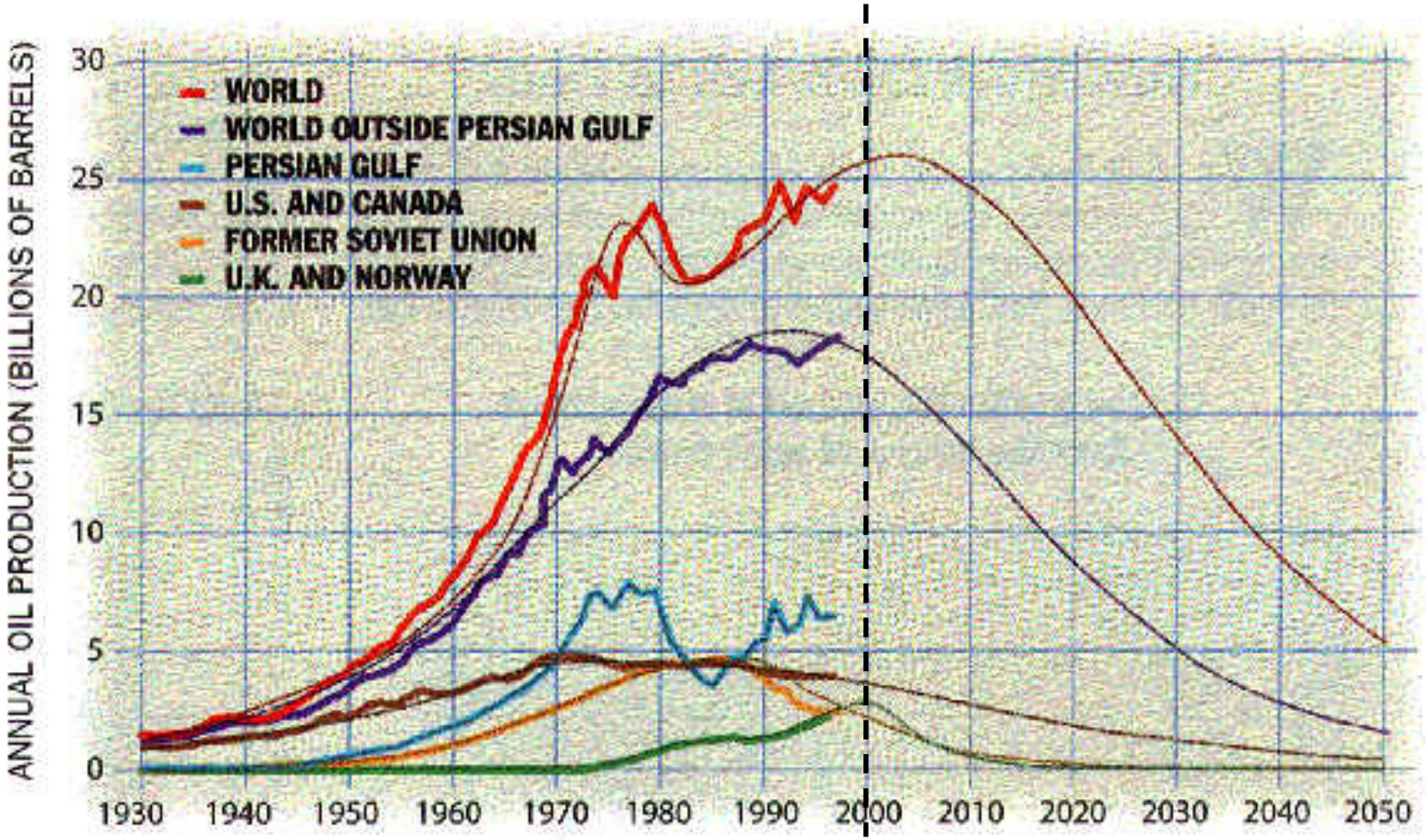
- The price of oil is a study in monopoly, nothing more. The question of mineral depletion doesn't really enter into it...[I]n fact, there is no 'fixed stock' of oil, says Adelman; there is only an inventory we call 'reserves,' which we replenish with new prospecting and lifting techniques. What we don't choose to find or lift remains a secret of the earth, 'unknown, probably unknowable, surely unimportant; a geological fact of no economic interest.' In the endless tug of war between diminishing returns and increasing knowledge,' he says, technology wins out...[The] worldwide stability of the development cost of new oil since 1955 shows that oil is no more scarce today than it was then. 'The great shortage is like the horizon, always receding as you go toward it,' says Adelman. What's left are the monopolistic political high-jinks.

•David Warsh, Larry, Curly & Moe in the Persian Gulf: Wither Oil Prices? *Boston Globe* (November 25, 1990) p. A33.

Adelman's View of Oil & Gas Discovery & Production



The Dangers of Pattern Matching



CJ Campbell & JH Laherrère, "The End of Cheap Oil," *Scientific American*, March 1998

Model Building Checklist I

1. **Units check** –check all equations for consistency in units.
2. **Naming variables** –The first letter of Stock names should be capitalized; CONSTANTS should be in all capitals, and names of all other variables, including flows are all lower case. "rate" is reserved for flows.
3. **Do not embed constants in equations**
4. **Do not mention parameter values in the documentation** –keeps documentation robust and avoids potential confusion.
5. **Choose appropriately small time steps** – Choose the time step to be ~ 1/8 the value of the smallest time constant in the model
6. **Stock values are only changed by flows** – The only elements with direct connections to stocks are flows. No constants or auxiliary variables should directly enter the stock equation, except for initial values of the stock.

Model Building Checklist II

7. **Every flow should be connected to a stock** – A flow only increases or decreases a stock; it cannot be used as a source of information
8. **Flows should not be linked to auxiliary variables or other flows –** Flows are instantaneous and cannot be measured in real-time, they can only be measured by calculating the change in stock value per unit time. It also takes time for information to move from one flow to another. If two flows are defined by the same structure, then one should use the same structure and equation to define both flows instead of connecting the two flows.
9. **Stocks should not be linked to stocks** – A stock is the integral of a flow. To show information transfer between two stocks, connect the first stock to the flow of the second stock.
10. **Using IF THEN ELSE, MIN/MAX and other logic statements** – Use table functions to avoid discontinuities introduced by such statements.
11. **Use of Initial Values –** should be clearly specified

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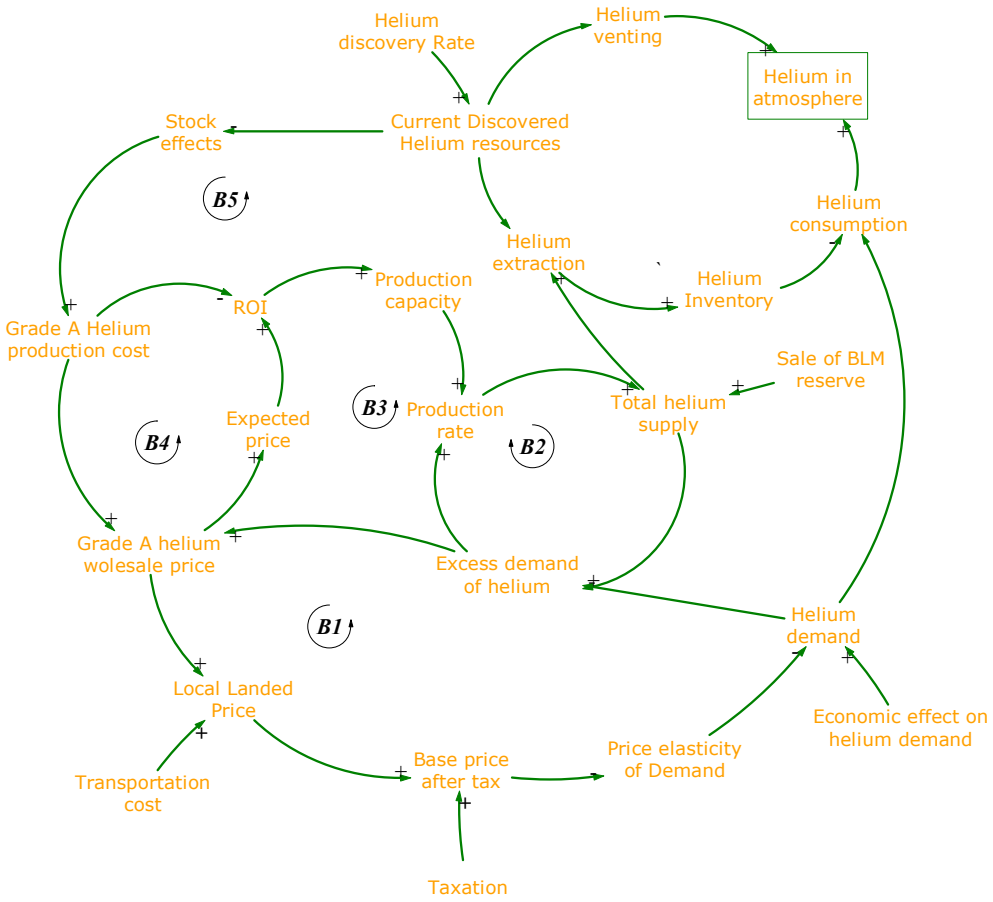
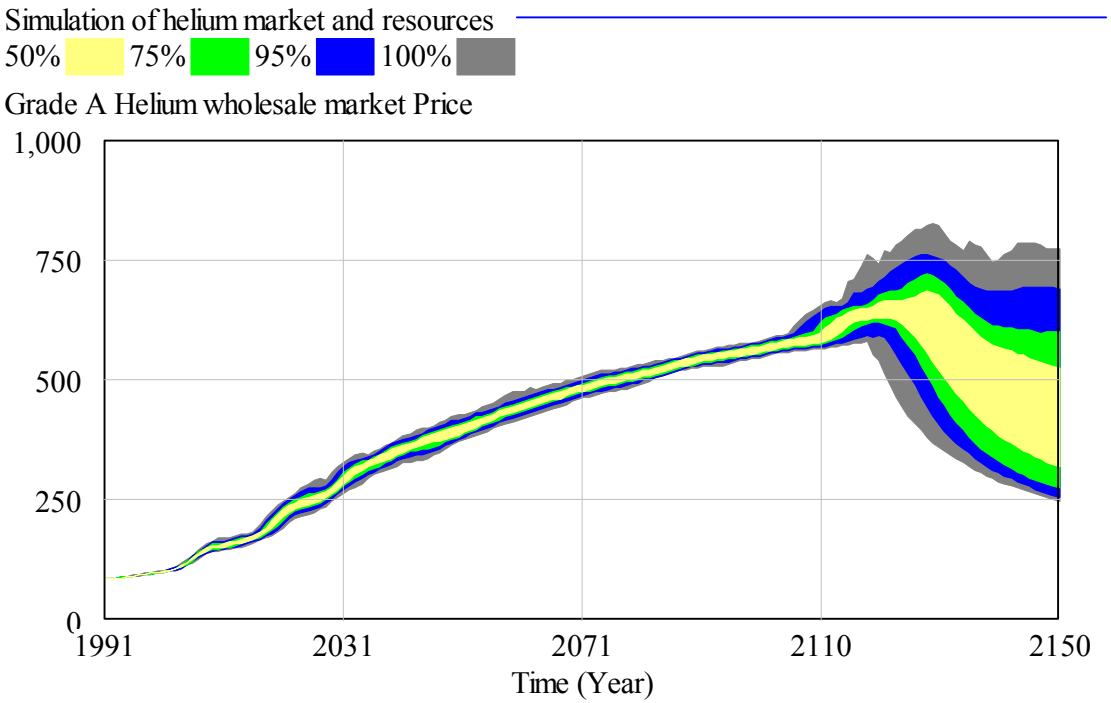
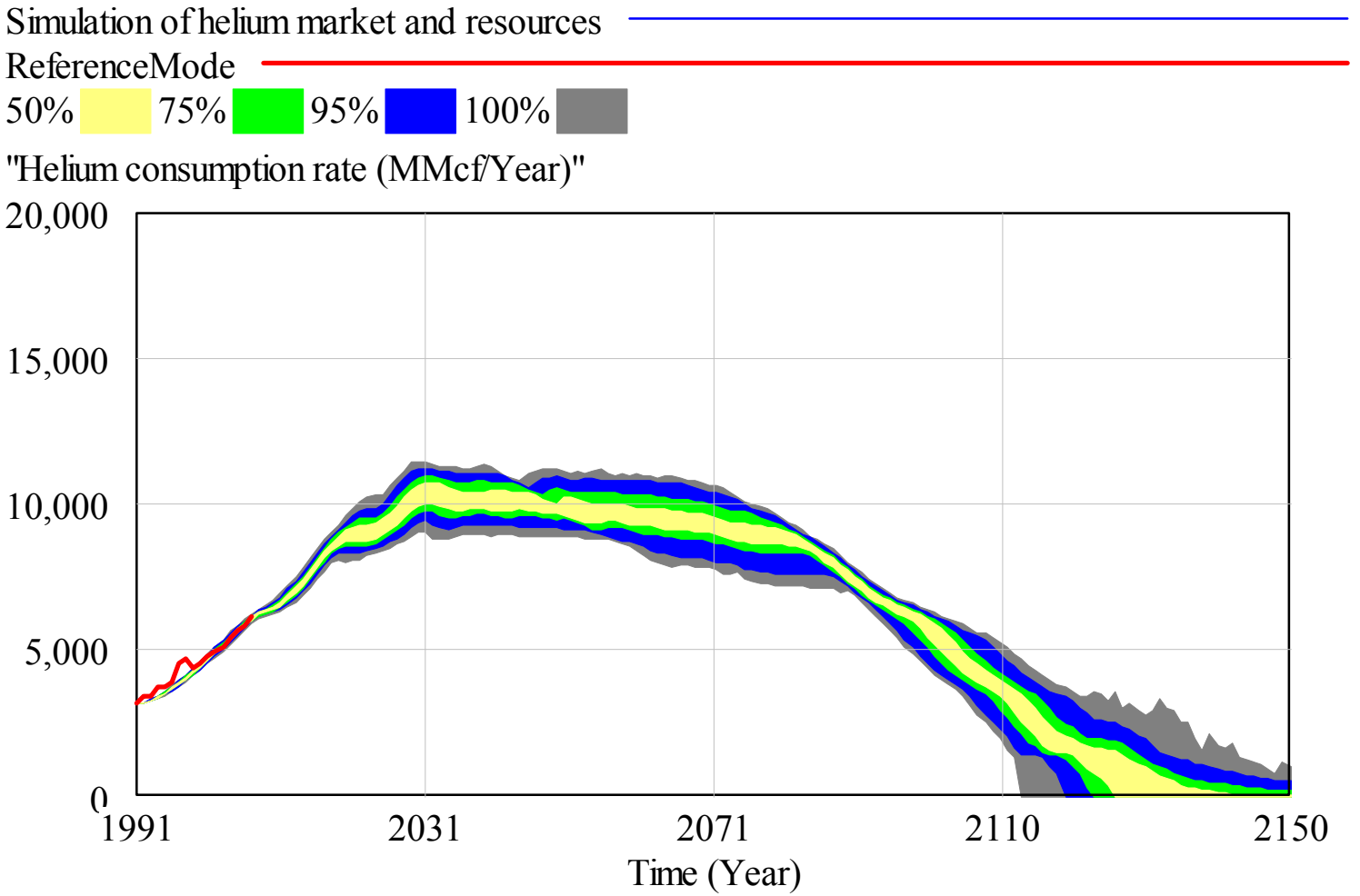
Causal Map of Global Helium Resources



Simulation results I



Simulation results II



Q & A?

- Thanks for attentions!
- Reference:
- Z. Cai, etc. Ongoing ascent to the helium production plateau—Insights from system dynamics. **Resources Policy**, Volume 35, Issue 2, June 2010, Pages 77-89. doi:10.1016/j.resourpol.2009.10.002