Aalto University
School of Science

System Dynamics – Complex systems

System Dynamics

- **System dynamics** (**SD**) is an approach to understanding the nonlinear behaviour of **complex systems** over time using stocks, flows, internal feedback loops, table functions and time delays. [Wikipedia]
- SD was originally developed in the 1950s to help corporate managers improve their understanding of industrial processes.
- Currently SD is being used throughout the public and private sector for policy analysis and design.

System Dynamics

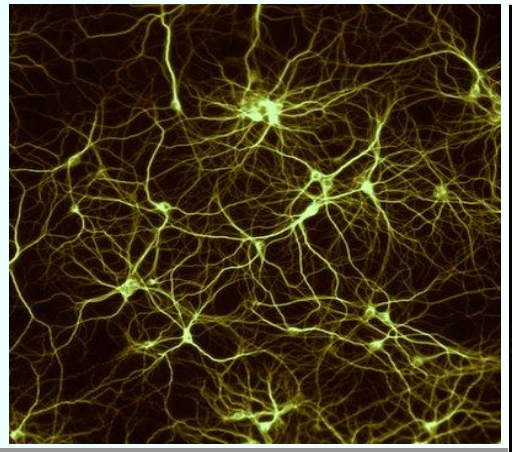
- Operationally SD applies simulation models to understand how systems behave and how to develop them
- SD uses all available sources of information and works with multiple disciplines: natural sciences, economy, psychology, sociology, …

Dynamic systems

- A system is **dynamic**, when its state is a function of earlier state
  - A dynamic system has memory and inertia
  - The response of the system to a stimulus may continue a long time after the stimulus – it is necessary to know the history of the system
- A **static** system has neither memory nor intertia
  - The response of a static system can be observed immediately after the stimulus

Complex systems

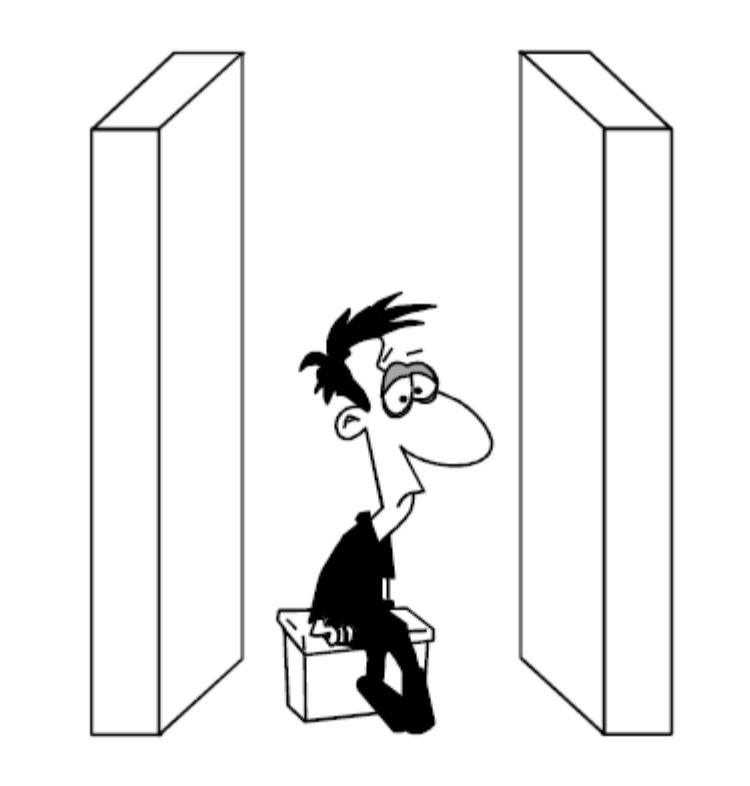
- A **complex system** is a system composed of many components which may interact with each other.
  - Examples: Earth's global climate, organisms, the human brain, infrastructure such as power grid, transportation or communication systems, social and economic organizations, an ecosystem, a living cell, and ultimately the entire universe.



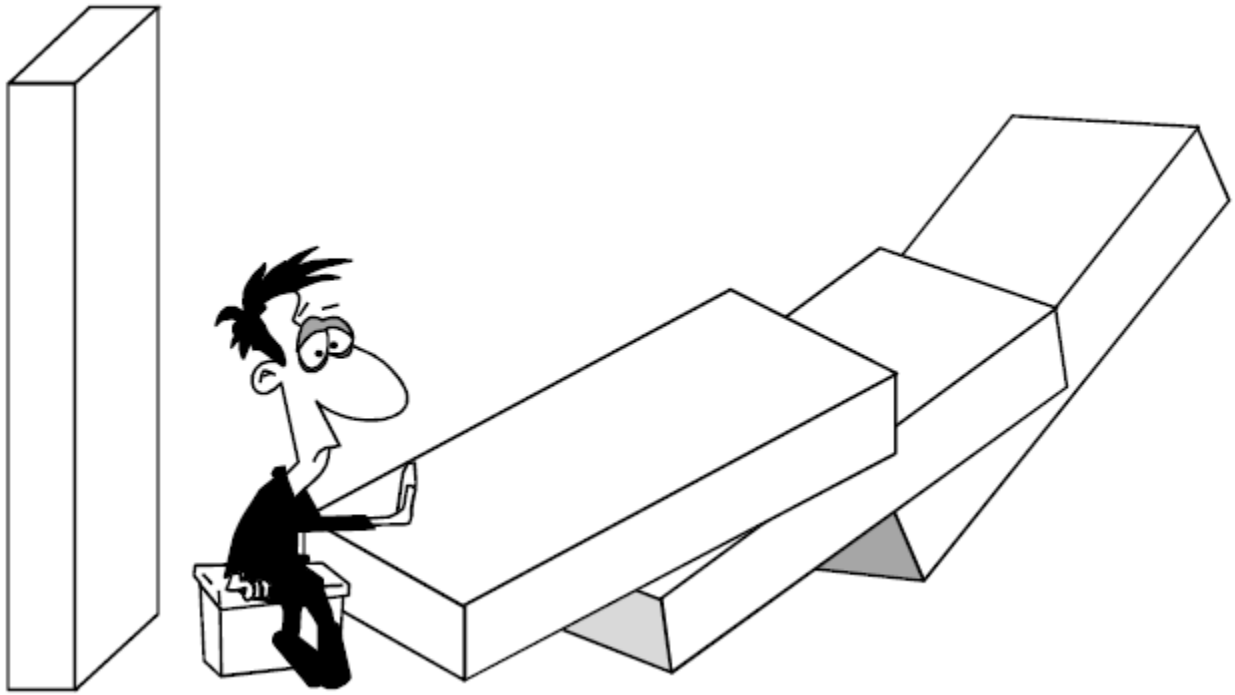
Complex systems

- Complex systems are systems whose behaviour is intrinsically difficult to model due to the dependencies, competitions, relationships, or other types of interactions between their parts or between a given system and its environment.
- Systems that are complex have distinct properties that arise from these relationships, such as nonlinearity, emergence, spontaneous ordering, adaptation, and feedback loops, among others.

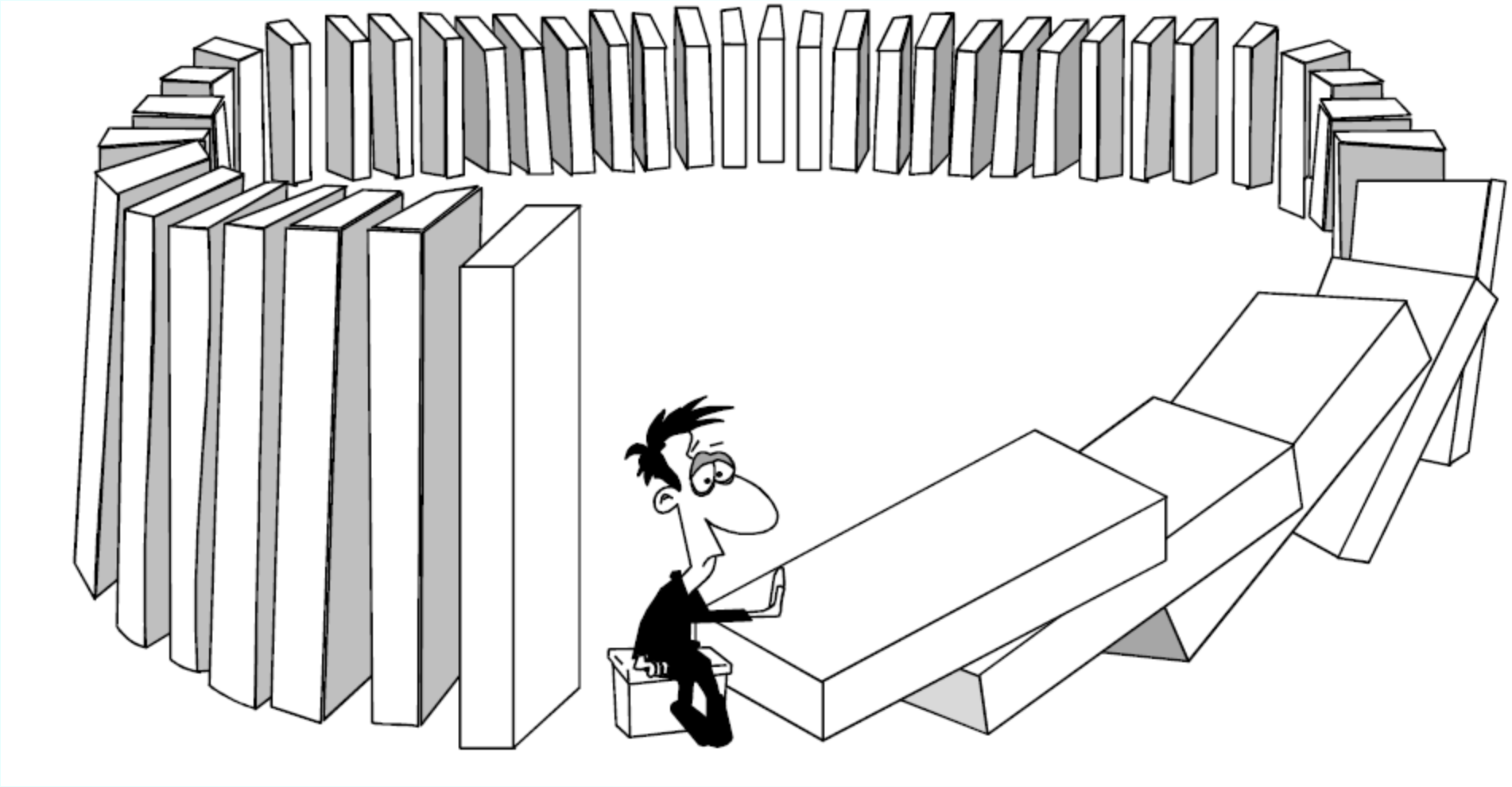
Complex systems



Complex systems



Complex systems



Policy resistance, the Law of Unintended Consequences and the Counterintuitive Behaviour of Social Systems

The unanticipated consequences of social action are always more important, and usually less agreeable, than the intended consequences. –Irving Kristol

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 first obligated to understand ... the whole systems. –Thomas Lewis

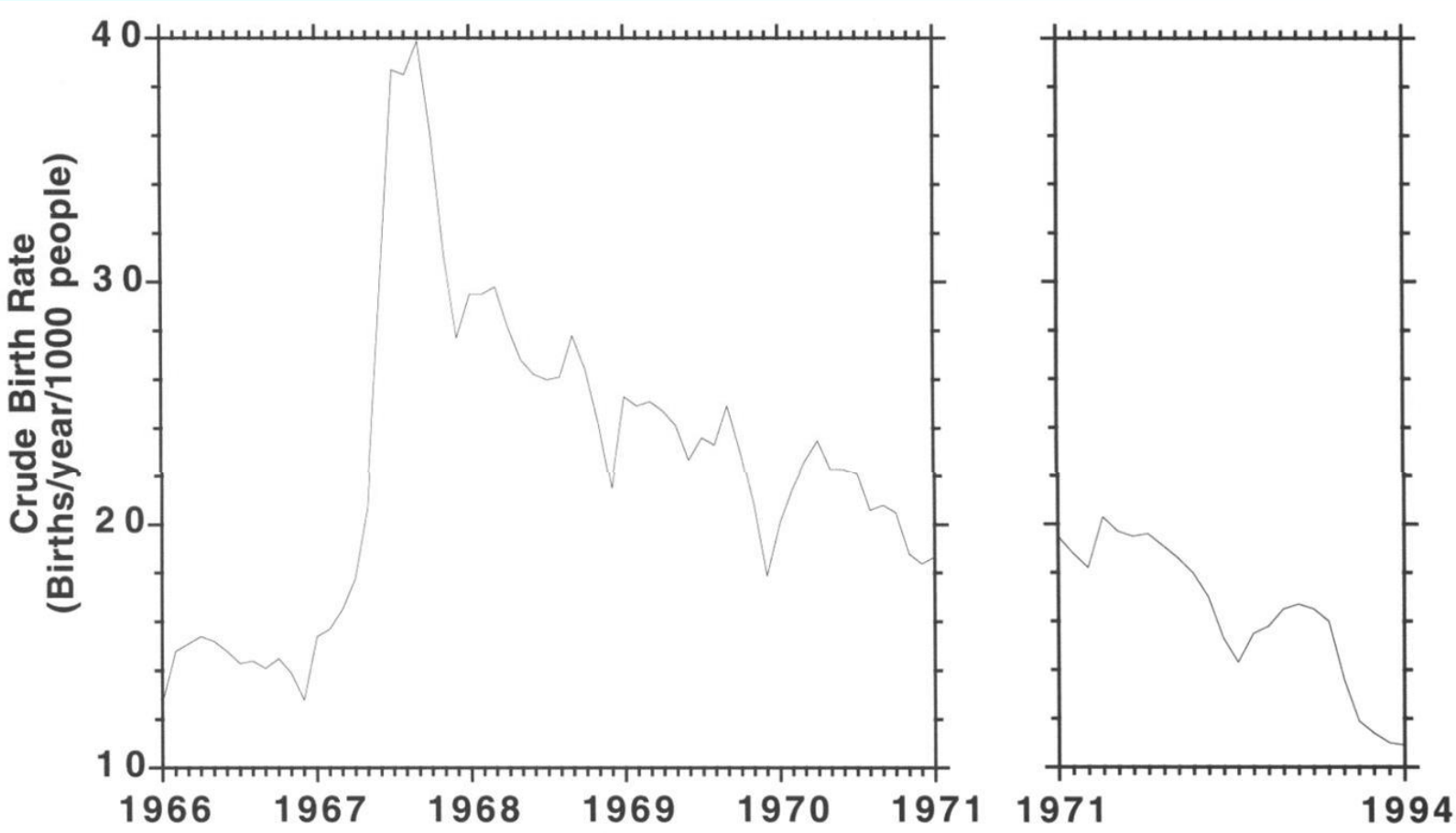
Policy resistance, the Law of Unintended Consequences and the Counterintuitive Behaviour of Social Systems

- *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 the one ill symptom produces others …*
  - Sir Thomas More
- *Anything that can go wrong will go wrong*
  - "Murphy"
- Too often attempts to solve serious problems fail because effects are
  - delayed, diluted, or worsen the situation

Case Romania

- Ceaușescu's communistic regime wanted to increase the low birth rate (1.5%) in late 60's by number of actions:
  - Abortion was banned
  - Contraceptives were banned
  - Propaganda to promote large families
  - Tax cuts for large families

Case Romania



Source: 1966–1971, David and Wright (1971); 1971–1994, *Romanian Statistical Yearbook 1995,* pp. 100–101. *Note:* 1971–1994 are annual averages.

Case Romania

- First policy seemed to have effect, but soon birth rate dropped again
- People found ways around the policy
  - Smuggling contraceptives from other countries
  - Illegal back-alley abortions
  - Deaths due to complications of abortions tripled
  - Number of neonatal deaths rose 300%
  - Due to powerty, people could not support their children, who were placed in state-run orphanages
  - Food was scarce in orphanages, blood transfusions were used as nutritionnal supplements
  - AIDS epidemic spread because needles were re-used
  - Government became highly impopular, bloody revolution in 1989

Other cases

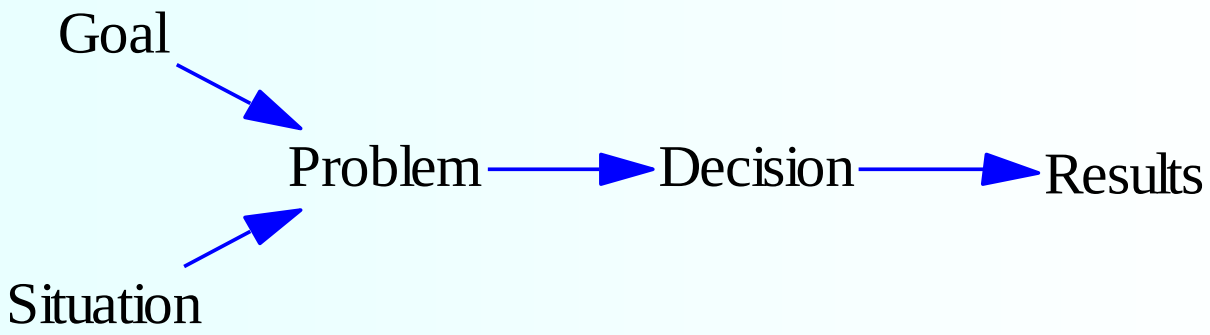
- Smokers of light cigarrettes get more carcinogens than normal cigarrette smokers
- Flood control efforts such as levee and dam constructions have led to more severe floods
- Antibiotics have stimulated evolution of drug-resistant pathogens
- Pesticides and herbicides have stimulated evolution of resistant pests and weeds
- Rat effect: In Hanoi, Vietnam under French colonial rule bounty was paid for each rat killed, evidenced by rat tail.
- Cobra effect: India under British rule
- IPCC carbon credits for destroying HFC-23
- Strong national CO2 reduction actions drive industry to other countries with less stringent policy

IPCC carbon credits for destroying HFC-23

- The UN Intergovernmental Panel on Climate Change kicked off an incentive scheme in 2005 to cut down on greenhouse gases. Companies disposing of polluting gases get rewarded with carbon credits
  - These can be converted into cash.
- The program set prices according to how serious the damage the pollutant could do to the environment was, and attributed one of the highest bounties for destroying HFC-23
  - a byproduct of a common coolant
- As a result, companies began to produce more of this coolant in order to destroy more of the by-product waste gas, and collect millions of dollars in credits.
- Credits for the destruction of HFC-23 were suspended in the European Union in 2013

Causes of policy resistance

- We tend to interpret experience as a sequence of events but not consider the possible feedbacks



Example: Company sales is 80M€ when goal is 100M€

Problem is to increase sales by 20%

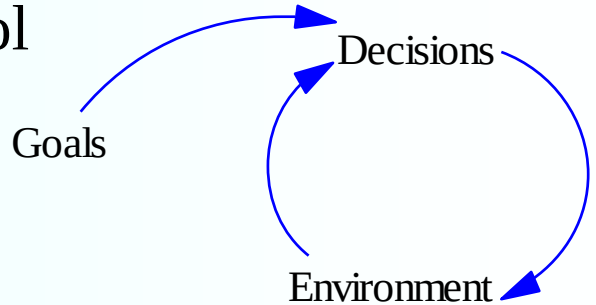
Possible action is to lower prices to boost sales

Market share increases and sales increases solving problem?

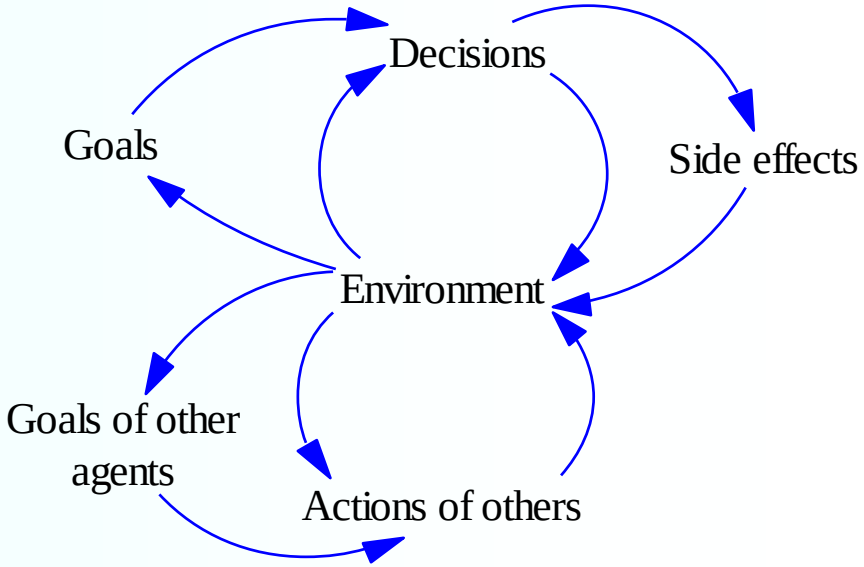
(But then also competitors may lower their prices…)

Causes of policy resistance

- Simple view that we can control everything

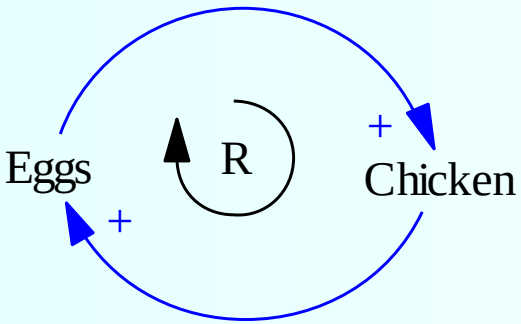


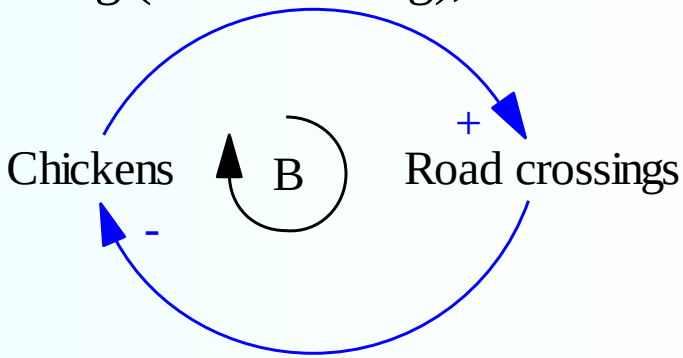
- In practice there may be
  - unexpected side-effects
  - delayed reactions,
  - changes in goals,
  - interventions of other agents
- Such feedbacks may lead to unexpected results and ineffective policies



Feedbacks

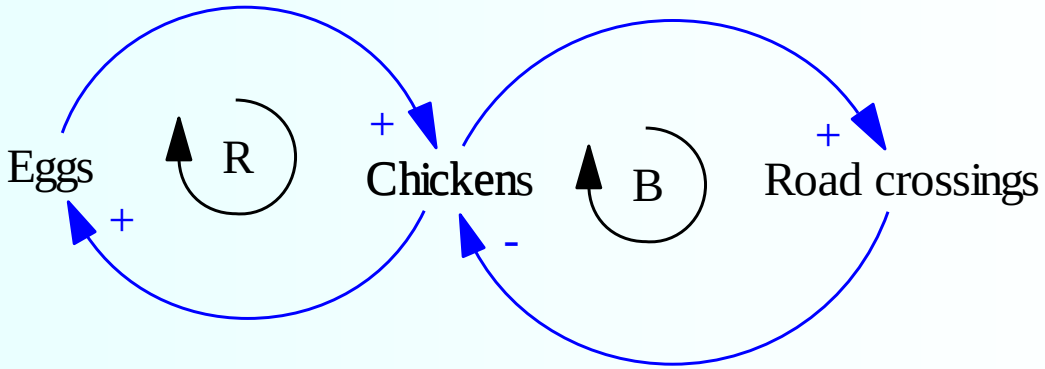
- Defining feedback is central in system dynamics
- Often complex behaviour is caused by feedbacks rather than individual system components
- Dynamics is caused by different feedback loops
- Two kinds of feedback
  - Positive feedback: self-reinforcing (**R**), boosts change of system state
  - Negative feedback: self-correcting (**B**=Balancing), resists change





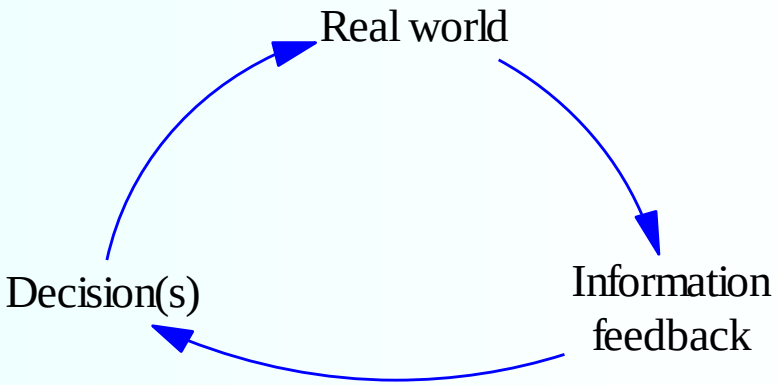
Multi-loop systems

- What happens when both loops are simultaneously active?



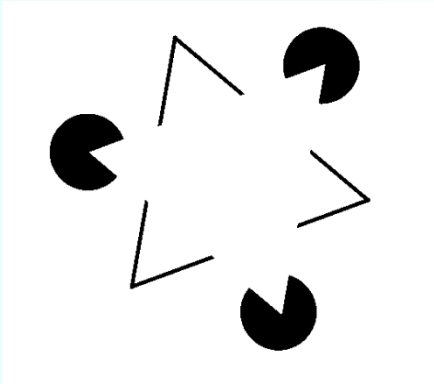
Learning is a feedback process

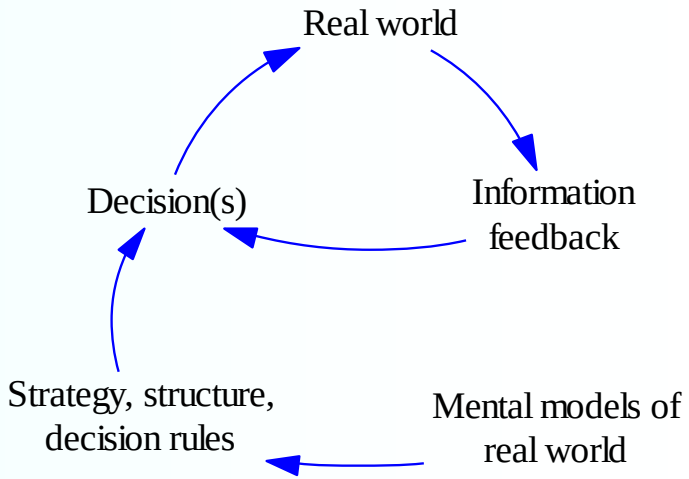
- All learning depends on feedback
- Feedback from the real world to the decision maker (DM) includeds all forms of information: both quantitative and qualitative
- Classical negative feedback system: DM compares system with his goal and takes actions that (he believes) moves the world towards desired state
  - Setting prices
  - Driving a car



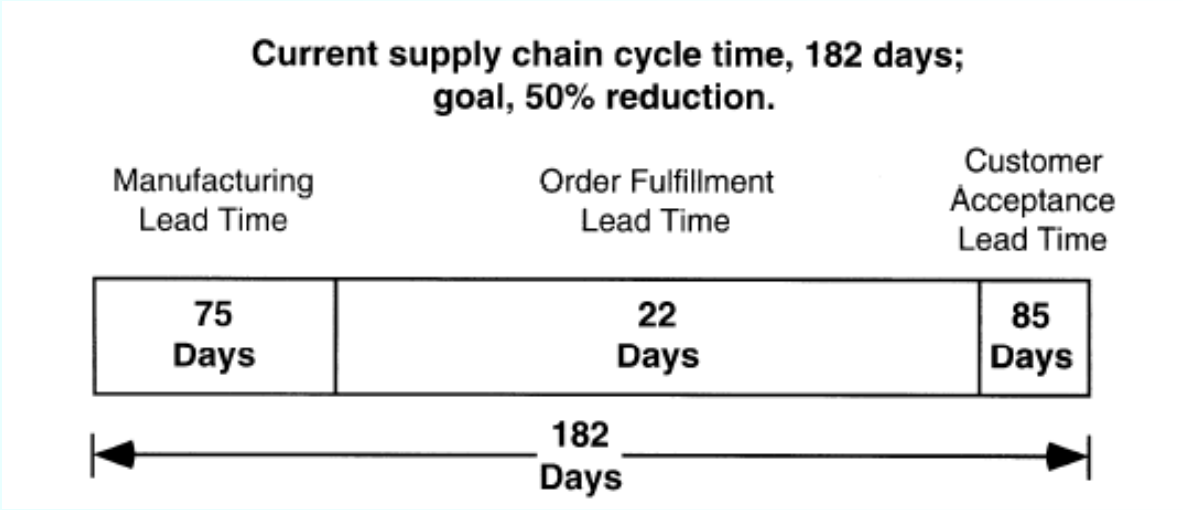
Learning as feedback process: single-loop and double-loop learning

- Decisions/policies are conditioned by institutional structures, organizational strategies and cultural norms
- These are governed by our **mental models** of the real world
  - Mental models restrict how we frame and define problems
- When mental models are invariant, this is called **single-loop learning**





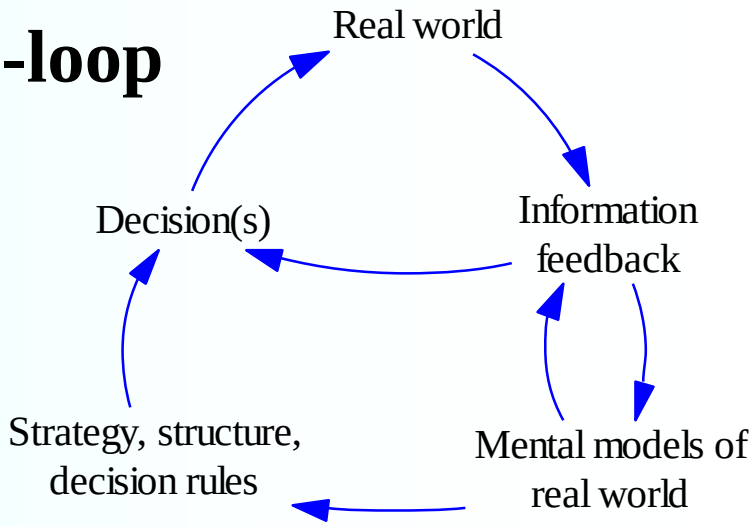
Mental model example: Supply chain streamlining



- To improve competitiveness of company, it was essential to cut cycle time of supply chain in half
- A team was formed to solve the problem, the above figure was presented at first meeting
- The team focussed on decreasing order fulfillment lead time. Why? What is wrong with that choice?

Learning as feedback process: single-loop and double loop-learning

- Feedback can stimulate changes also in the mental model
- Such learing involves new undestanding or reframing of a situation, and leads to new goals and new decision rules, not just new decisions
- This process is called **double-loop learning**

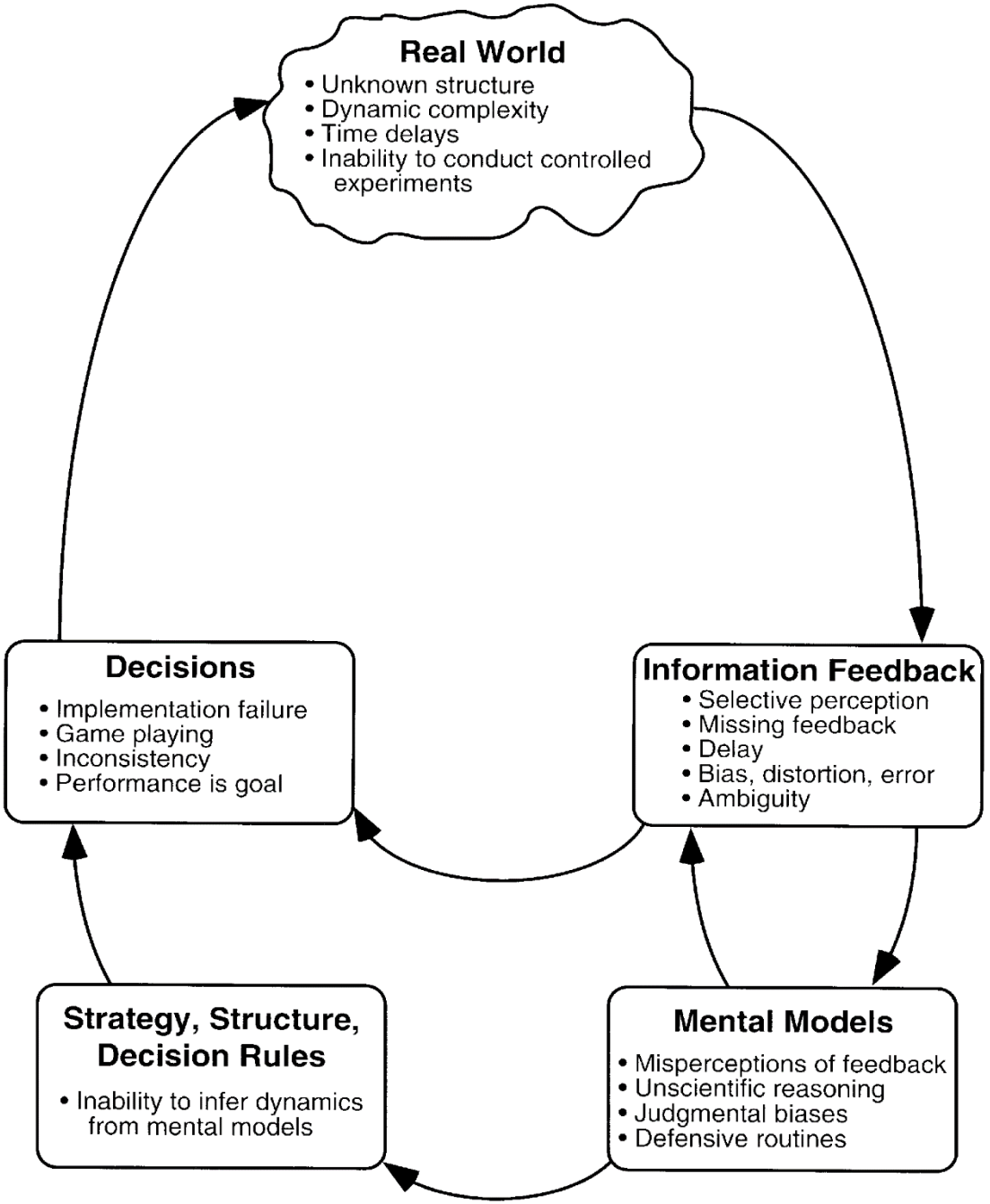


Barriers to learning as feedback process: Example

- Prior to 1600, scurvy (vitamin C deficiency) was greates killer of seafarers
- In 1601 a controlled experiment proved that 3 tsp lemon juice daily prevented scurvy
- In 1795 British Royal Navy begins using citrus → Scurvy is wiped out on their ships
- In 1865 The British Board of Trade mandates citrus use → Scurvy is wiped out in merchant marine

Barriers to learning

- In double-loop learning both loops must work effectively and quickly in relation to speed of change in the real system
- …but often these feedbacks work neither well nor fast in the real world



Dynamic complexity arises because systems are

- Constantly changing – difficult to see long-term effects of individual actions
- Tightly coupled – everything is connected with everything
- Governed by feedback – actions cause effects that affect future decisions
- Non-linear
- History-dependent – many actions are irreversible, you cannot unscramble an egg
- Self-organizing – small perturbations are amplified by feedback
- Adaptive – capabilities and decision rules change over time
- Counter-intuitive – cause and effect distant in time and place
- Policy-resistant – seemingly obvious solutions fail/worsen situation
- Characterized by trade-offs – improving this worsens that

Limited information

- We experience the real world through filters
  - Estimates, distortions, delays, biases, errors
  - Known, unknown or unknowable imperfections
- ”The eye sees only what the mind is prepared to comprehend” - [Henri Bergson]
- Case: Deep ozone hole in Antarctis was scientifically proved in 1985
  - Nimbus 7 satellite by NASA had made measurements since 1978 and never indicated an ozone hole
  - NASA computers were programmed to reject very low ozone readings as instrument errors

Bounded Rationality and the Misperceptions of Feedback

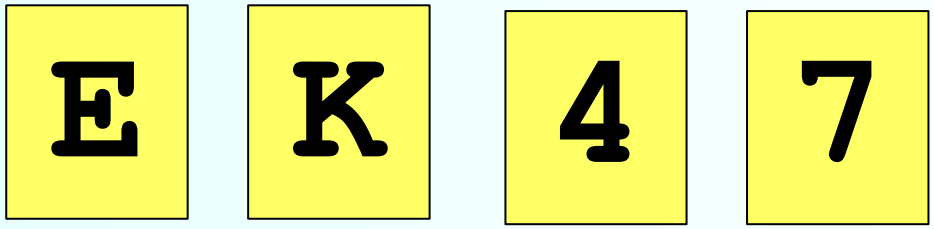
- Even with accurate feedback and proper mental models, it is difficult to make correct decisions
  - Emotions, reflex, unconscious motivations and other non-rational factors affect decision making
  - Even without the above factors, the complexity dynamic systems easily exceeds human capacity (Principle of bounded rationality by H. Simon)
  - Humans resort to rules of thumb, habits, and simple mental models
  - Humans can judge correctly only the most simple dynamic systems
    - Rice grains on chess board and exponential growth

Unscientific reasoning: Judgmental Errors and Biases

- To learn effectively in a world of dynamic complexity and imperfect information people would need ’insight skills’
- However, people
  - have difficulties generating alternative explanations,
  - underestimate uncertainty,
  - are over-confident with their judgments,
  - assess desired outcomes more likely than undesired outcomes (wishful thinking),
  - miscalculate probabilities and have the illusion of control over random phenomena

Hypothesis testing

- You see four cards. Each card has a letter on one side an number on other side.
- What is the smallest number of cards to turn to test the hypothesis: cards with vowels on one side have even numbers on the reverse? Which cards are they?



Virtual Worlds and Simulation

- Virtual worlds make learning/understanding easier
  - White box model with known structure and complete information
- Simulation is
  - Cheap, safe, fast
- Caveats
  - Accuracy of model
  - SD is not a spectator sport