Stocks and Flows

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INTRODUCTION

- Stock and flows, along with feedback are the two central concepts of system dynamics theory
- But before that, a brief history…

A Brief History

- *System Dynamics* was developed during mid-1950s by Prof. Jay W. Forrester (1918-2016) of M.I.T
- J. W. Forrester, electrical engineer by training, headed *Whirlwind Project* in 1940s-50s: storage device development, forerunner of today's RAM.
- In 1950's when Sloan School of Management was setup, he was invited to be part of it.
- Developed *System Dynamics* to study industrial systems.
  - Book: Industrial Dynamics (1961)
    - Business structure, Sales, Inventory, Ordering policies
    - Looked at expanding effects on supply chain due to fluctuating demands (now known as *bullwhip effect*)
    - Helped develop/ use computer simulation: SIMPLE→ DYNAMO

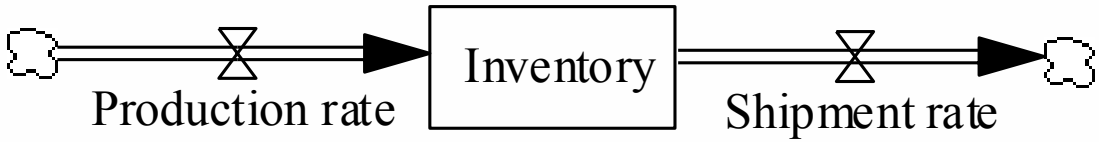
A Brief History (contd.)

- Other Books by J.W. Forrester
  - Urban Dynamics (1969): Problems of cities and urban development
  - World Dynamics (1971): World population, energy needs, environment
- These helped initiate the feasibility of modelling societal problems (still an ongoing debate though!)
- Forrester argues … "use of computerized system models to inform social policy is far superior to simple debate, both in generating insight into the root causes of problems and in understanding the likely effects of proposed solutions." (***Counterintuitive Behavior of Social Systems***, 1971 paper by JWF).

Modeling Basics

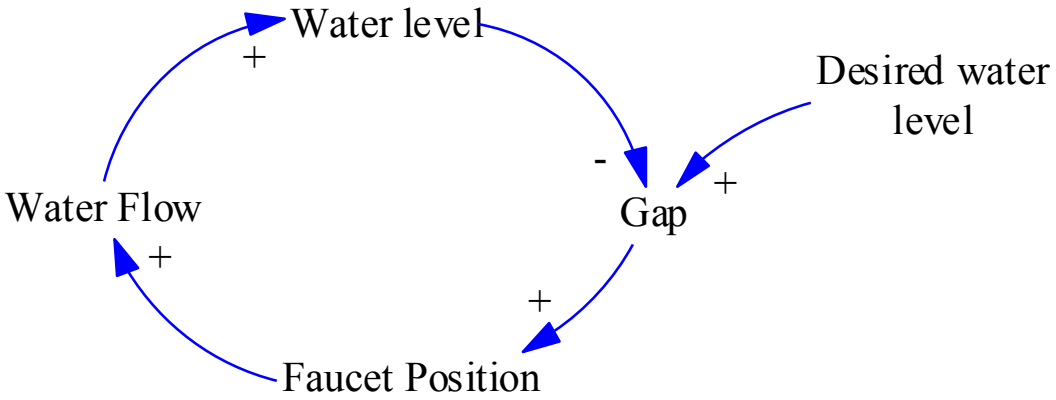
- **Stocks or Level**: Accumulate over time
- **Flow or Rate**: Causes Stocks to change over time
- **Auxiliary variable or Information**: Helps define other instantaneous variables/ calculations

Example:



- Mathematical representation

Example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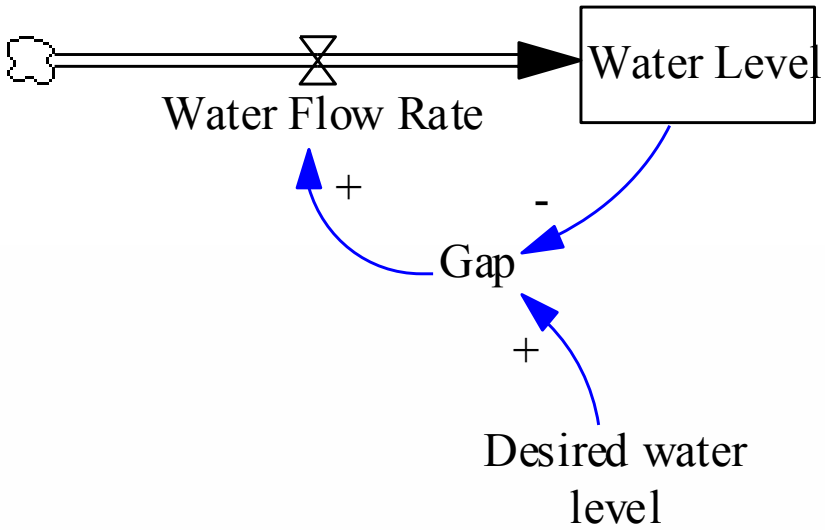
+
Desired water level
-
+
Water Flow
Gap
+
+
Faucet Position


Water Level
Water Flow Rate
+
-
Gap
+
Desired water level

Role of *Stocks*

- Stocks characterize the state of system
  - Provide snapshot status of system
  - Data to help make decisions
- Stocks provide system with inertia & memory
  - Stocks only change through rates
- Stocks are source of delays
  - All delays involve stocks
- Stocks decouple rates of flow and create disequilibrium dynamics
  - Absorbs differences between inflow & outflow

Identify stock and flows

- Using units of measure
  - Stocks are a *quantity*
  - Associated rates are same units *per time period*
- The Snapshot test
  - Imagine freezing the scene

- Stocks can be physical quantity, Information or Memories & beliefs
- Choice of time unit must be consistent
- Flow can be positive or negative
- Contents of stock-flow network is conserved

Examples

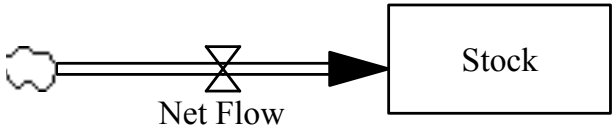
- Identification of Stock and Flows
- Mapping SFD model example

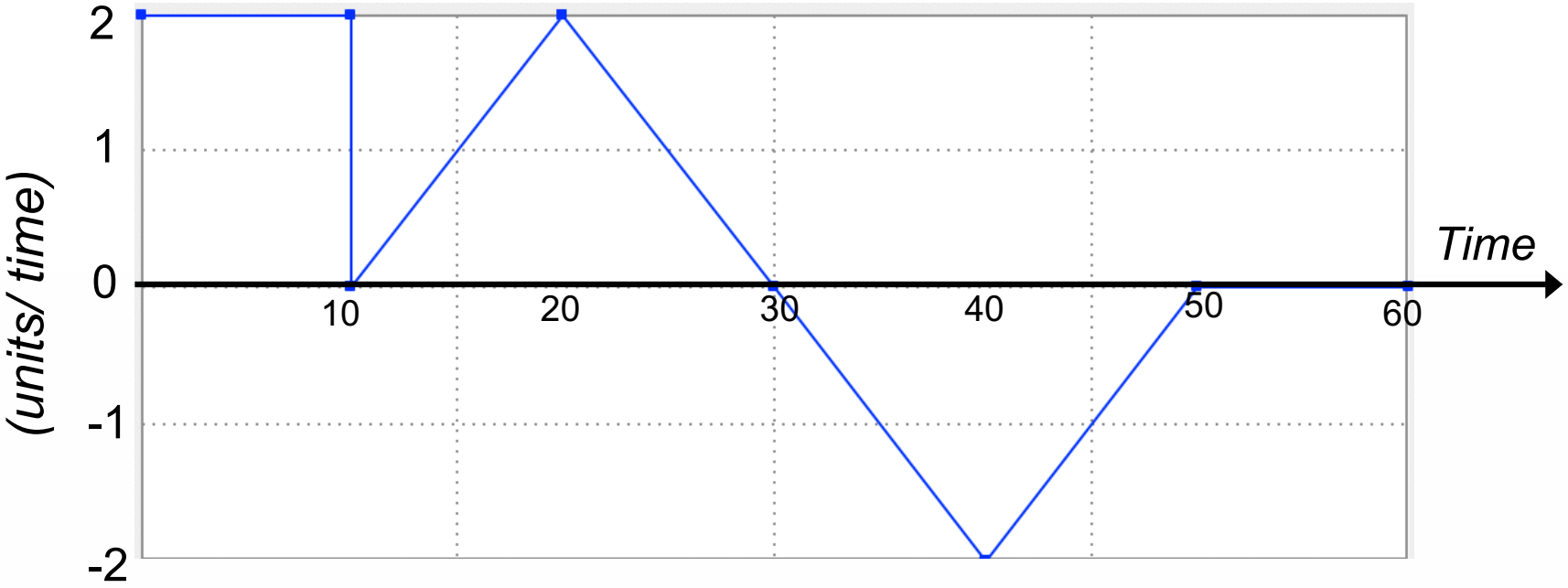
A manufacturing firm orders raw materials from outside, which it processes and produces finished products. The firm maintains an inventory of finished goods from which it ships to customers.

Customer order when received, is not immediately fulfilled. There is a delay caused by order processing, credit checks, etc, after which the order is fulfilled, subject to availability.

Dynamics of Stocks and Flows

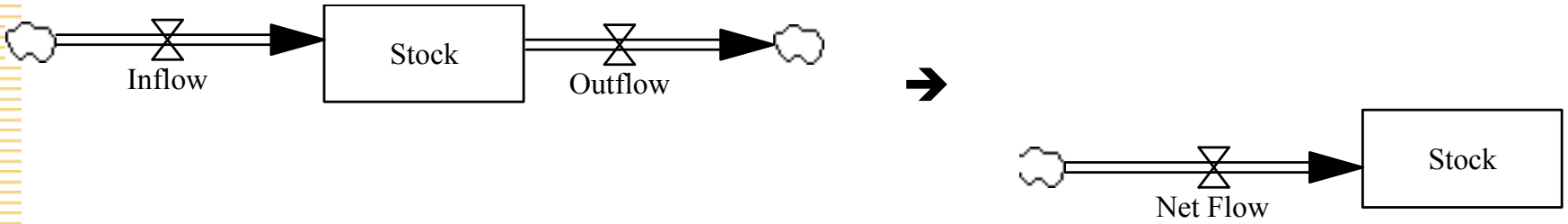
- Behavior of stock, given the flow rates
- Graphical integration
- Net Rate Example

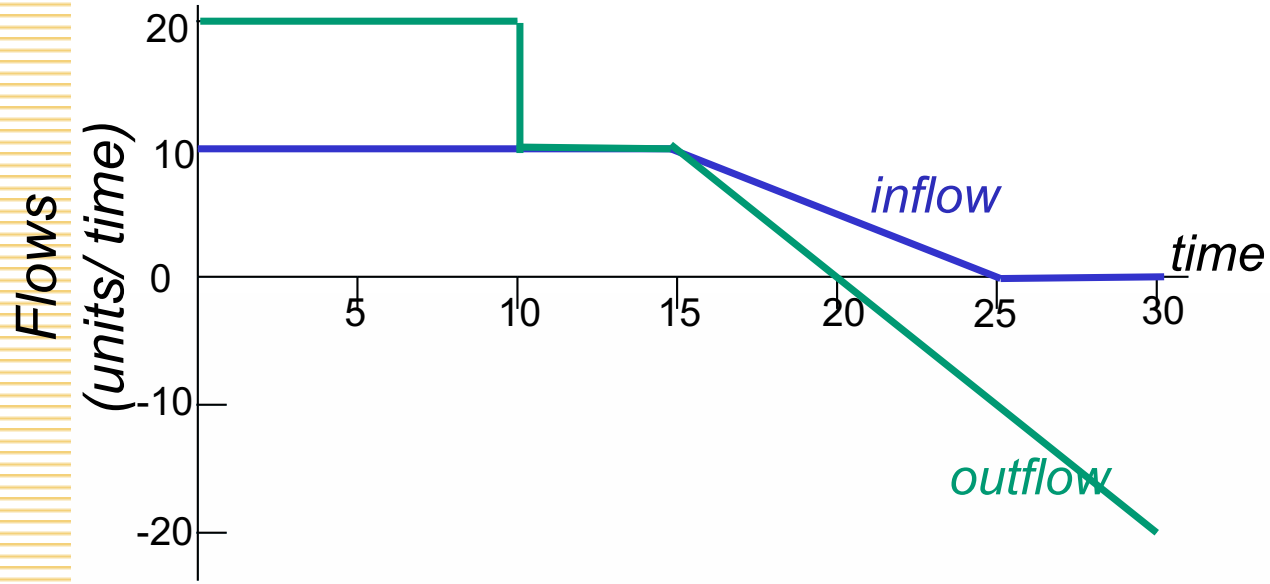




Dynamics of Stocks and Flows

- Computing Net Rate
- Net Rate(t) = Inflow(t) – Outflow(t)

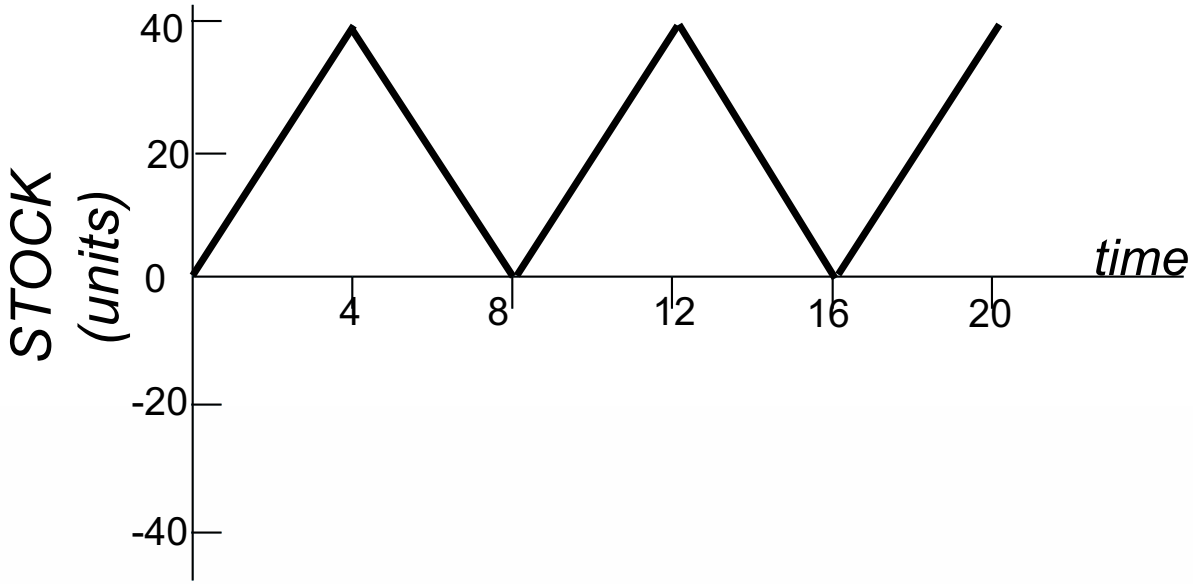




➔ Netflow?

Dynamics of Stocks and Flows

- Behavior of flows, *given stock behavior*
  - Graphical differentiation
  - Can only compute NetFlowRate(t)



➔ NetFlow?

Patterns of Behavior

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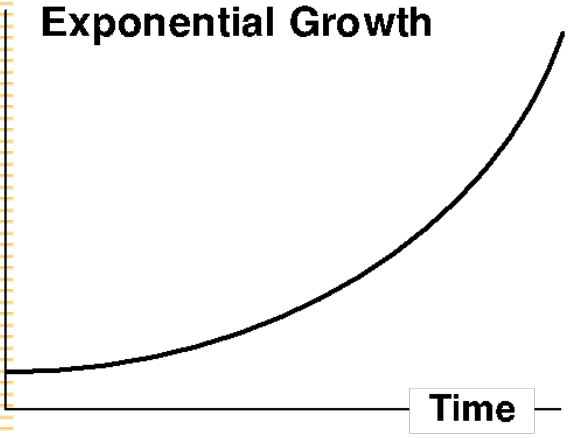
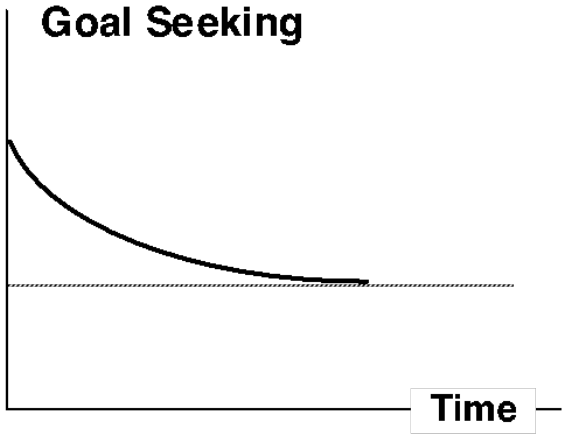
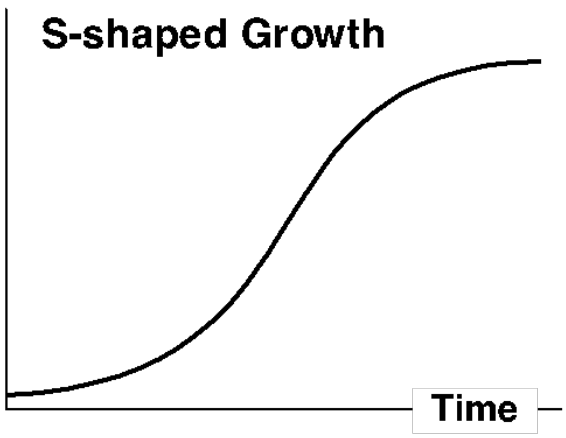
Behavior of Dynamic Systems

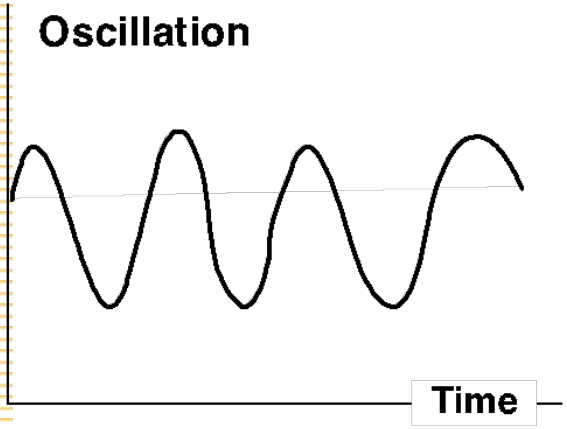
- Behavior of a system arises from its structure.
- Agenda:
  - Overview of the dynamics, focusing on the relationship between structure and behavior.
  - The basic modes of behavior in dynamic systems along with the feedback structures generating them.

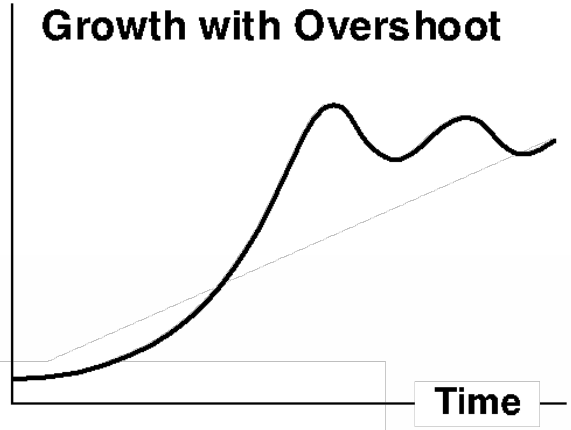
Common Modes of Behavior

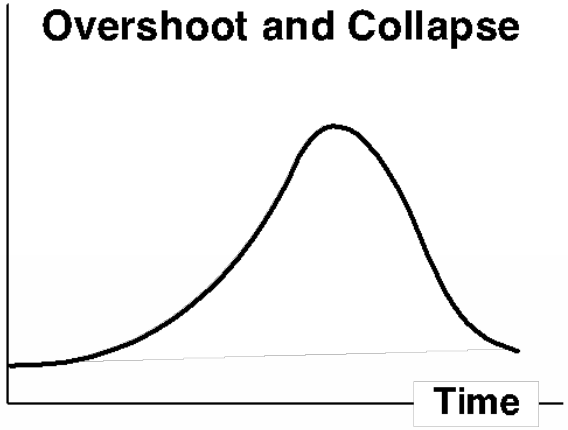








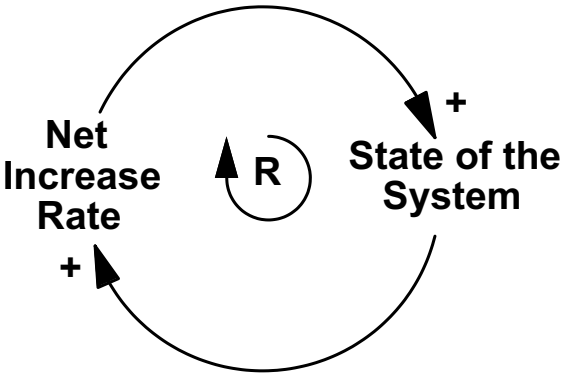


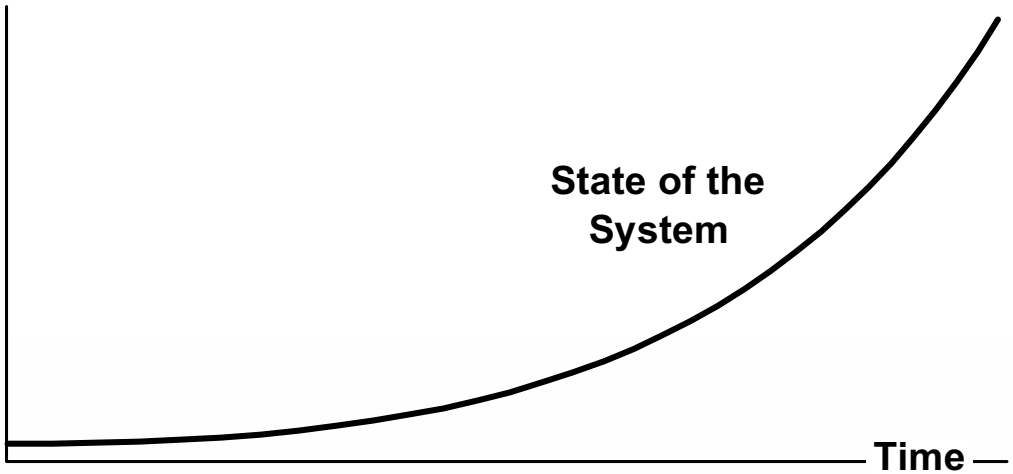


Exponential Growth

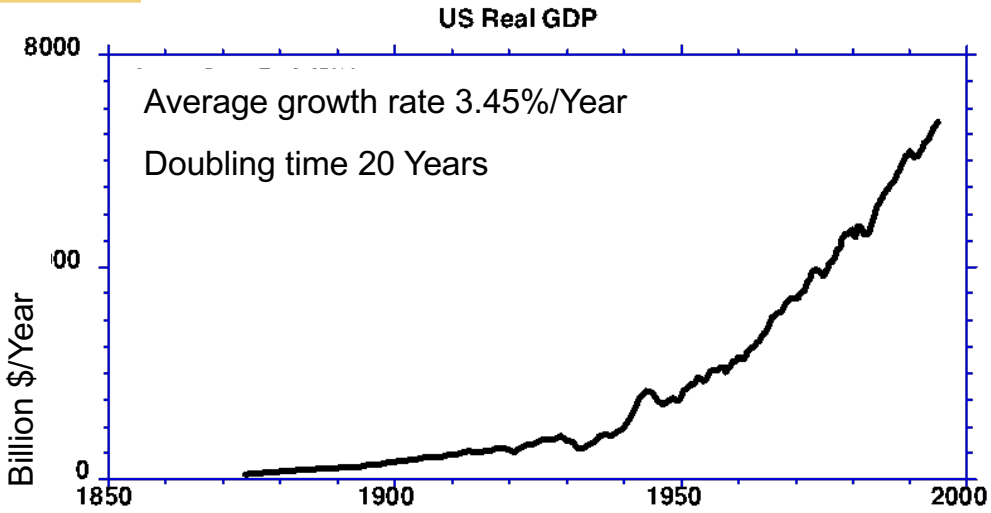
Exponential growth arises from positive (self-reinforcing) feedback.

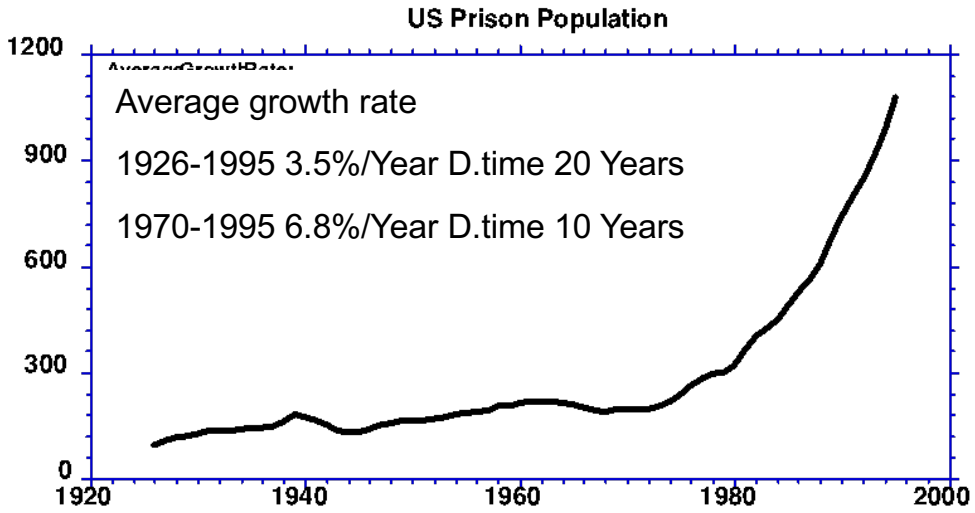
The larger the quantity, the greater its net increase, further augmenting the quantity and leading to ever-faster growth

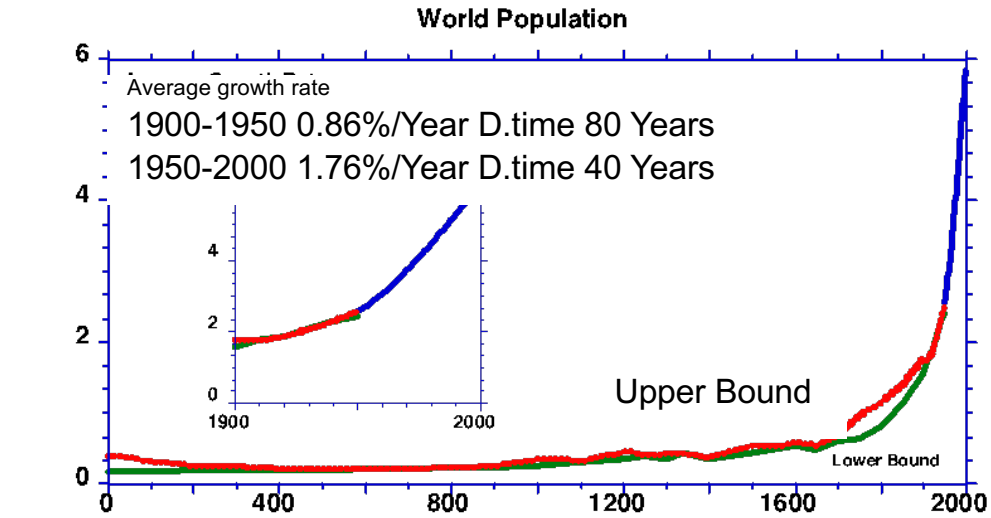


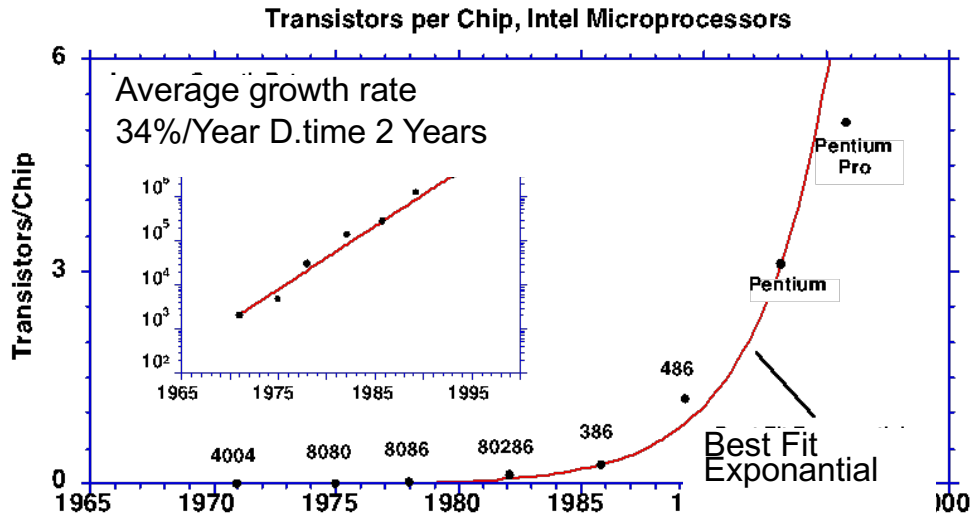


Exponential Growth: Example









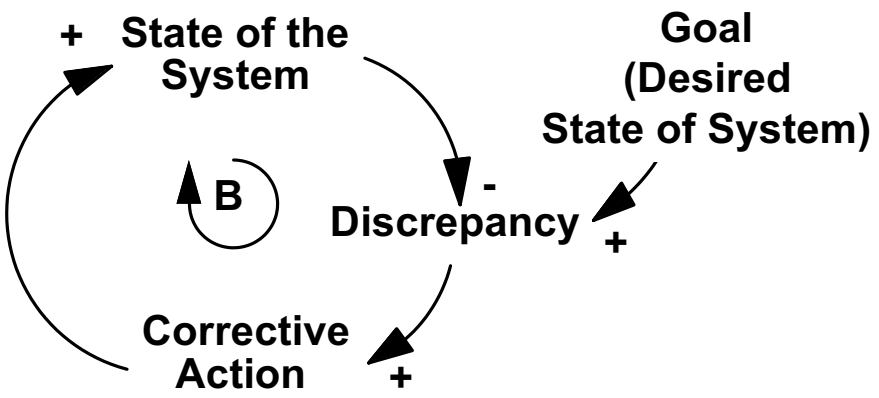
Exponential Growth (contd)

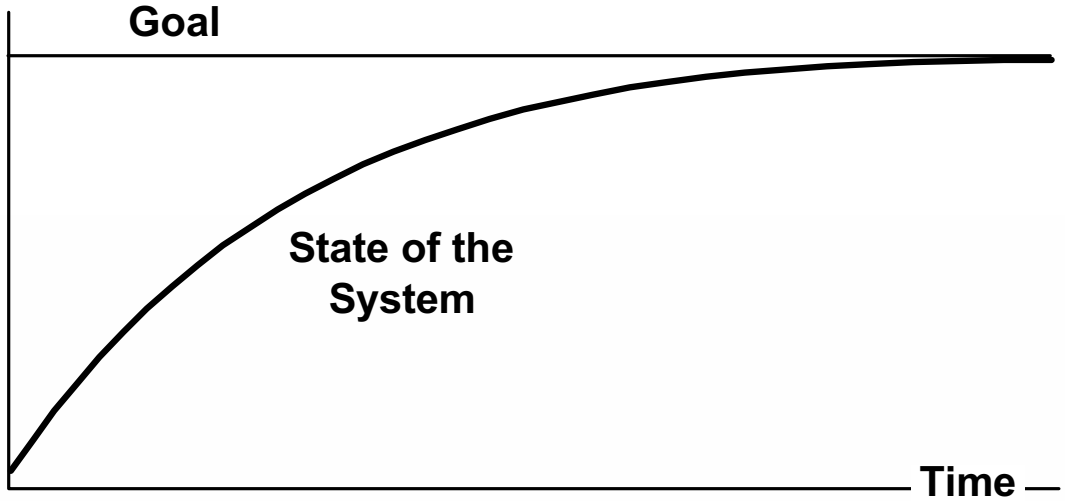
- Positive feedback need not always generate growth. It can also create self-reinforcing decline
  - A drop in stock prices erodes investor confidence which leads to more selling, lower prices, and still lower confidence.
- **What about linear growth?**
  - Linear growth is actually quite rare.
  - Linear growth requires that there be no feedback from the state of the system to the net increase rate, because the net increase remains constant even as the state of the system changes.
  - What appears to be linear growth is often actually exponential, but viewed over a time horizon too short to observe the acceleration.

Goal Seeking Behavior

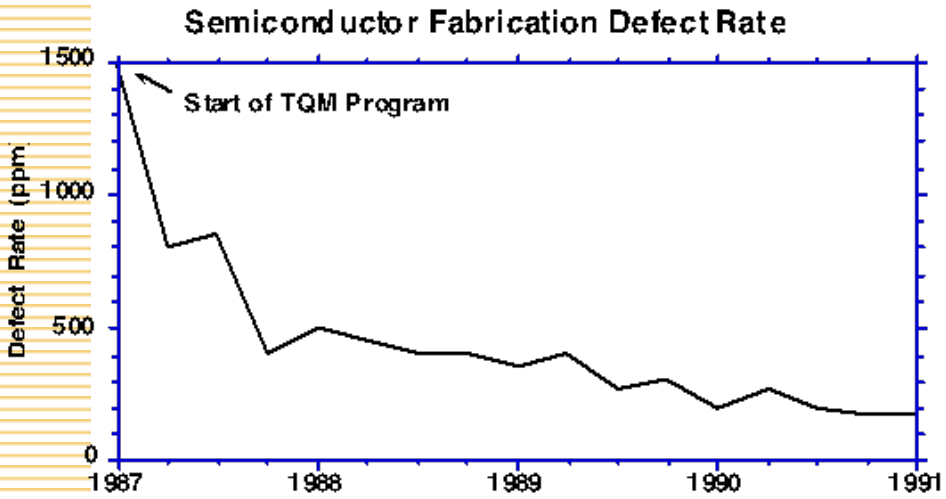
Negative loops seek balance, equilibrium, and stasis.

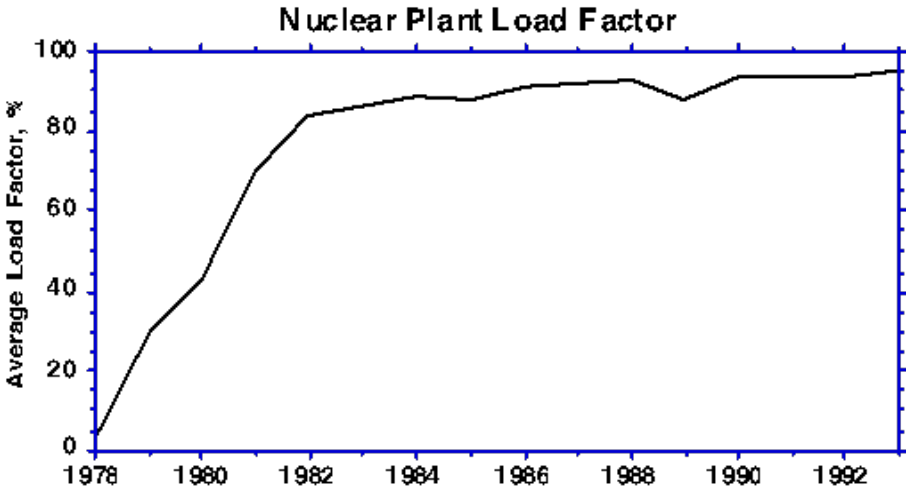
Negative feedback loops act to bring the state of the system in line with a goal or desired state.

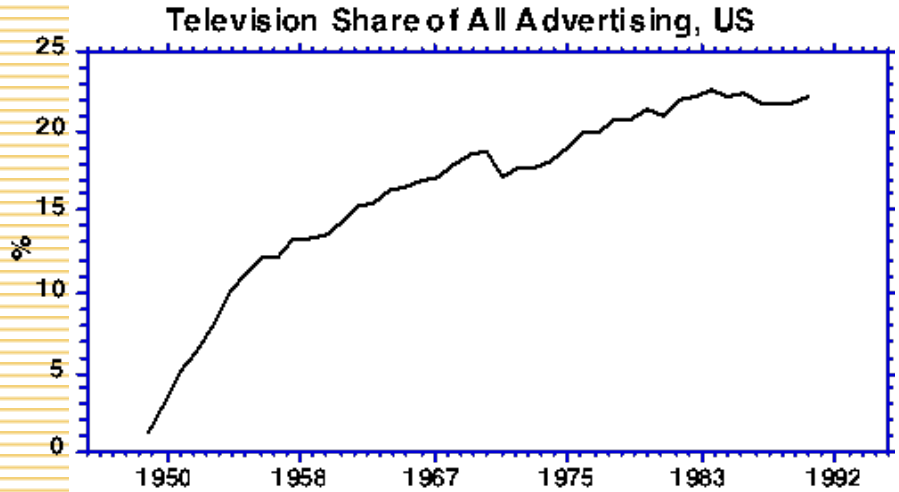


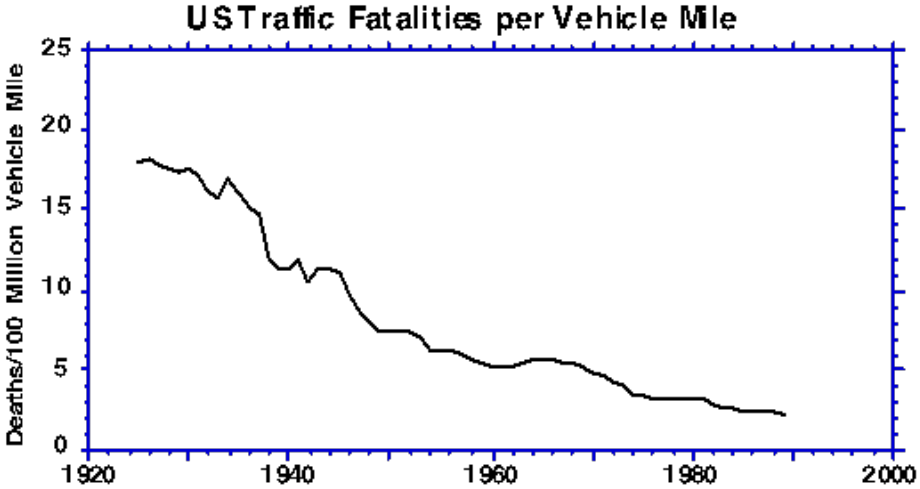


Goal Seeking Behavior: Examples









OSCILLATIONS

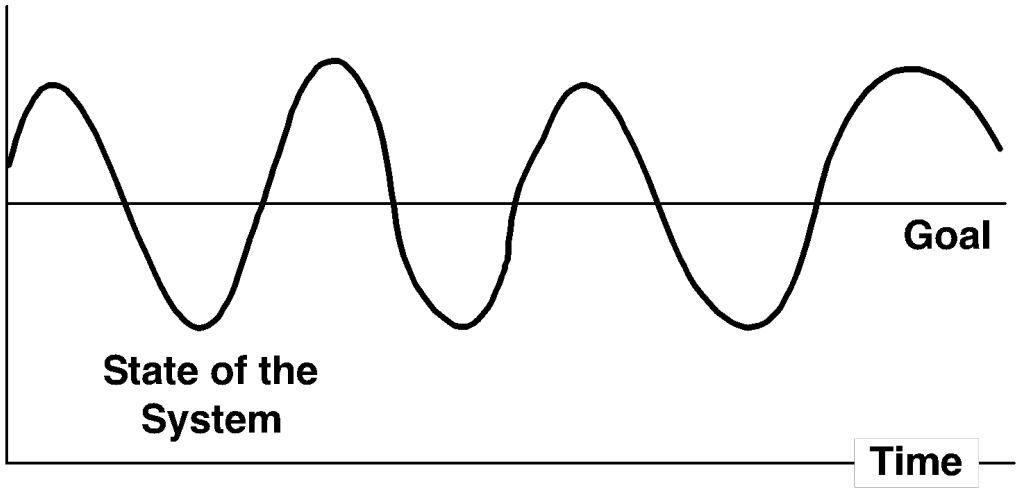
- Oscillation: third fundamental mode of dynamic behavior
- Like goal-seeking behavior, oscillations caused by negative feedback loops.
- In an oscillatory system, the state of the system constantly overshoots its goal or equilibrium state, reverses, then undershoots, and so on.
- Overshooting arises from presence of **significant time delays** in the negative loop.
- The time delays cause corrective actions to continue even after the state of the system reaches its goal, forcing the system to adjust too much, and triggering a new correction in the opposite direction

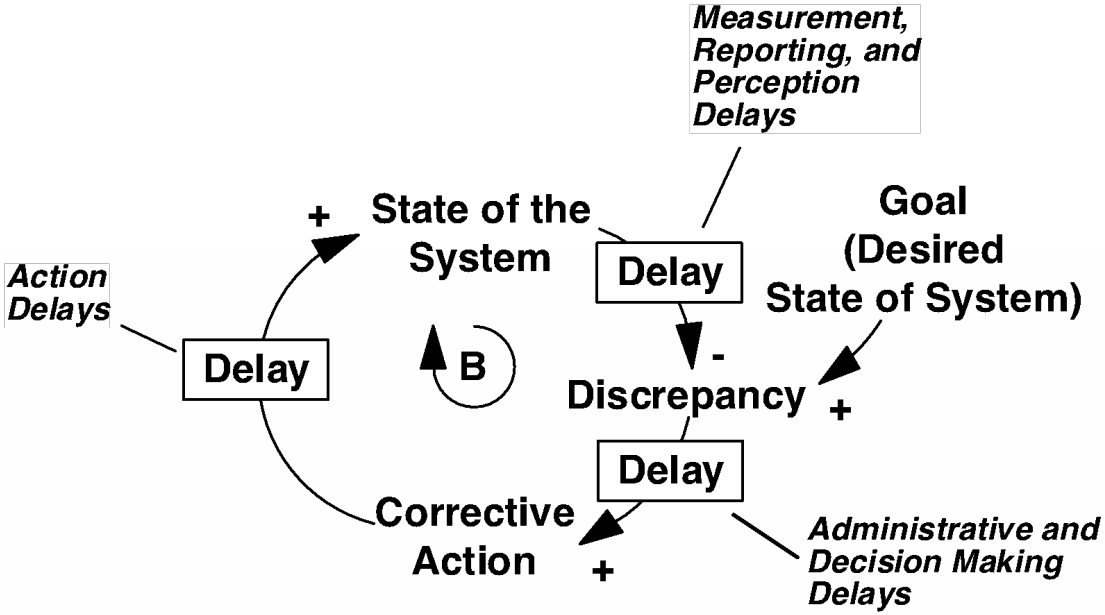
OSCILLATIONS

It takes time for a company to measure and report inventory levels, time for management to meet and decide how much to produce, and more time while raw materials procurement, the labor force, and other needed resources respond to the new production schedule.

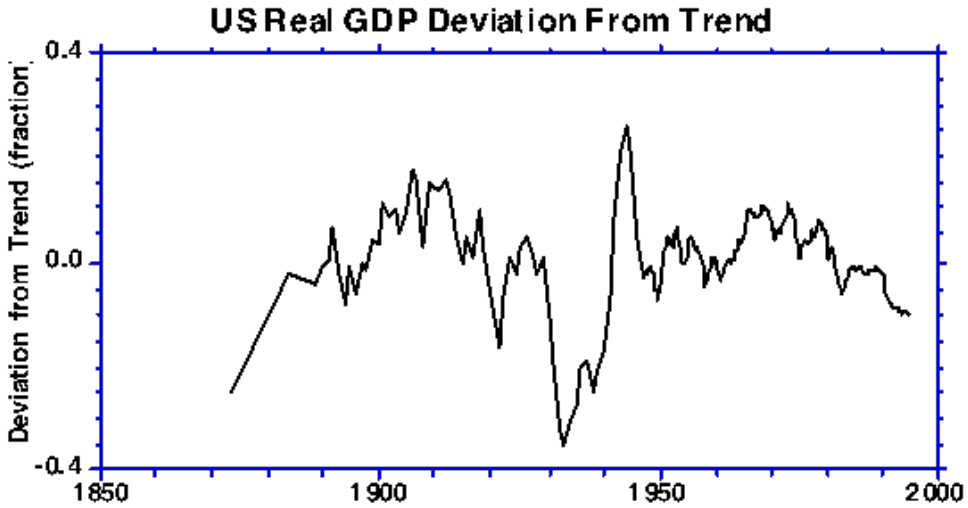
Sufficiently long delays at anyone of these points could cause inventory to oscillate.

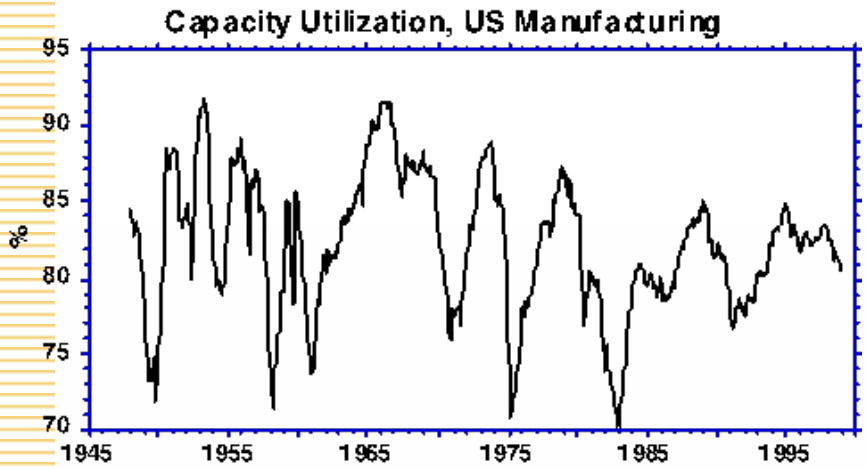
OSCILLATION: STRUCTURE

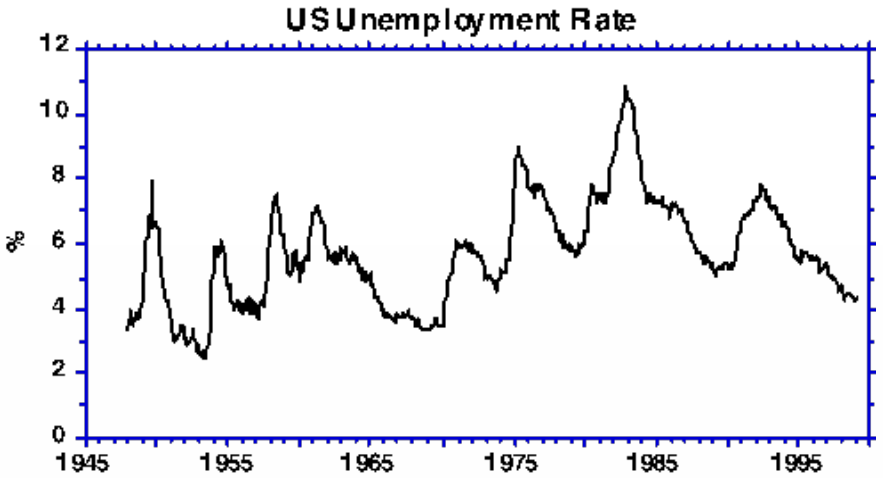




Oscillations Examples







Interactions of Fundamental Modes

Three basic modes of behavior

- Exponential Growth (positive loop)
- Goal Seeking (negative loop)
- Oscillations (negative loop with delays)

More complex patterns of behavior arise through the **nonlinear** interaction of these structure with one another

- S-shaped Growth
- S-shaped Growth with overshoot
- Overshoot and collapse

S-Shaped Growth

No real quantity can grow forever: eventually one or more constraints halt the growth.

A commonly observed mode of behavior in dynamic systems is ***S-shaped growth*** → *Growth* is exponential at first, but then gradually slows until the state of the system reaches an equilibrium level.

The shape of the curve resembles a stretched-out "**S**"

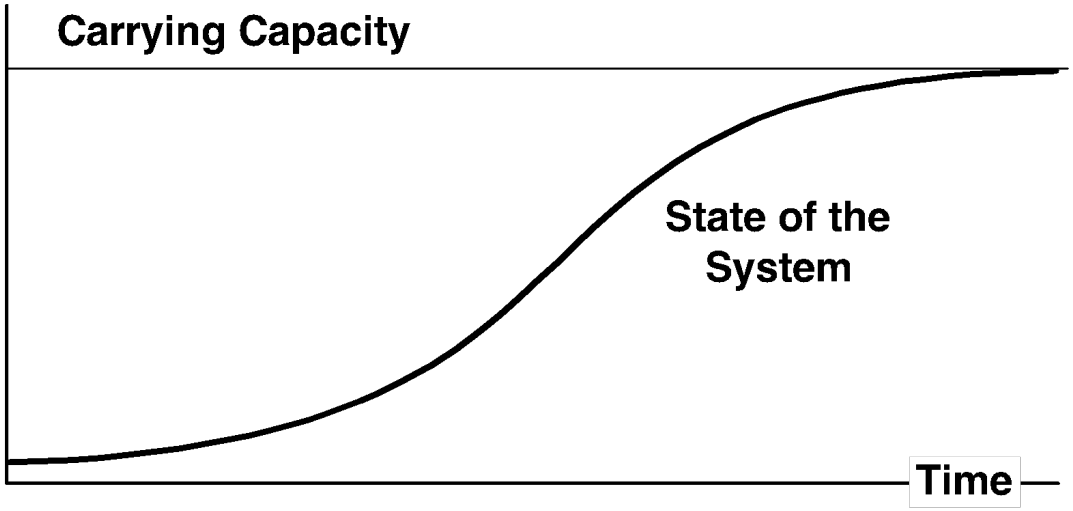
S-Shaped Growth

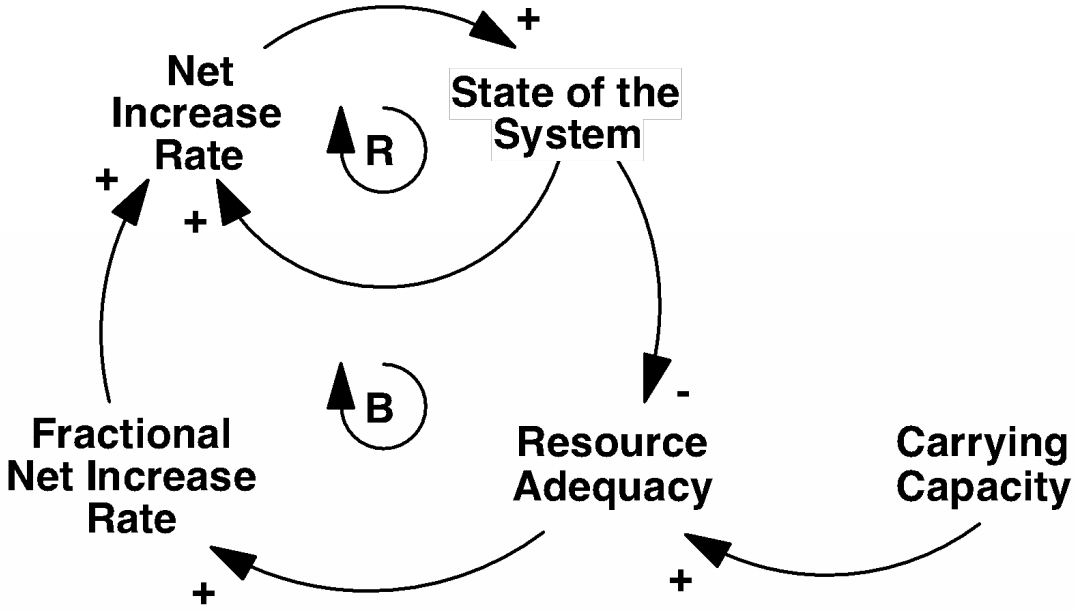
To understand the structure underlying S-shaped growth it is helpful to use the ecological concept of carrying capacity.

The carrying capacity of any habitat is the number of organisms of a particular type it can support and is determined by the resources available in the environment and the resource requirements of the population.

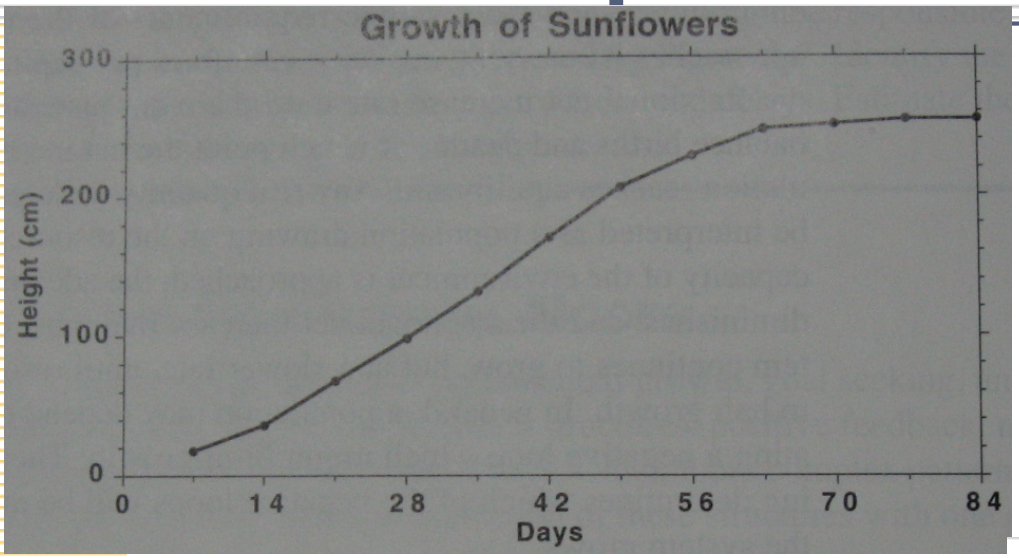
As a population approaches its carrying capacity, resources per capita diminish thereby reducing the fractional net increase rate until there are just enough resources per capita to balance births and deaths

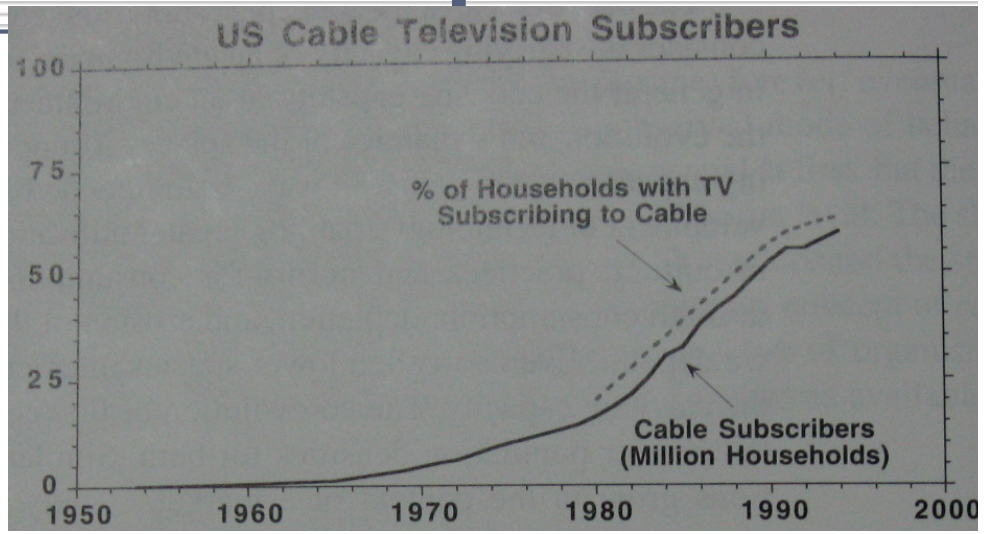
S-Shaped Growth

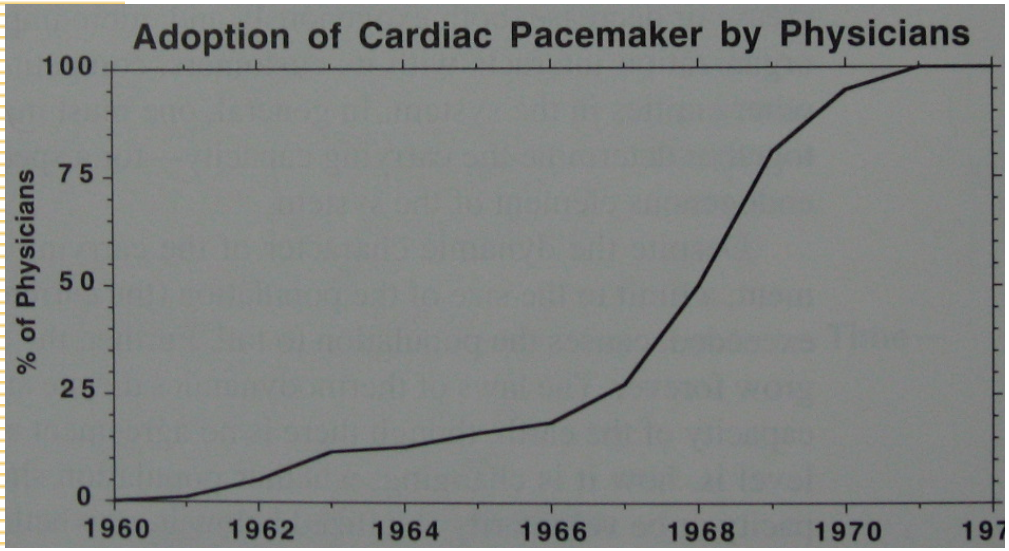


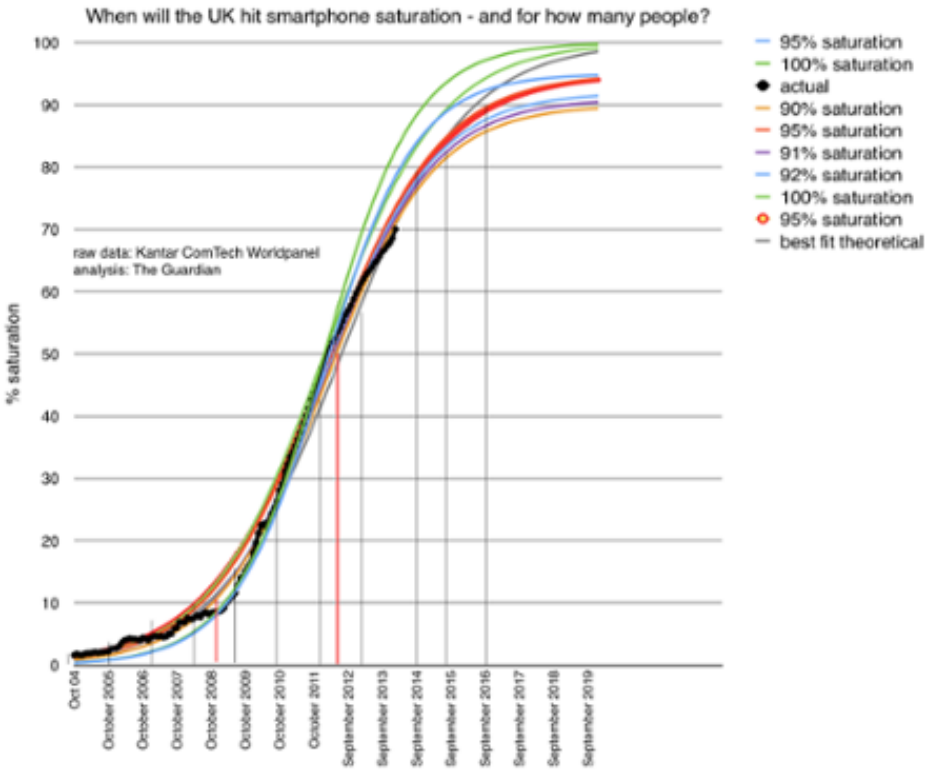


S-Shaped Growth Examples









Source: Sterman, John D.
Business Dynamics (Fig 4-9)

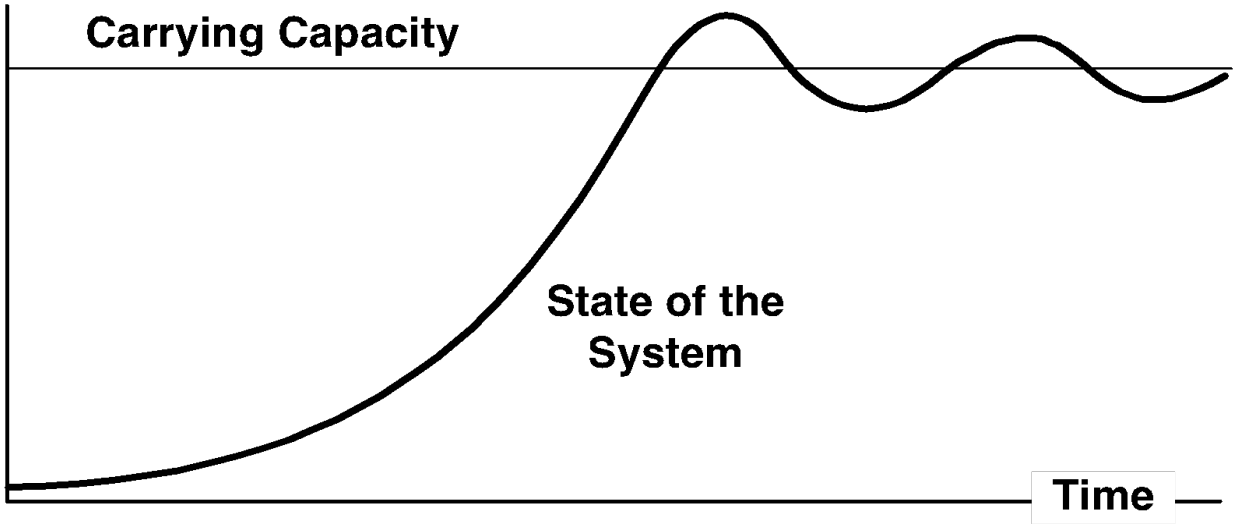
S-shaped growth with overshoot

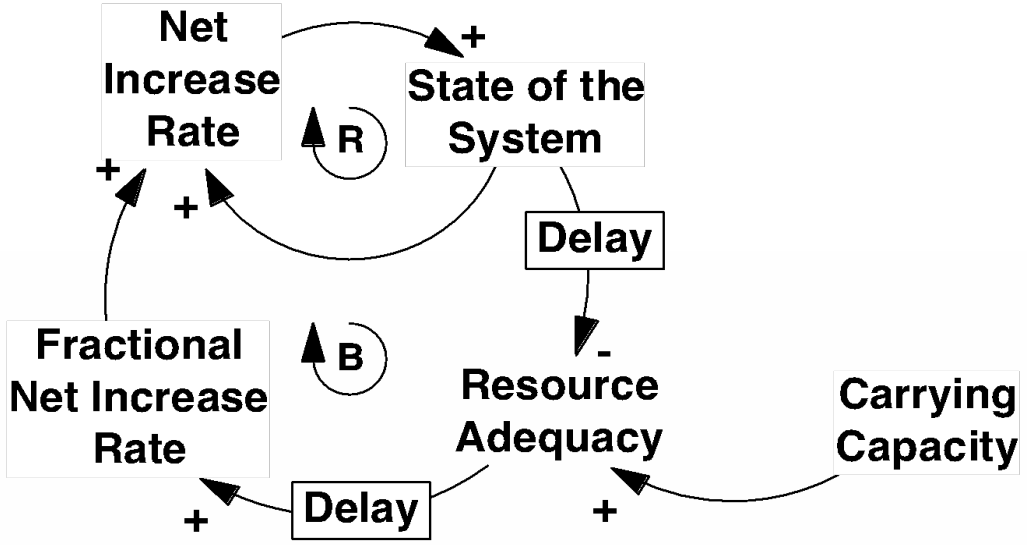
S-shaped growth requires the negative feedbacks that constrain growth to act swiftly as the carrying capacity is approached.

Often, however, there are **significant time delays** in these negative loops.

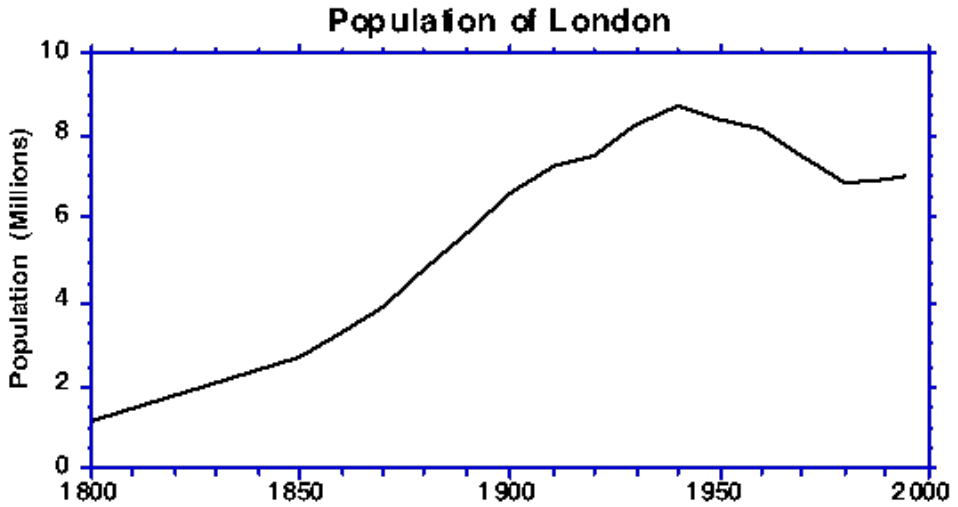
Time delays in the negative loops lead to the possibility that the state of the **system will overshoot and oscillate** around the carrying capacity

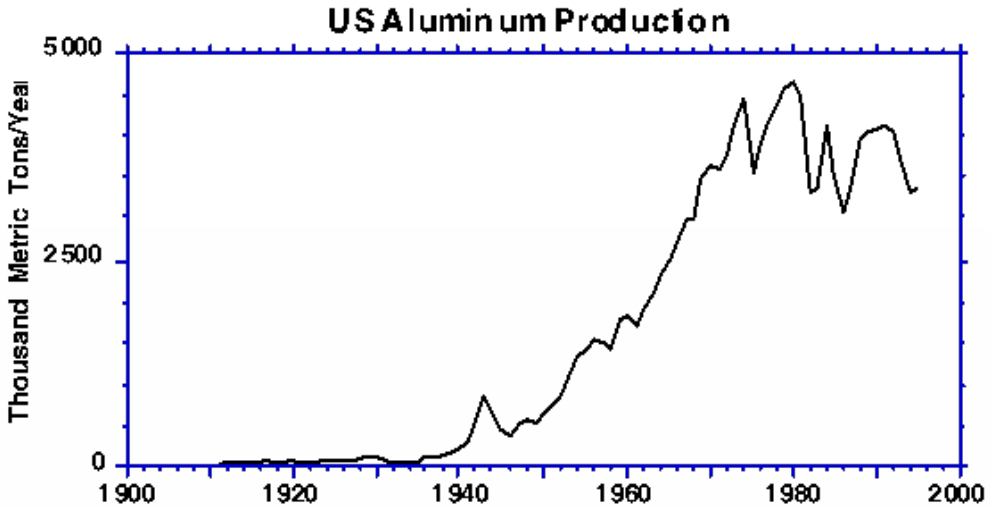
S-hsaped growth with overshoot





S-shaped w/ overshoot: Example





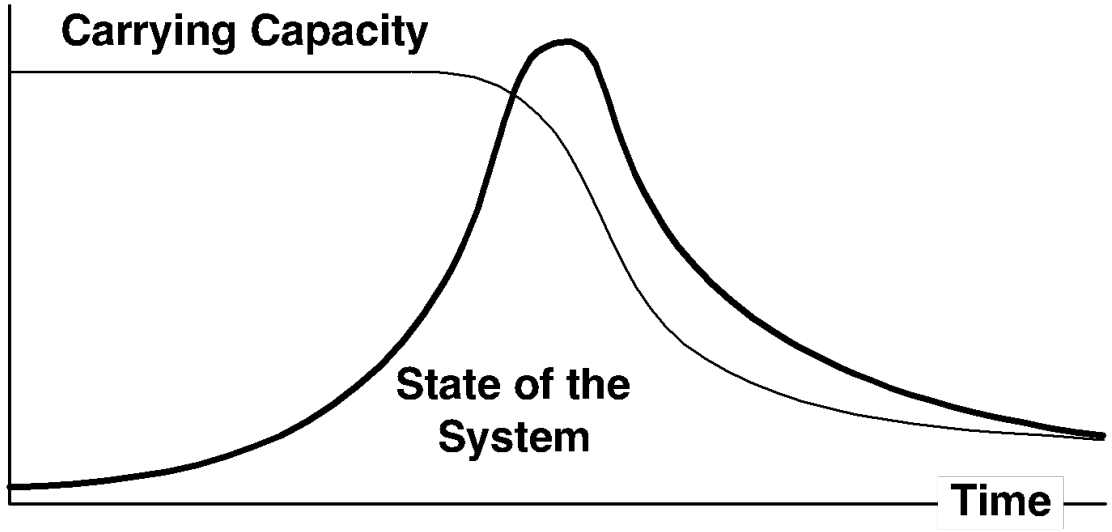
OVERSHOOT AND COLLAPSE

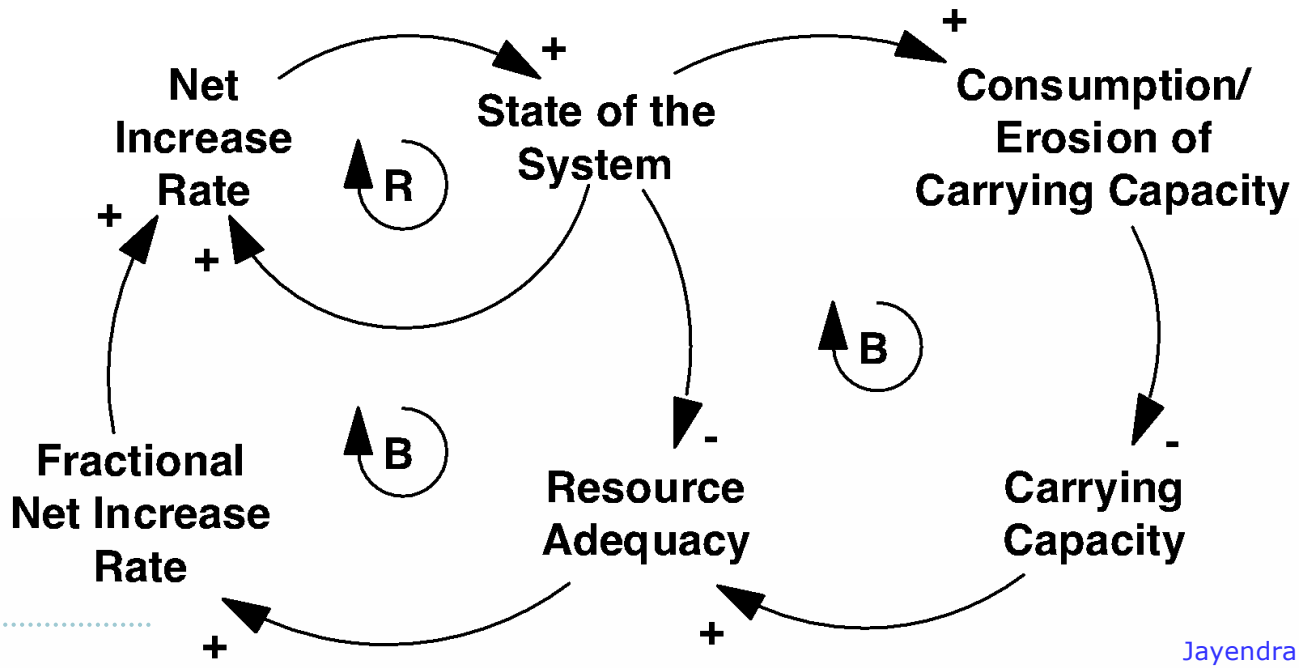
The second critical assumption underlying S-shaped growth is that the carrying capacity is fixed.

Often, however, the ability of the environment to support a growing population is eroded or consumed by the population itself.

For example, the population of deer in a forest can grow so large that they over-browse the vegetation, leading to starvation and a precipitous decline in the population.

OVERSHOOT AND COLLAPSE





Why care about behavior modes?

The principle that the structure of the system generates its behavior is a useful heursitic

- Helps modeler discover the feedback structure of system
- When we see data/pattern of behavior, we can then know which basic feedback structure must have been dominant

CAUTION

- Modelers to take care to try and include in their model the feedback structures that have not been important in generating dynamics to date, but that may become active as system evolves.