Aachen Summer Simulation Seminar 2014

Lecture 04

Simulation Methods: System Dynamics Simulation

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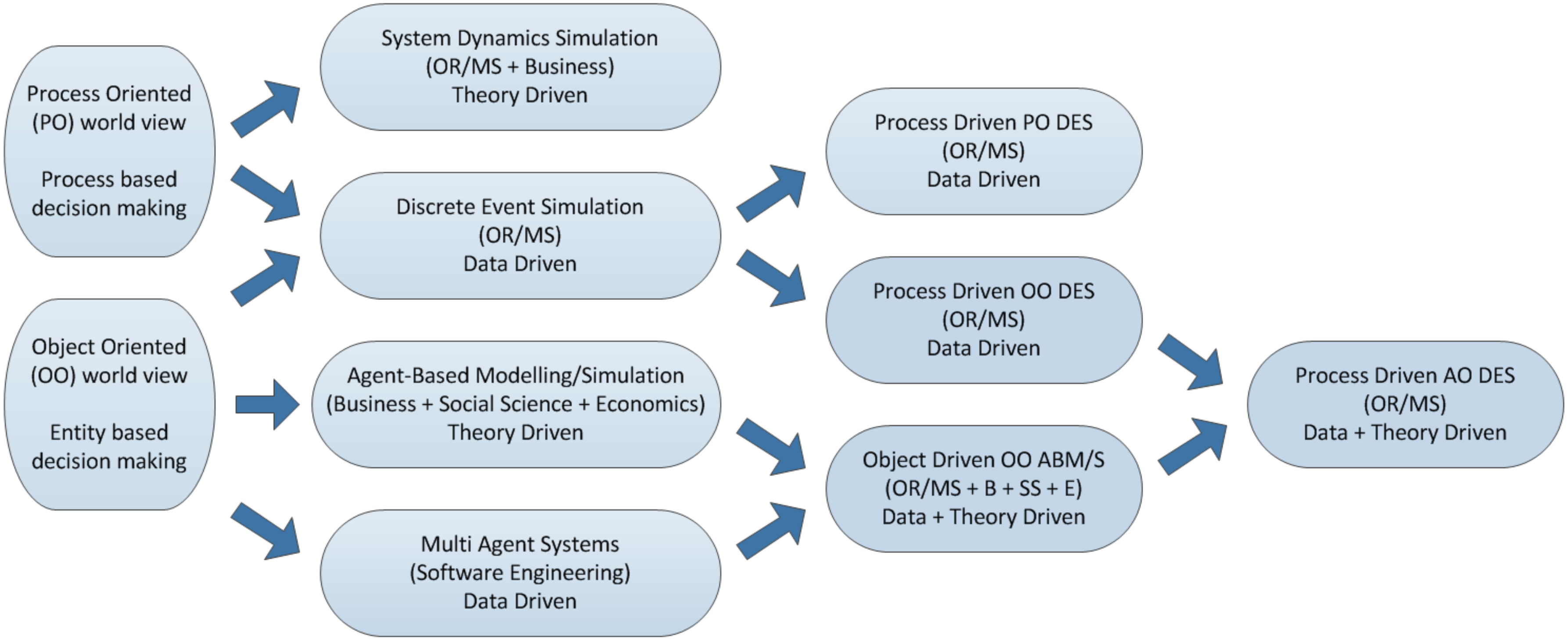
Motivation

- Introduce the concepts of System Dynamics (SD)
- Provide some insight into the design of SD simulation models
  - Patterns of Behaviour
  - Feedback and Causal Loop Diagrams
  - Stock and Flow Diagrams

Simulation Paradigms: Update



Data Driven: Data for model formulation (in Social Sciences can be quantitative and qualitative); data for model validation
Theory Driven: Theories for model formulation; data for model validation

Simulation Paradigms: Update

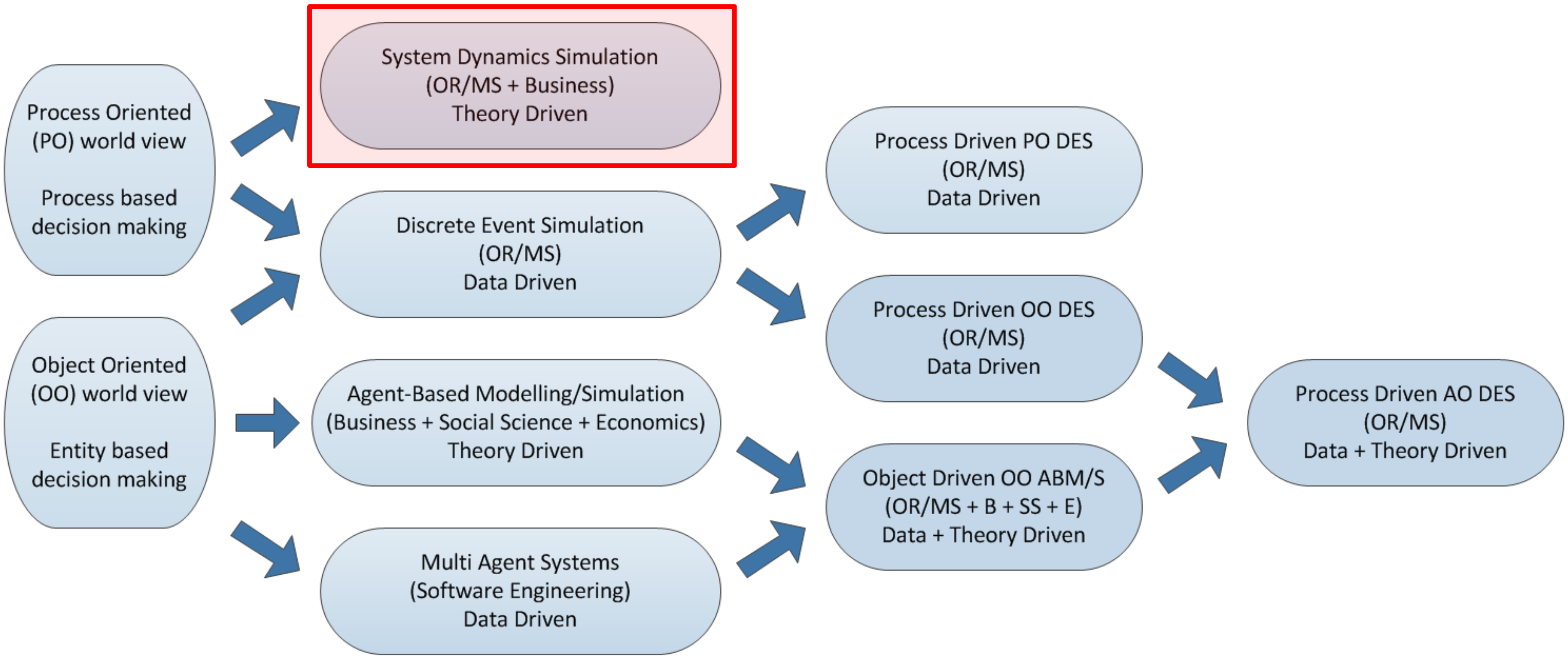
- Process Driven Process Oriented DES
  - Traditional DES (usually what is described in books and papers)
  - Entities are routed through the system
- Process Driven Object Oriented DES
  - Entities defined as classes
  - Entities make decisions where to go

Simulation Paradigms: Update

- Object Driven Object Oriented ABM/S
  - Entities defined as classes
  - Entities are intelligent objects that interact
  - Entities make decisions and have a memory
  - Process: No concept of queues and flows

- Process Driven Agent Oriented DES
  - Entities defined as classes
  - Entities are intelligent objects that interact
  - Entities make decisions and have a memory
  - Process: Organised in terms of queues and flows

Simulation Paradigms: Update



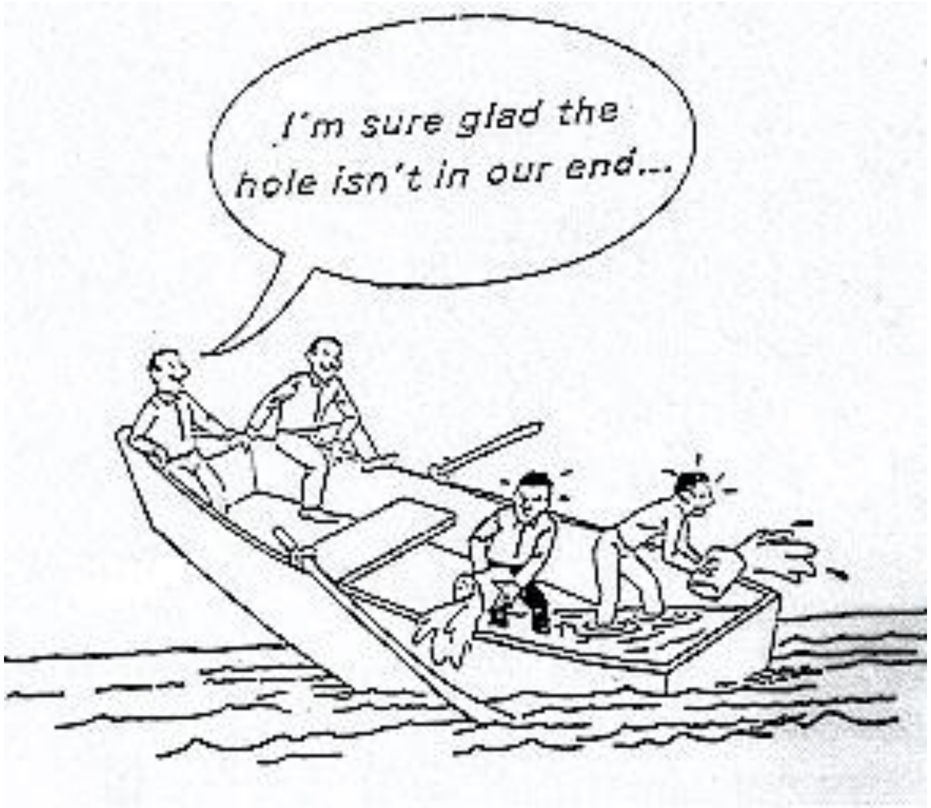
Data Driven: Data for model formulation (in Social Sciences can be quantitative and qualitative); data for model validation
Theory Driven: Theories for model formulation; data for model validation

Systems Thinking

- We are quick problem solvers. We quickly determine a cause for any event that we think is a problem. Usually we conclude that the cause is another event.
  - Example: Sales are poor (event) because staff are insufficient motivated (cause); staff are insufficient motivated (event) because ...

- Difficulty: You can always find yet another event that caused the one that you thought was the cause. This makes it very difficult to determine what to do to improve performance.

Systems Thinking



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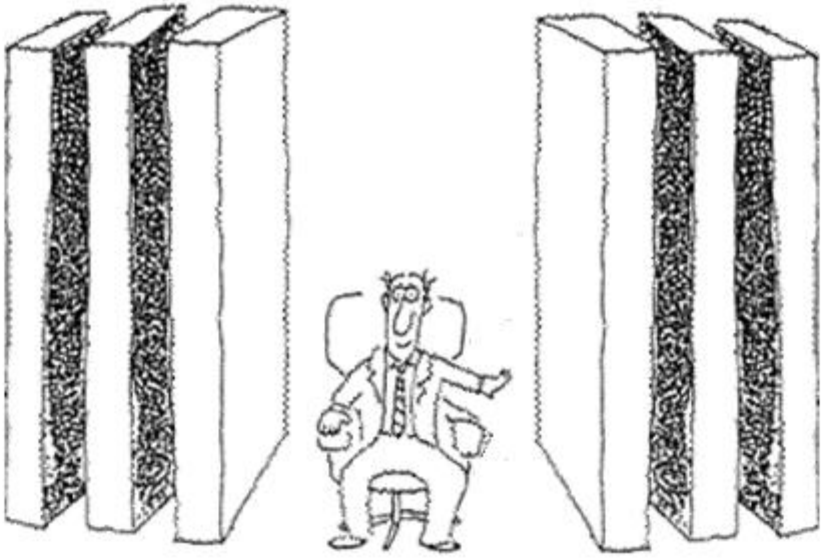
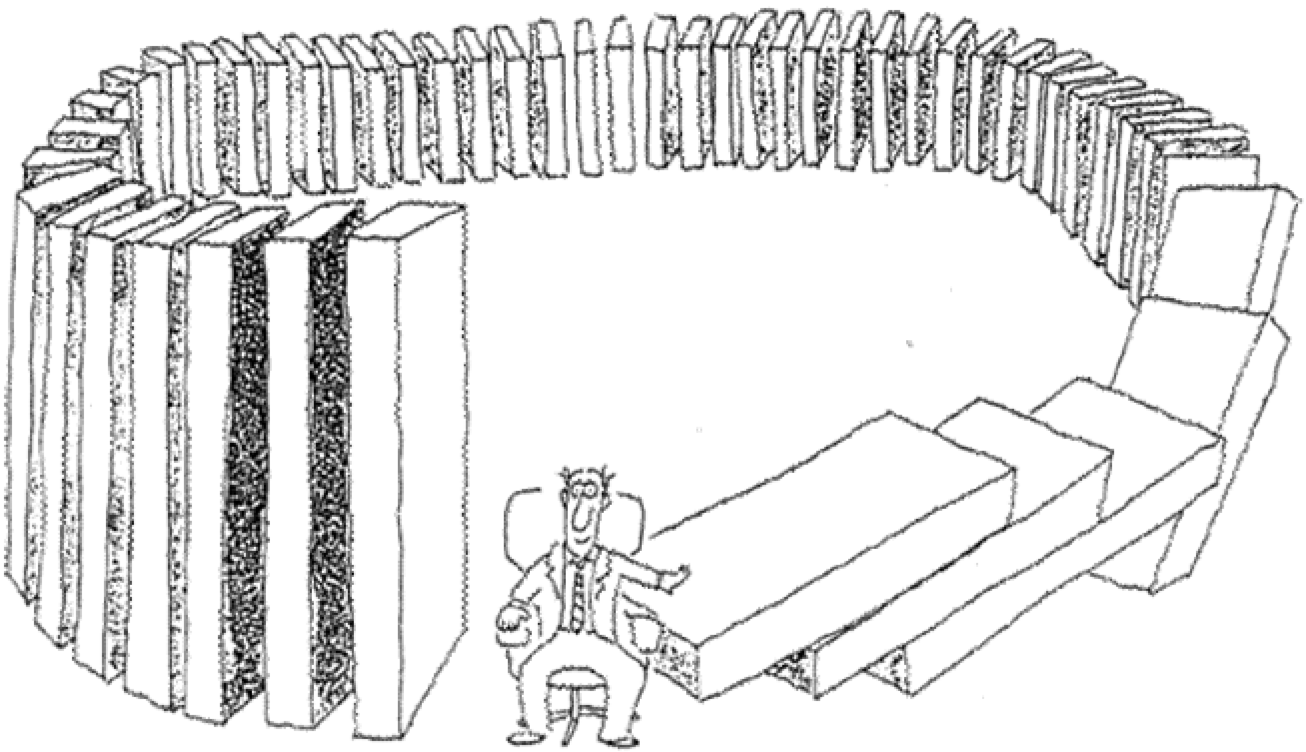
Systems Thinking



Systems Thinking



Systems Thinking / System Dynamics

- **Systems Thinking (ST):** The process of understanding how things influence one another within a whole. [Wikipedia]

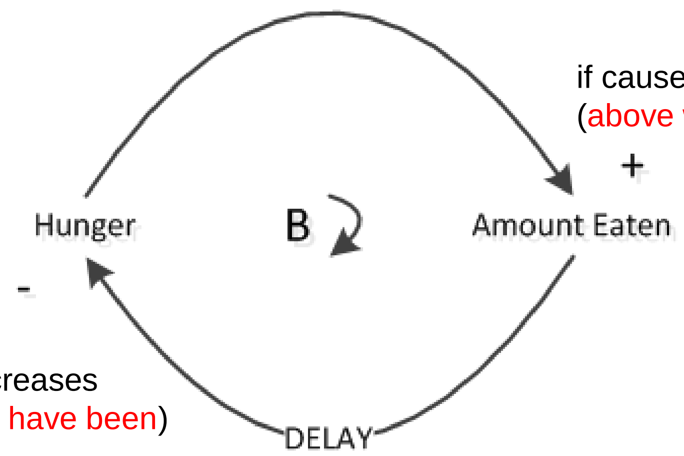
- **System Dynamics (SD):** An approach to understanding the behaviour of complex systems over time. It deals with internal feedback loops and time delays that affect the behaviour of the entire system. [Wikipedia]

System Dynamics

- Model representations
  - Causal loop diagrams (qualitative)
  - Stock and Flow diagrams (quantitative)

- Example: Simple causal loop diagram of food intake [Morecroft 2007]

if cause increases ... effect increases
(above what it would otherwise have been)



if cause increases ... effect decreases
(above what it would otherwise have been)

How to build SD simulation models

- Conceptualisation
  - Define the purpose of the model
  - Define the model boundaries and identify key variables
  - Describe the behaviour of the key variables
  - Diagram the basic mechanisms (feedback loops) of the system

- Formulation
  - Convert diagrams to stock and flow equations
  - Estimate and select parameter values
  - Create the simulation model

How to build SD simulation models

- Testing
  - Test the dynamic hypothesis (the potential explanation of how structure is causing observed behaviour)
  - Test model behaviour and sensitivity to perturbations

- Implementation
  - Test model's responses to different policies
  - Translate study insight to an accessible form

Patterns of Behaviour

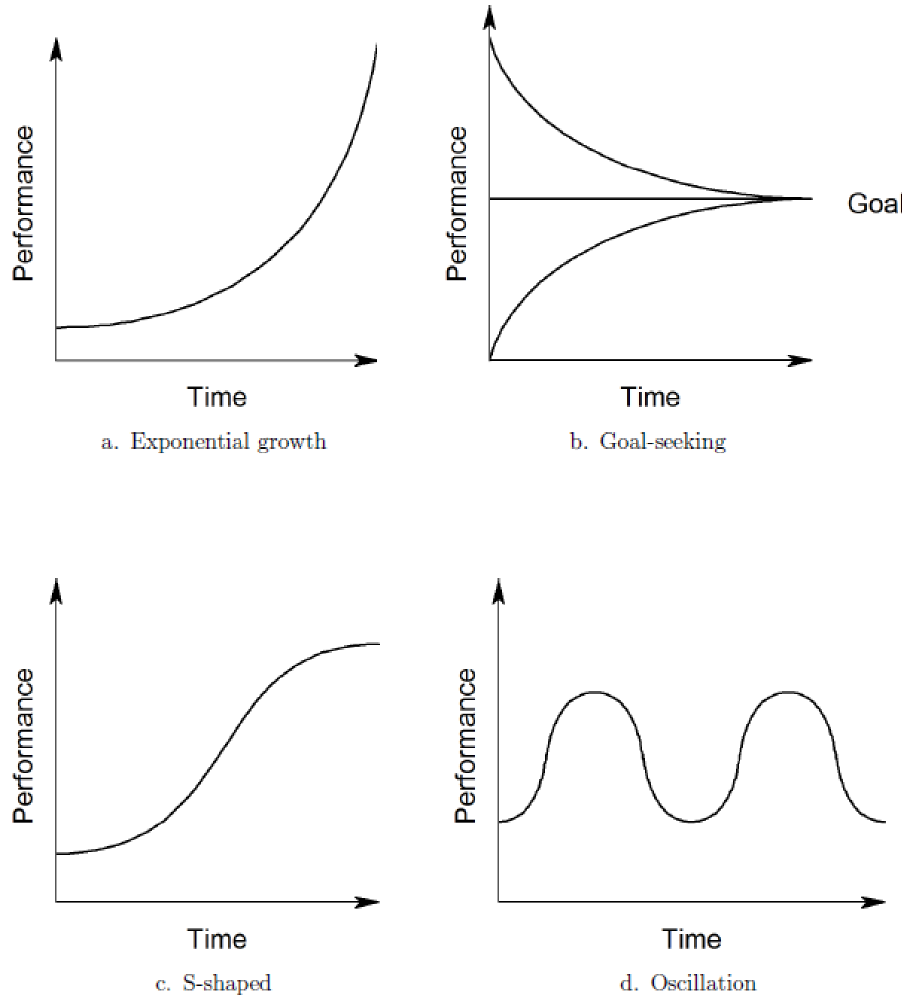
- Generalise from the specific events to consider patterns of behaviour that characterise the situation

- Once we have identified a pattern of behaviour that is a problem, we can look for the system structure that is known to cause this pattern

- By finding and modifying this system structure you have the possibility to permanently eliminate the problem pattern of behaviour.

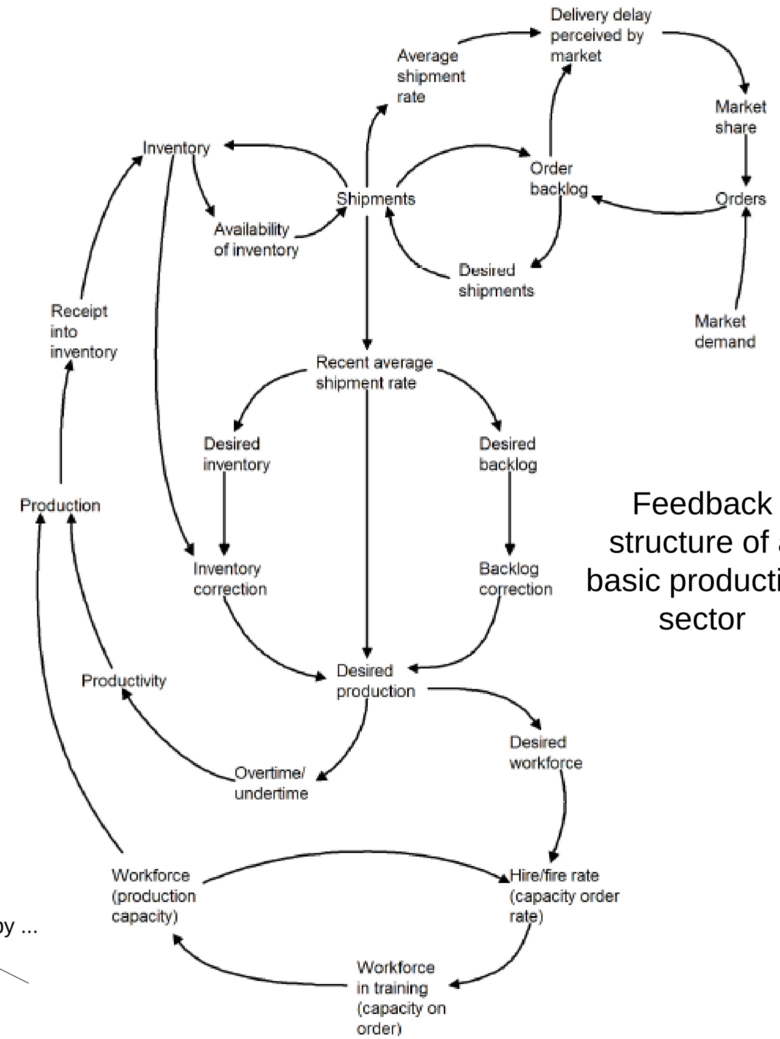
Patterns of Behaviour

- Common patterns that show up either individually or combined

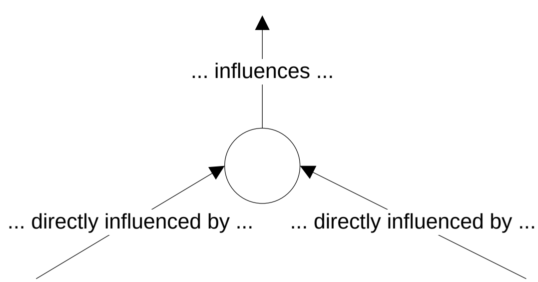


Feedback and Causal Loop Diagrams

- Notation for presenting system structures
  - Short descriptive phrases represent the elements which make up the sector.
  - Arrows represent causal influences between these elements

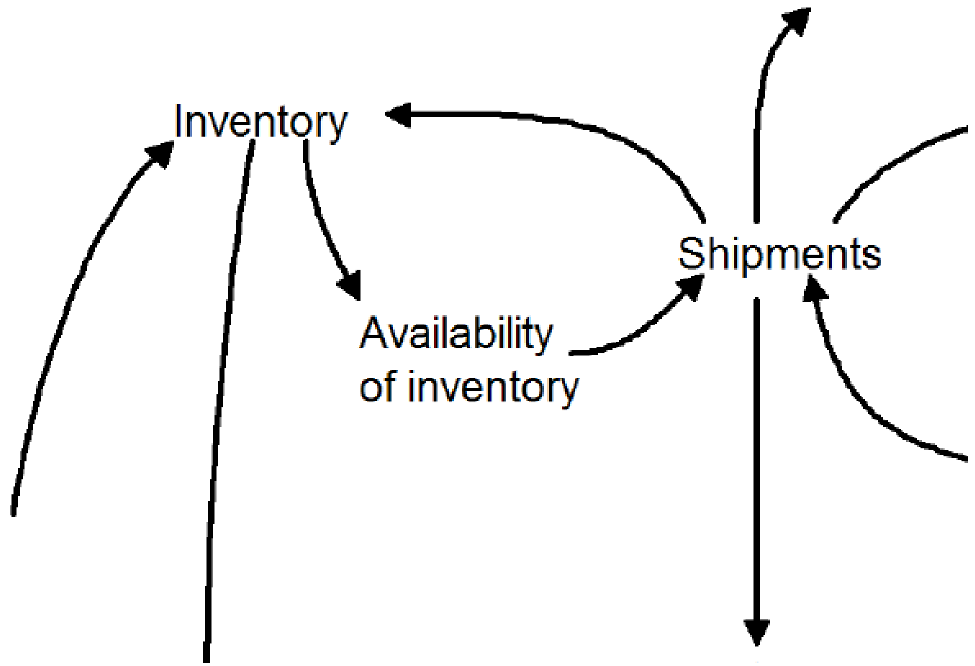


Feedback structure of a basic production sector



Feedback and Causal Loop Diagrams

- Feedback loop or causal loop: Element of a system indirectly influences itself



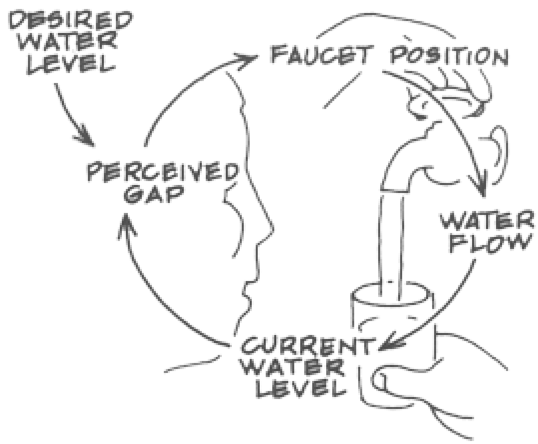
Feedback and Causal Loop Diagrams

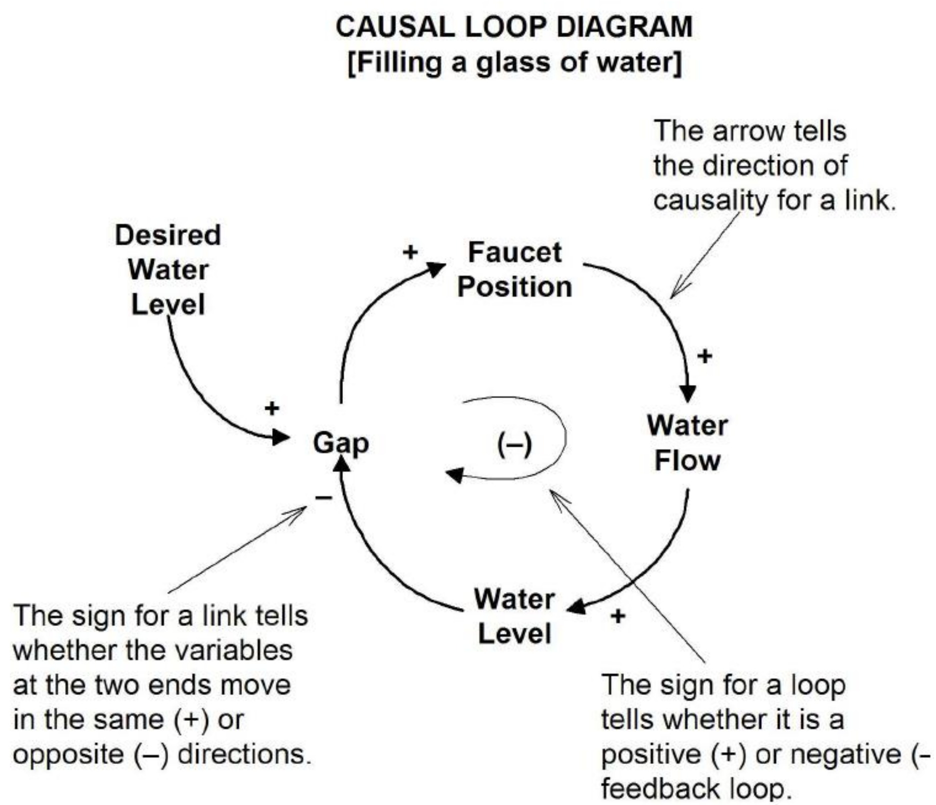
- Causal link
  - Causal link from element A to B is positive (+ or s) if either A adds to B or a change in A produces a change in B in the same direction
  - Causal link from element A to B is negative (- or o) if either A subtracts from B or a change in A produces a change in B in the opposite direction

- Feedback loop
  - A feedback loop is positive (+ or R) if it contains an even number of negative causal links
  - A feedback loop is negative (- or B) if it contains an uneven number of negative causal links

s=same; o=opposite; R=reinforcing; B=balancing

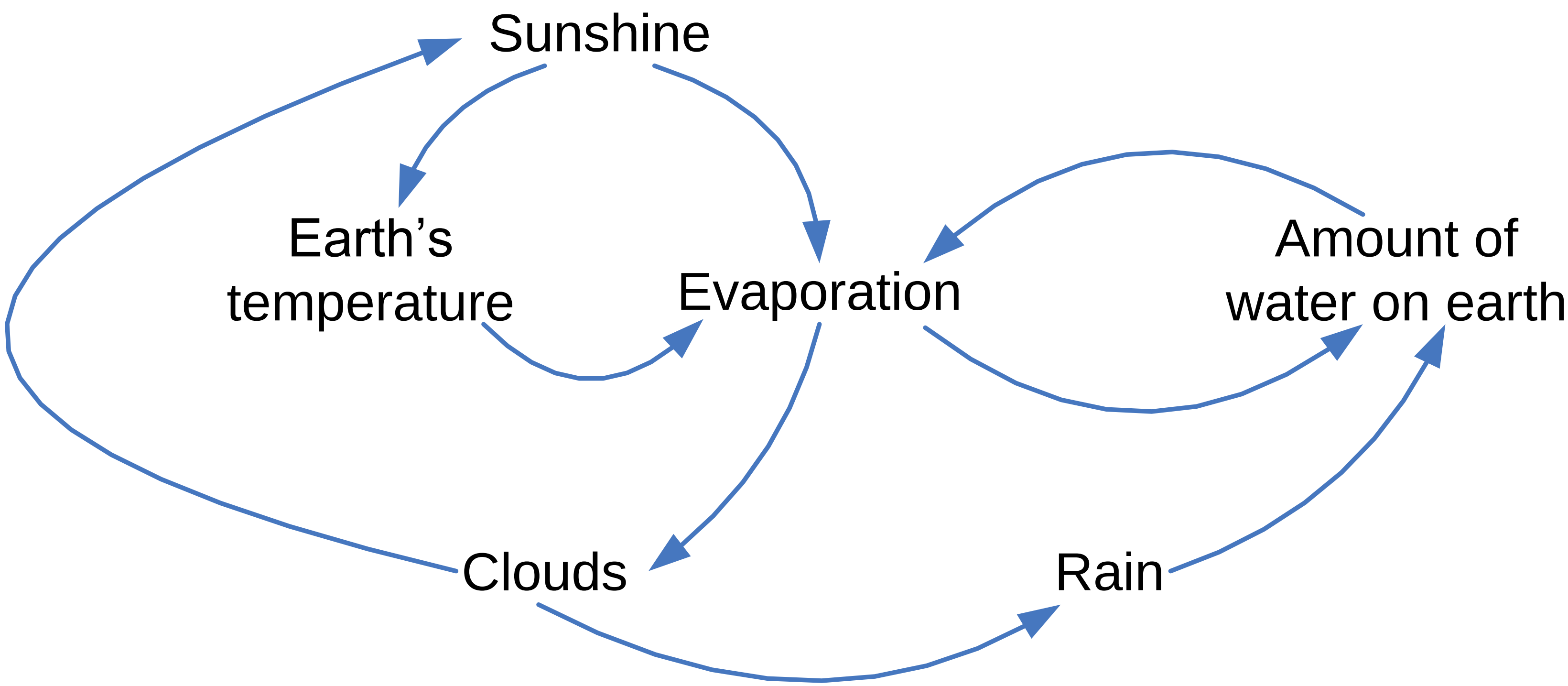
Feedback and Causal Loop Diagrams





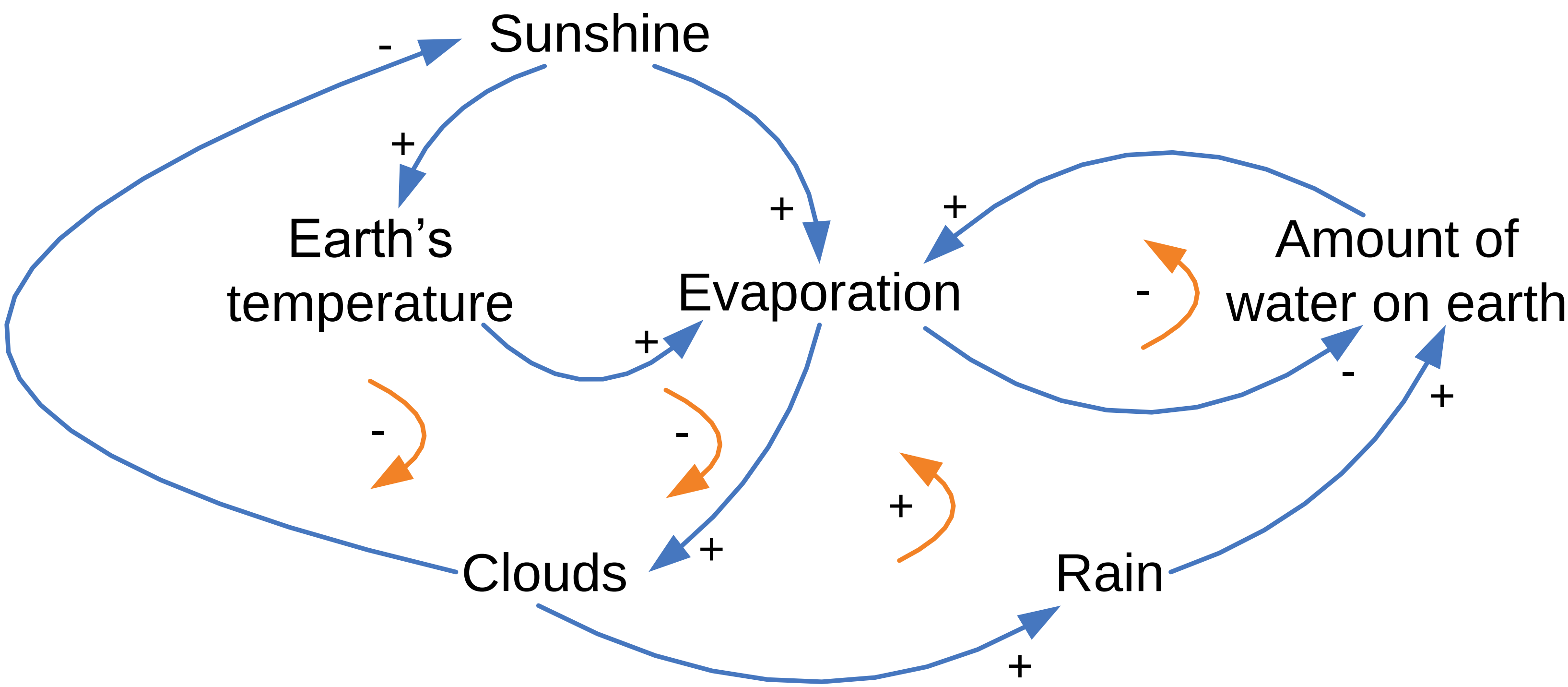
Feedback and Causal Loop Diagrams

- Self regulating biosphere



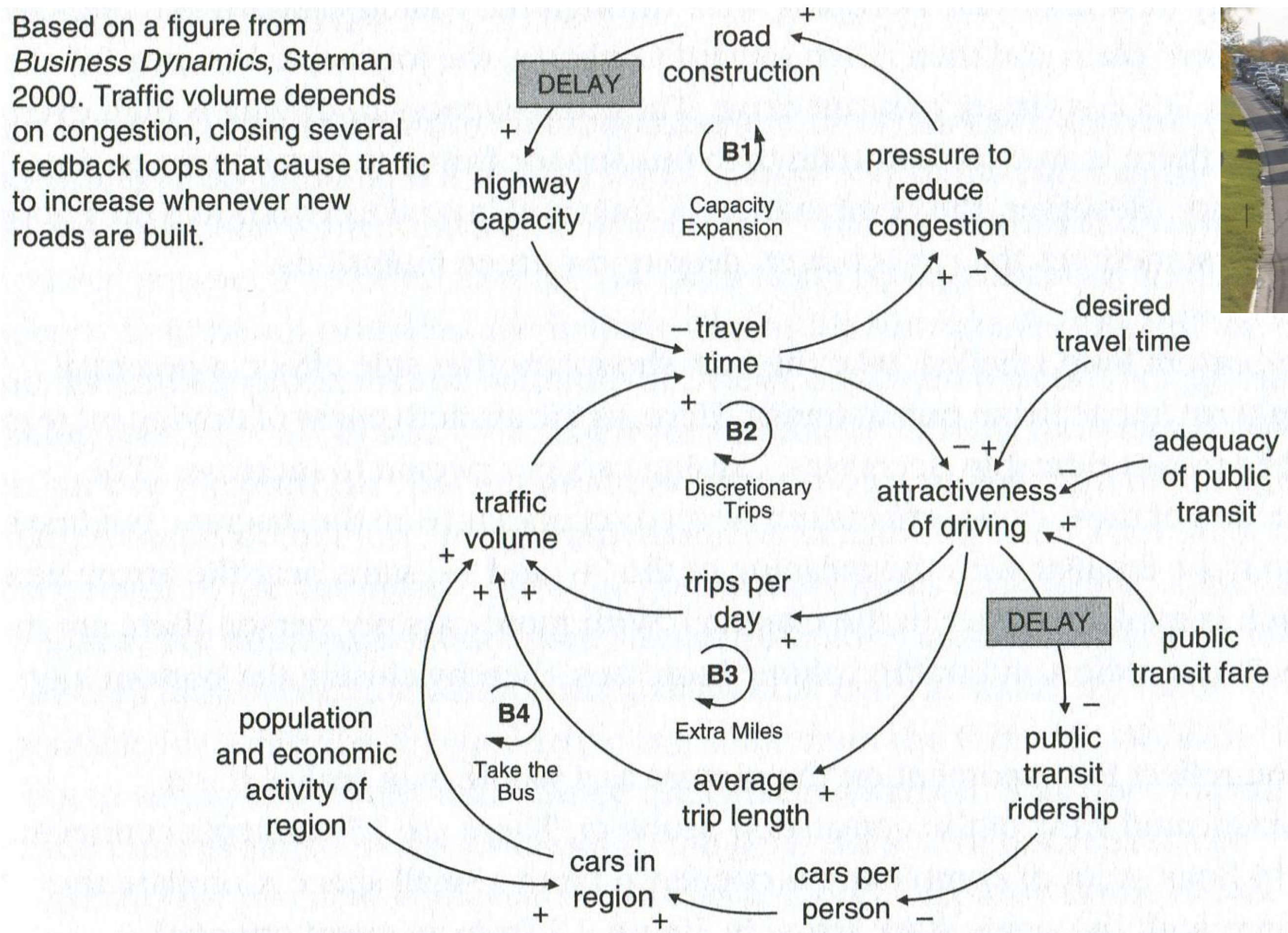
Feedback and Causal Loop Diagrams

- Self regulating biosphere



Example: Reduce Road Congestion

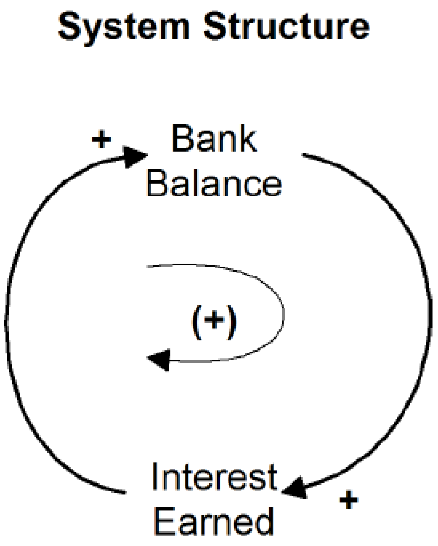
Based on a figure from *Business Dynamics*, Sterman 2000. Traffic volume depends on congestion, closing several feedback loops that cause traffic to increase whenever new roads are built.

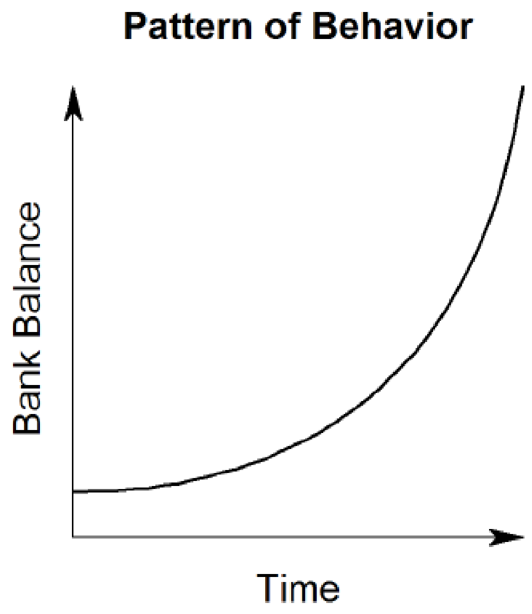


[Morecroft 2007]

System Structures and Patterns of Behaviour

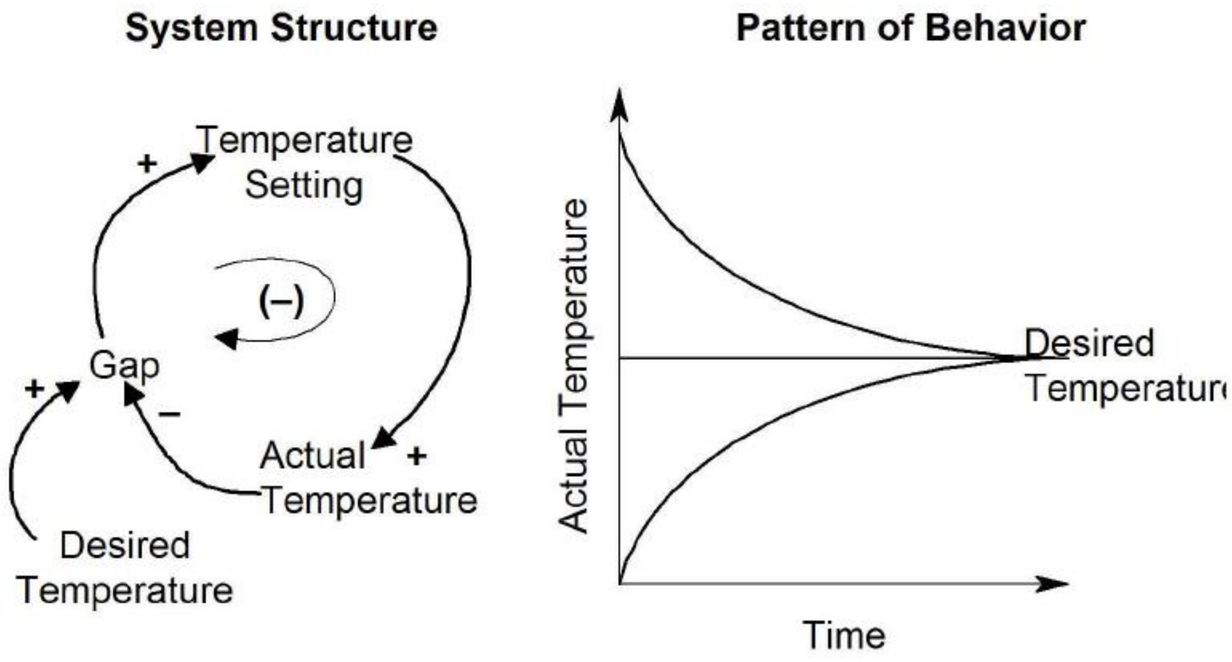
- Positive (reinforcing) feedback loop [e.g. growth of bank balance]





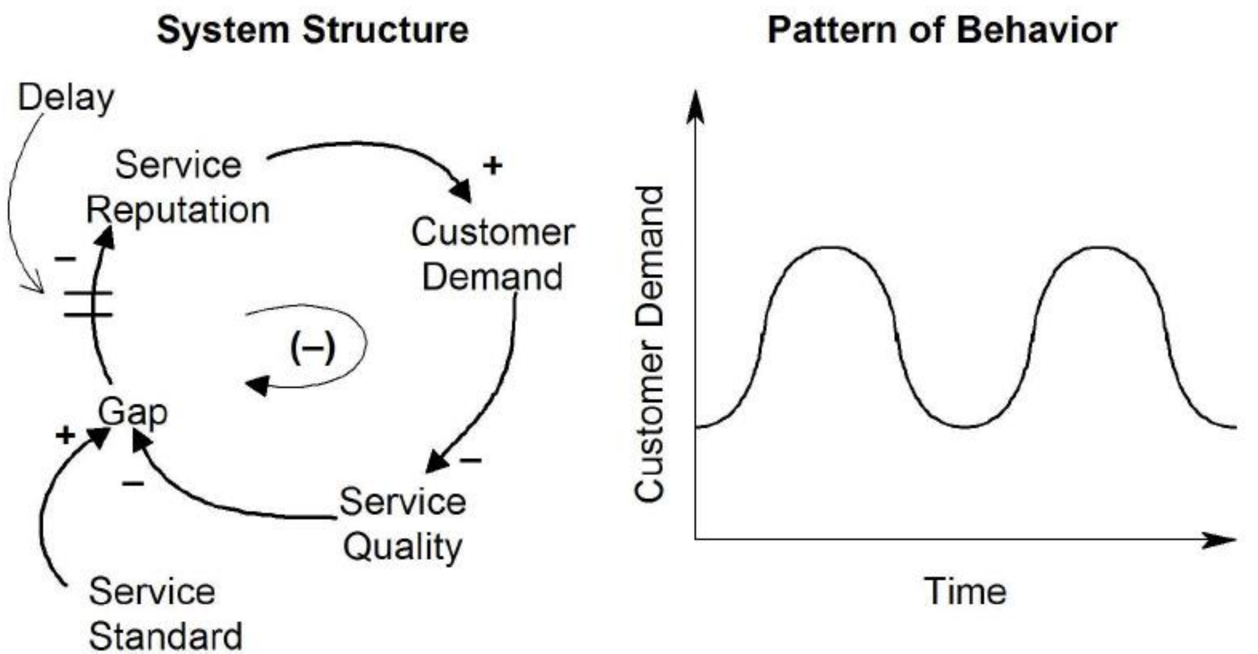
System Structures and Patterns of Behaviour

- Negative (balancing) feedback loop [e.g. electric blanket]



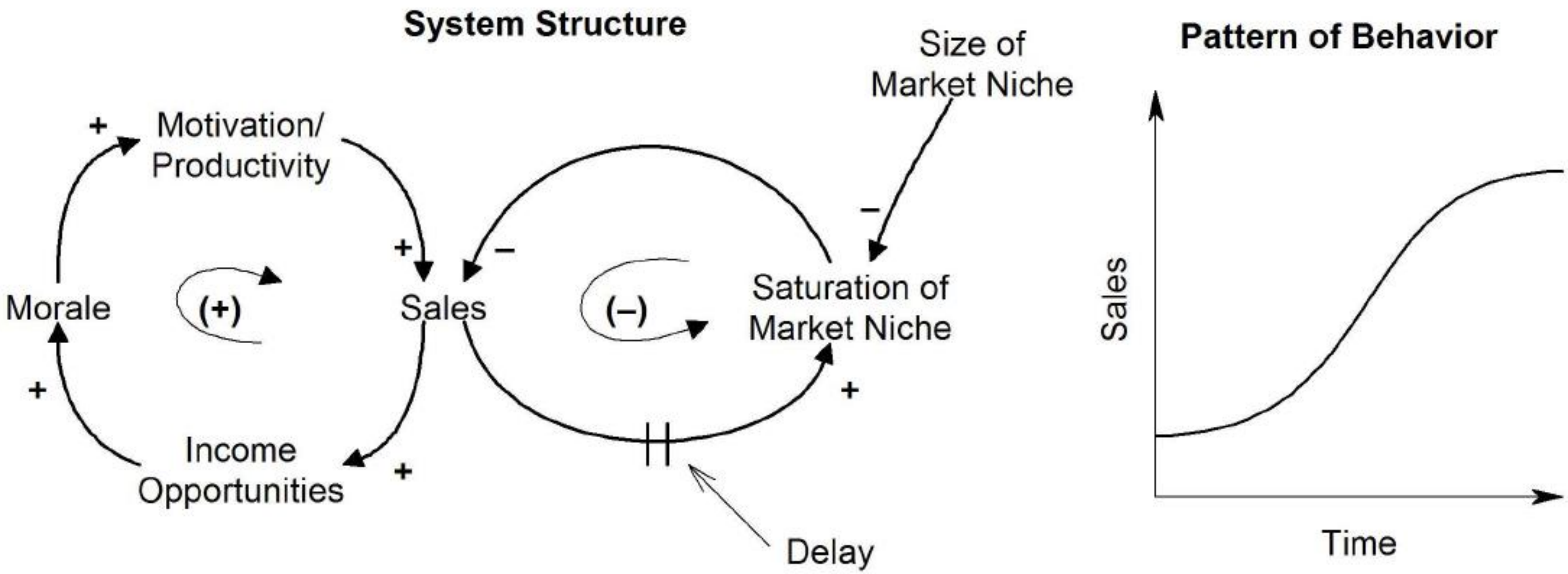
System Structures and Patterns of Behaviour

- Negative feedback loop with delay [e.g. service quality]



System Structures and Patterns of Behaviour

- Combination of positive and negative loop [e.g. sales growth]



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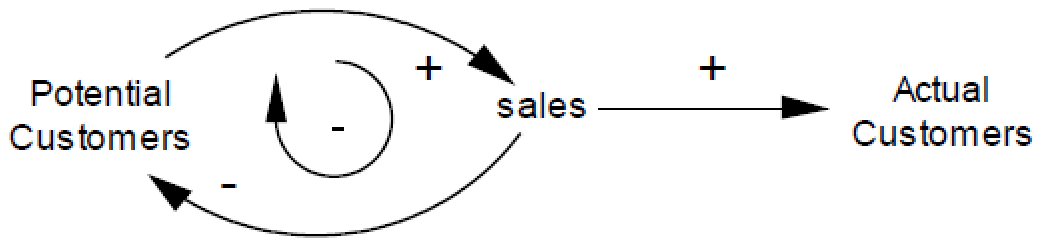
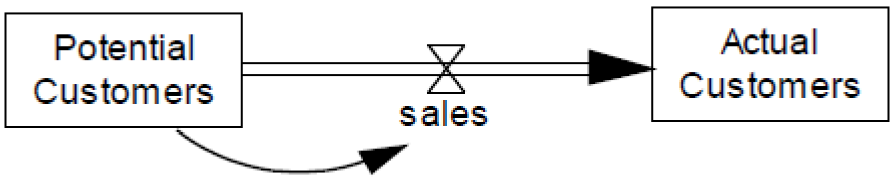
Stock and Flow Diagrams

- Example: Advertising for a durable good



a. Causal loop diagram



b. Stock and flow diagram

Stock and Flow Diagrams

- Stock and flow diagram:
  - Shows relationships among variables which have the potential to change over time (like causal loop diagrams)
  - Distinguishes between different types of variables (unlike causal loop diagrams)

- Basic notation:
  - Stock (level, accumulation, or state variable) {Symbol: Box}
    - Accumulation of "something" over time
    - Value of stock changes by accumulating or integrating flows
    - Physical entities which can accumulate and move around (e.g. materials, personnel, capital equipment, orders, stocks of money)

Stock and Flow Diagrams

- Basic notation (cont.)
  - Flow (rate, activity, movement) {Symbol: valve}
    - Flow or movement of the "something" from one stock to another
    - The value of a flow is dependent on the stocks in a system along with exogenous influences
  - Information {Symbol: curved arrow}
    - Between a stock and a flow: Indicates that information about a stock influences a flow

Stock and Flow Diagrams

- Additional notation
  - Auxiliary {Symbol: Circle}
    - Arise when the formulation of a stock's influence on a flow involves one or more intermediate calculations
    - Often useful in formulating complex flow equations
  - Source and Sink {Symbol: Cloud}
    - Source represents systems of stocks and flows outside the boundary of the model
    - Sink is where flows terminate outside the system

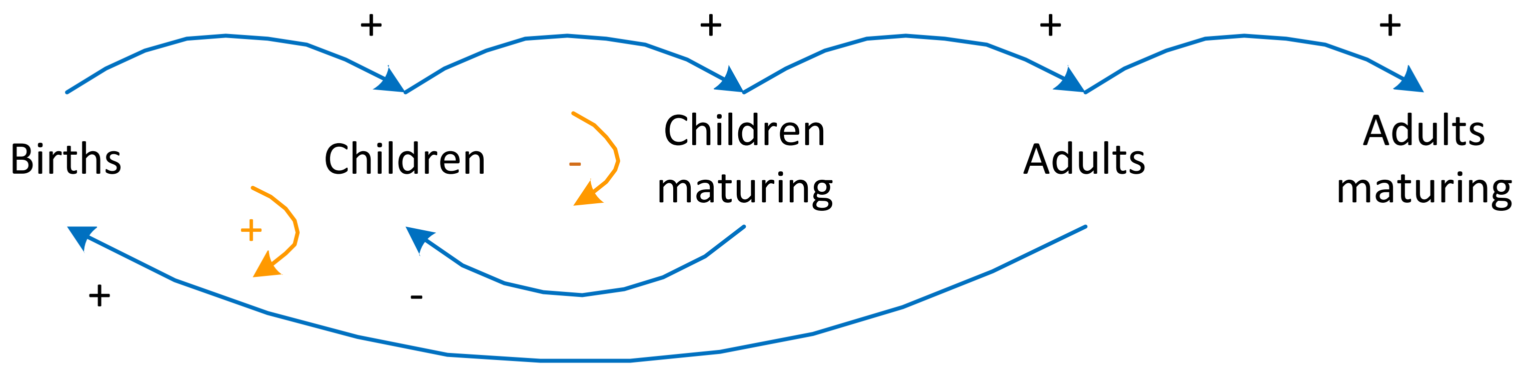
Stock and Flow Diagrams

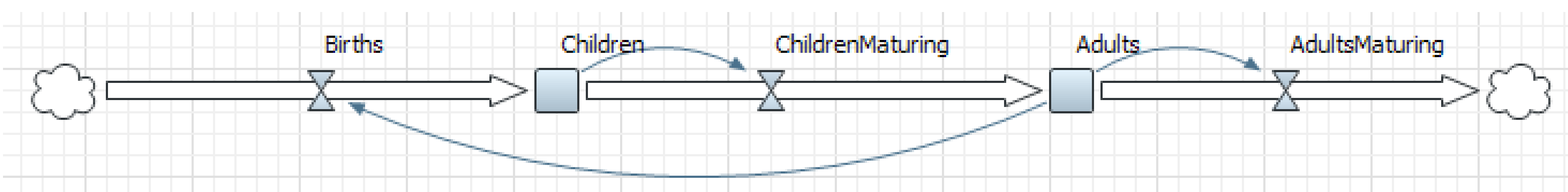
- Growth of population through birth
  - Find the causal links and feedback loops

Births | Children | Children maturing | Adults | Adults maturing

Stock and Flow Diagrams

- Growth of population through birth



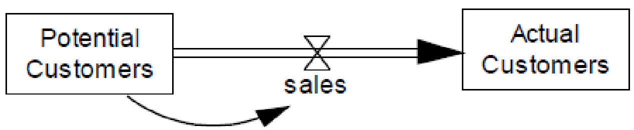


System Dynamics Simulation

- Computation behind the System Dynamics simulation
  - Time slicing
    - At each time point ...
      - Compute new stock levels at time point
      - Compute new flow rates after the stocks have been updated (flow rate held constant over dt)
      - Move clock forward to next time point
  - The software must apply numerical methods to solve the integrations
    - Integration errors

System Dynamics Simulation

- Back to the advertising example ...
  - Can our stock and flow diagram below help us answering the question: How will the number of potential customers vary with time?



b. Stock and flow diagram

No!

  - We need to consider the quantitative features of the process
    - Initial number of potential and actual customers
    - Specific way in which sales flow depends on potential customers

System Dynamics Simulation

- Simplifying assumptions
  - Aggregate approach is sufficient
  - Flows within processes are continuous
  - Flows do not have a random component

- Analogy: Plumbing system
  - Stocks are tanks full of liquid
  - Flows are pumps that control the flow between the tanks

- To completely specify the process model
  - Initial value of each stock + equation for each flow

System Dynamics Simulation

- Number of potential customers at any time t

$$\text{Potential Customers}(t) = 1,000,000 - \int_0^t \text{sales}(\tau)\, d\tau.$$

- Number of actual customers at any time t

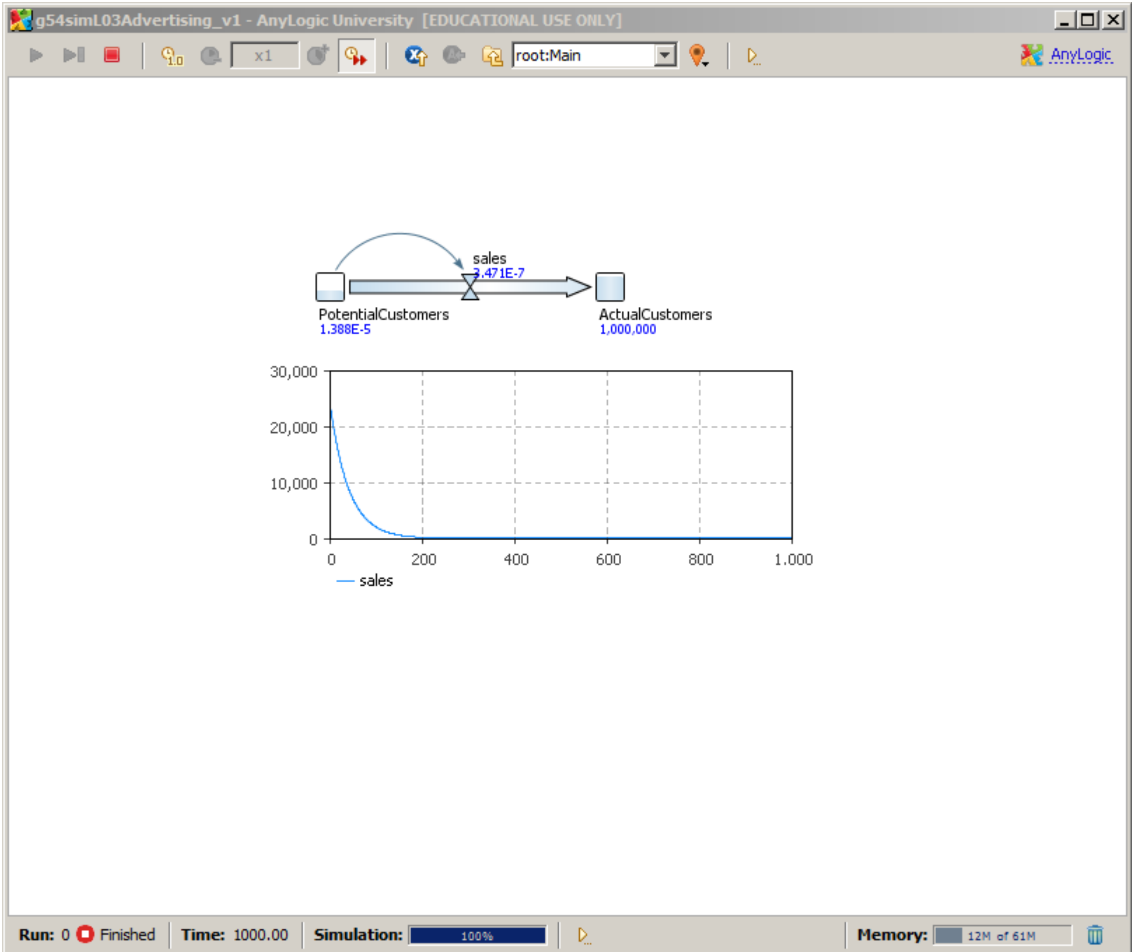
$$\text{Actual Customers} = \int_0^t \text{sales}(\tau)\, d\tau.$$

- Many possible flow equations! It is up to the modeller to choose a realistic one

$$\text{sales}(t) = 0.025 \times \text{Potential Customers}(t)\text{rs}(t) > 0$$

$$0, \qquad \text{otherwise}$$

System Dynamics Simulation



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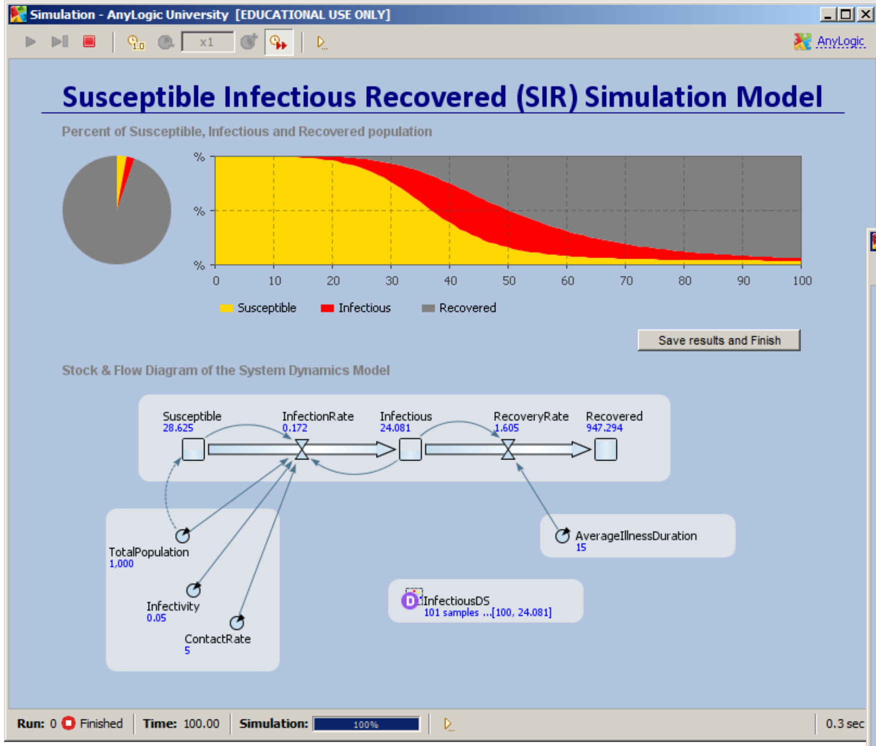
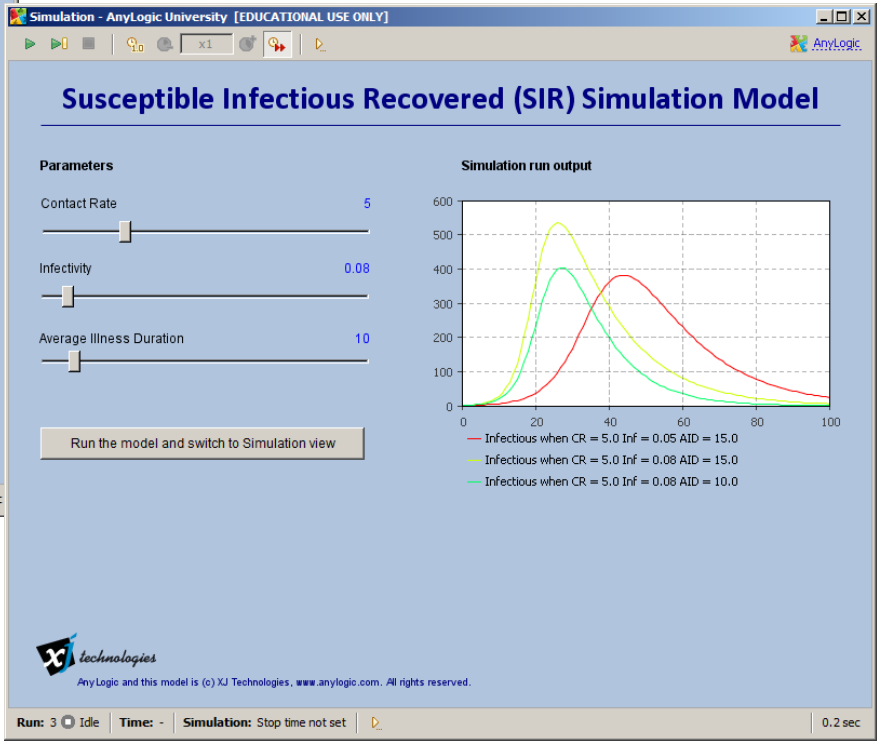
System Dynamics Simulation





Further Reading & Acknowledgement

- Further reading:
  - Kirkwood (1998) System Dynamics Methods: A Quick Introduction
  - Morecroft (2007) Strategic Modelling and Business Dynamics
  - Sterman (2000) Business Dynamics: Systems Thinking and Modeling for a Complex World (all simulation models in this book are available as AnyLogic sample models - see AnyLogic Help)
  - Proceedings of the International System Dynamics Conference
  - VenSim User's Guide

- Acknowledgement:
  - Slides are based on Kirkwood (1998) and Fishwick (2011)

Summary

- What did you learn?

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Questions / Comments

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References

- Fishwick P (2011) CAP4800/5805 Computer Simulation: System Dynamics Lecture Slides (http://www.cise.ufl.edu/~fishwick/cap4800/sd1.ppt)
- Kirkwood CW (1998) System Dynamics Methods: A Quick Introduction (http://www.public.asu.edu/~kirkwood/sysdyn/SDIntro/SDIntro.htm)
- Morecroft JD (2007) Strategic Modelling and Business Dynamics. Wiley, Chichester, UK.
- Proceedings of the International System Dynamics Conference (1983-2012) (http://conference.systemdynamics.org/past_conference/)
- Sterman JD (2000) Business Dynamics: Systems Thinking and Modeling for a Complex World. McGraw Hill, Boston, USA.
- VenSim User's Guide (http://www.vensim.com/ffiles/VensimUsersGuide.zip)