Sustainability: Principles and Practices
Spring 2014

PPT Set 5

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Some properties of systems

Systems can be managed but not controlled.

Many relationships in systems are non-linear. A non-linear relationship is one in which the cause does not produce a proportional effect. These systems cannot be solved and cannot be added together.

There will always be limits to growth.
They can be self-imposed or system-imposed.

When long delays occur in feedback loops,
foresight is essential.

Meadows, *Thinking in Systems*, 2008

Three characteristics of healthy, well-working systems

- resilience
- self-organization
- heirarchy

Meadows, *Thinking in Systems*, 2008

1. Resilience

Resilience is a measure of a system's ability to survive and persist within a variable environment. The opposite of resilience is **brittleness** or **rigidity**.

System resilience is conferred by multiple feedback loops that restore the system after a large perturbation; *e.g.*, balancing feedback loops.

At higher levels there are feedback loops that restore/rebuild feedback loops. At even higher levels there are feedback loops that can learn or adapt (self-organization).

Meadows, *Thinking in Systems*, 2008

2. Self-organization

Self-organization is the capacity of a system to make its own structure more complex.

Systems often have the ability to structure themselves, to create new structure, to learn, to diversity and to complexify.

Like resilience, self-organization is often sacrificed for short-term productivity and stability.

Meadows, *Thinking in Systems*, 2008

3. Heirarchy

The arrangement of systems and subsystems is called a heirarchy.

Subsystems are aggregated into larger subsystems, which are aggregated into still larger subsystems.

Examples of heirarchies: corporate systems, military systems, ecological systems, living organisms, economic systems

Meadows, *Thinking in Systems*, 2008

Heirarchies give a system stability and resilience.

In heirarchical systems, relationships within each subsystem are denser and stronger than relationships between subsystems.

Heirarchies evolve from the lowest level up, from the pieces to the whole.

The purpose of a heirarchy is to help its originating subsystems do their jobs better.

Meadows, *Thinking in Systems*, 2008

To be a functional system, a heirarchy must balance the welfare, freedoms, and responsibilities of the subsystems and the total system. The purpose of the upper layers of a heirarchy is to serve the purposes of the lower layers.

Too much **central control** can damage a heirarchical system.

When a subsystem's goals dominate at the expense of the total system's goals, the resulting behavior is called **suboptimization**.

Meadows, *Thinking in Systems*, 2008

The Collapse of Complex Societies

Joseph Tainter, Cambridge, 2011

Concepts important to understanding the driving forces behind the collapse of a community (system)

a. Human societies are problem-solving organizations.
b. Sociopolitical systems require energy for their maintenance.
c. Increased complexity carries with it increased costs per capita.
d. Investment in sociopolitical complexity as a problem-solving response often reaches a point of <u>declining marginal returns.</u>

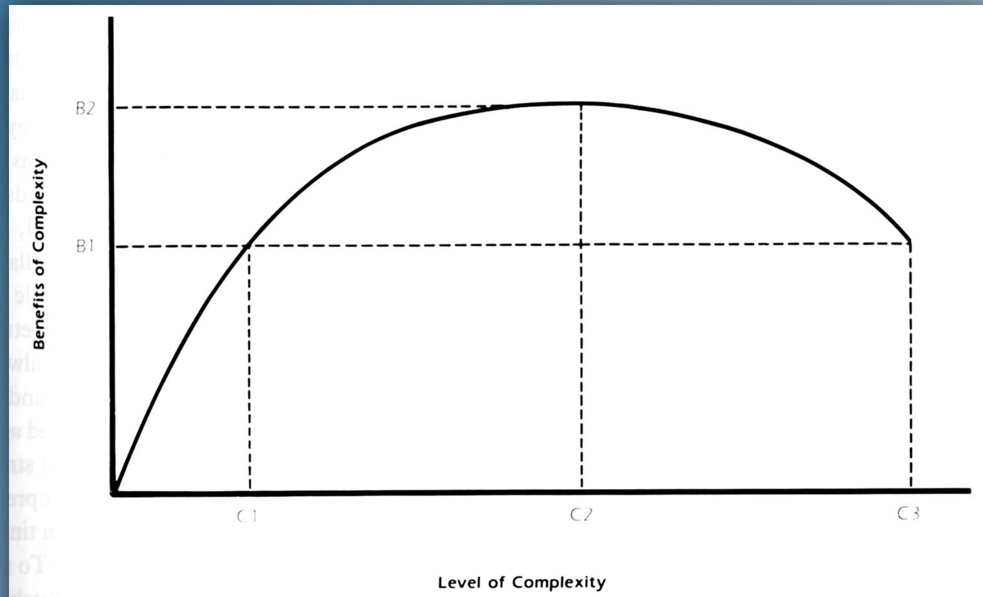

Fig. 19. The marginal product of increasing complexity.

At B1/C1: Marginal productivity has reached the point where it can no longer rise given the basic technology and energy resources available. Beyond this point, for a while, benefits still rise in response to increasing complexity, but at a declining marginal rate.

Between B2/C2 and B1/C3: A critical region; the region of extreme vulnerability(*e.g.*, from a major perturbation or stress) due to inadequate reserves.

Components of system diagrams

(stock-flow-loop diagrams)

Stocks: a store; a quantity; material; information; can be increased by decreasing its outflow rate and/or increasing its inflow rate; change slowly; act as delays or buffers in systems

Flows: cause changes in stocks

Meadows, *Thinking in Systems*, 2008

A simple system diagram with no feedback loops

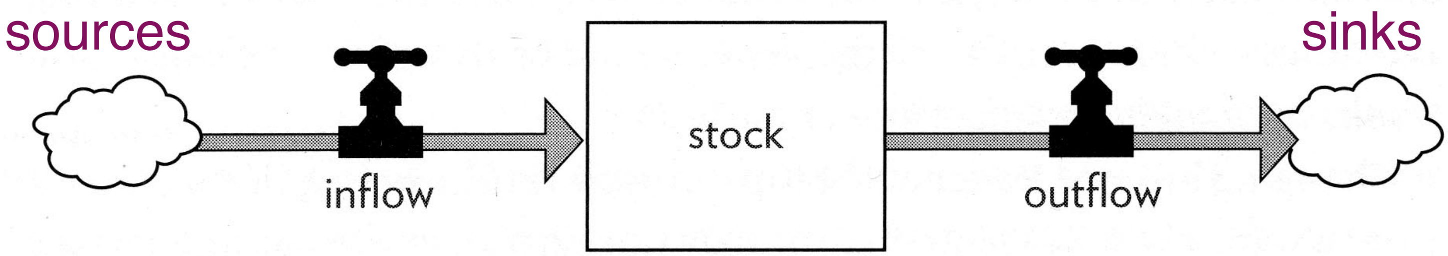

Figure 1. How to read stock-and-flow diagrams. In this book, stocks are shown as boxes, and flows as arrow-headed "pipes" leading into or out of the stocks. The small T on each flow signifies a "faucet;" it can be turned higher or lower, on or off. The "clouds" stand for wherever the flows come from and go to—the sources and sinks that are being ignored for the purposes of the present discussion.

Meadows, *Thinking in Systems*, 2008

Types of feedback loops

A **feedback loop** forms when changes in a stock affect the flows into and out of that same stock. There are two major types of feedback loops: **balancing** and **reinforcing**.

Balancing feedback loops stabilize stock levels (denoted as "B" in system diagrams).

Reinforcing feedback loops are amplifying, reinforcing and self-enhancing. They are responsible for exponential growth (denoted as "R" in system diagrams).

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Meadows, *Thinking in Systems*, 2008

Interpreting feedback loops

Action or change in a stock always occurs by adjusting flows.

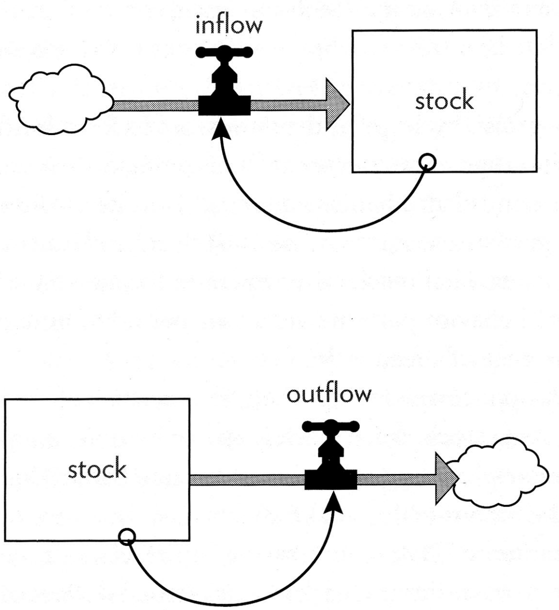

Figure 8. How to read a stock-and-flow diagram with feedback loops. Each diagram distinguishes the stock, the flow that changes the stock, and the information link (shown as a thin, curved arrow) that directs the action. It emphasizes that action or change always proceeds through adjusting flows.

Meadows, *Thinking in Systems*, 2008

Balancing feedback loops are equilibrating or goal-seeking structures in systems and are both sources of stability and resistance to change.

Meadows, *Thinking in Systems*, 2008

An example of balancing feedback loops

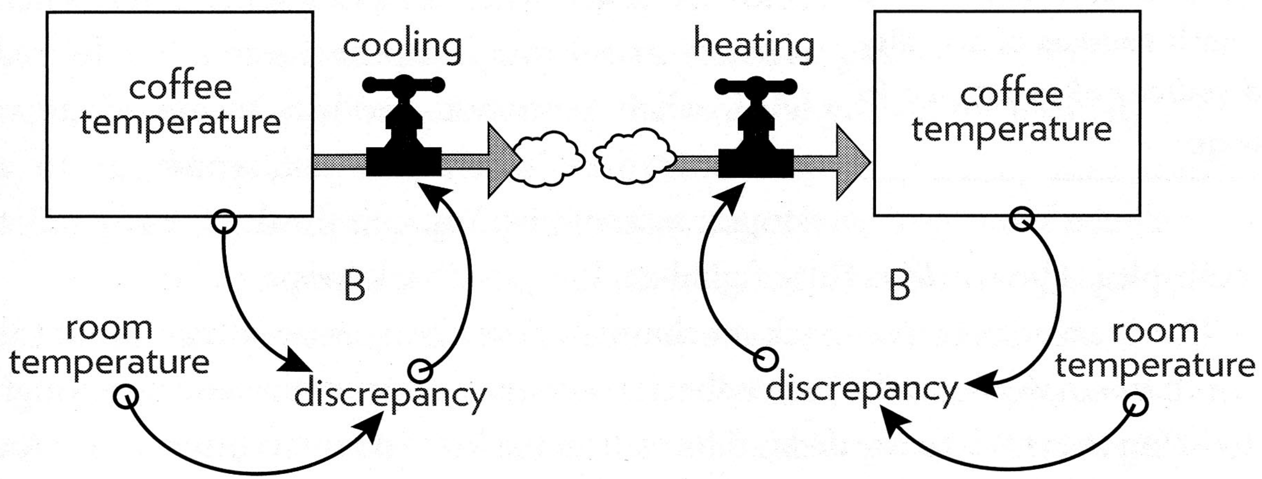

Figure 10. A cup of coffee cooling (*left*) or warming (*right*).

Meadows, *Thinking in Systems*, 2008

Effects of the two balancing feedback loops to either cool or warm a cup of coffee to the prevailing room temperature

The loops insure that the same end-point is reached regardless of the initial state. The rate of change slows as the discrepancy between the stock and the goal decreases.

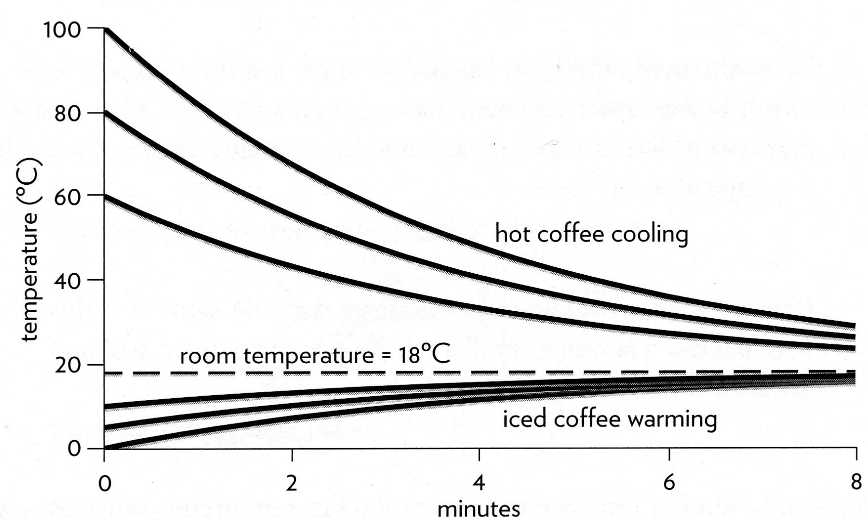

Figure 11. Coffee temperature as it approaches a room temperature of 18°C.

Meadows, *Thinking in Systems*, 2008

Reinforcing feedback loops

Reinforcing feedback loops are self-enhancing, leading to exponential growth or to runaway collapse over time. They occur whenever a stock has the capacity to reinforce or reproduce itself.

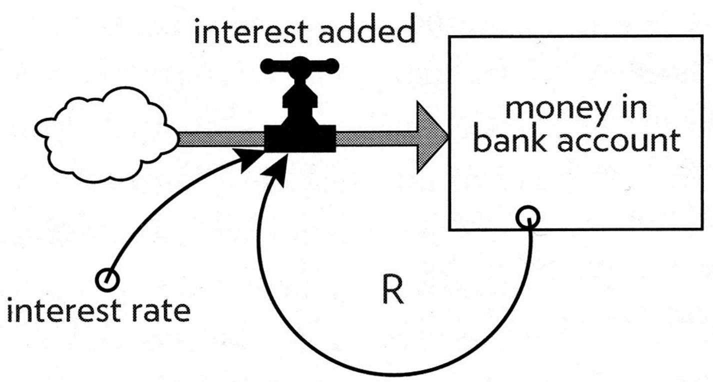

Figure 12. Interest-bearing bank account.

Meadows, *Thinking in Systems*, 2008

A bank account (stock) increases as a result of a **reinforcing feedback loop**. Compounding interest is an example of non-linear (exponential) growth.

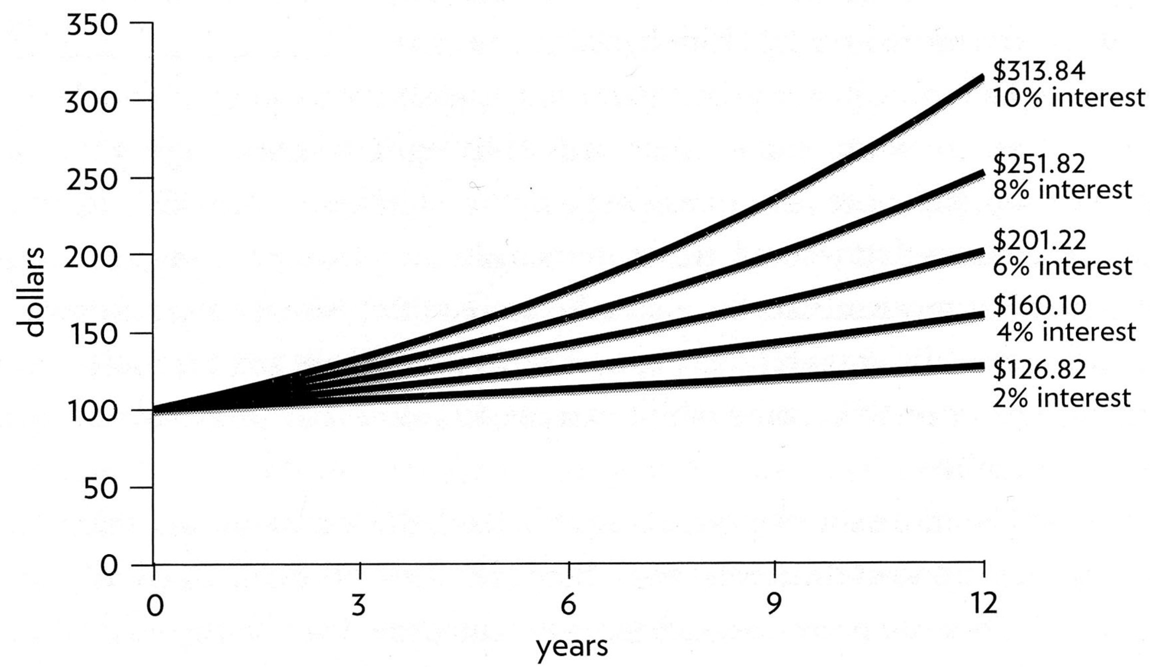

Figure 13. Growth in savings with various interest rates.

Meadows, *Thinking in Systems*, 2008

Estimating doubling times

The time it takes for an exponentially-growing stock to double in size (the doubling time) equals approximately 70 divided by the growth rate (expressed as a percentage).

Example: $100 at 7% interest per year; 70/7 = 10. The money doubles every 10 years.

Meadows, *Thinking in Systems*, 2008

Combining reinforcing and balancing feedback loops: Population

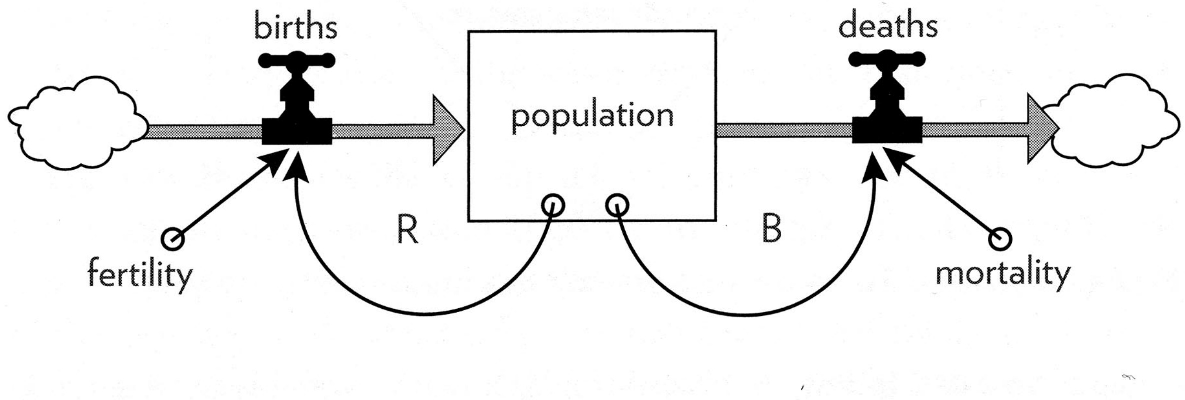

Figure 21. Population governed by a reinforcing loop of births and a balancing loop of deaths.

If the fertility and mortality rates are constant, then the population either grows or contracts exponentially, depending on which of the two rates is stronger.

Meadows, *Thinking in Systems*, 2008

If world fertility falls steadily to equal mortality by 2035
and both stay constant thereafter, the population
will level off (**dynamic equilibrium**).

The concept of shifting dominance

Complex behaviors of systems often arise as the relative
strengths of feedback loops shift, causing first one loop
and then another to dominate behavior.

Meadows, *Thinking in Systems*, 2008

Other system components

Delays

When present in a balancing feedback loop, delays make the system oscillate. Changing the length of a delay can change the behavior of a system significantly.

Meadows, *Thinking in Systems*, 2008

System behavior when multiple delays are included to better mimic the real world

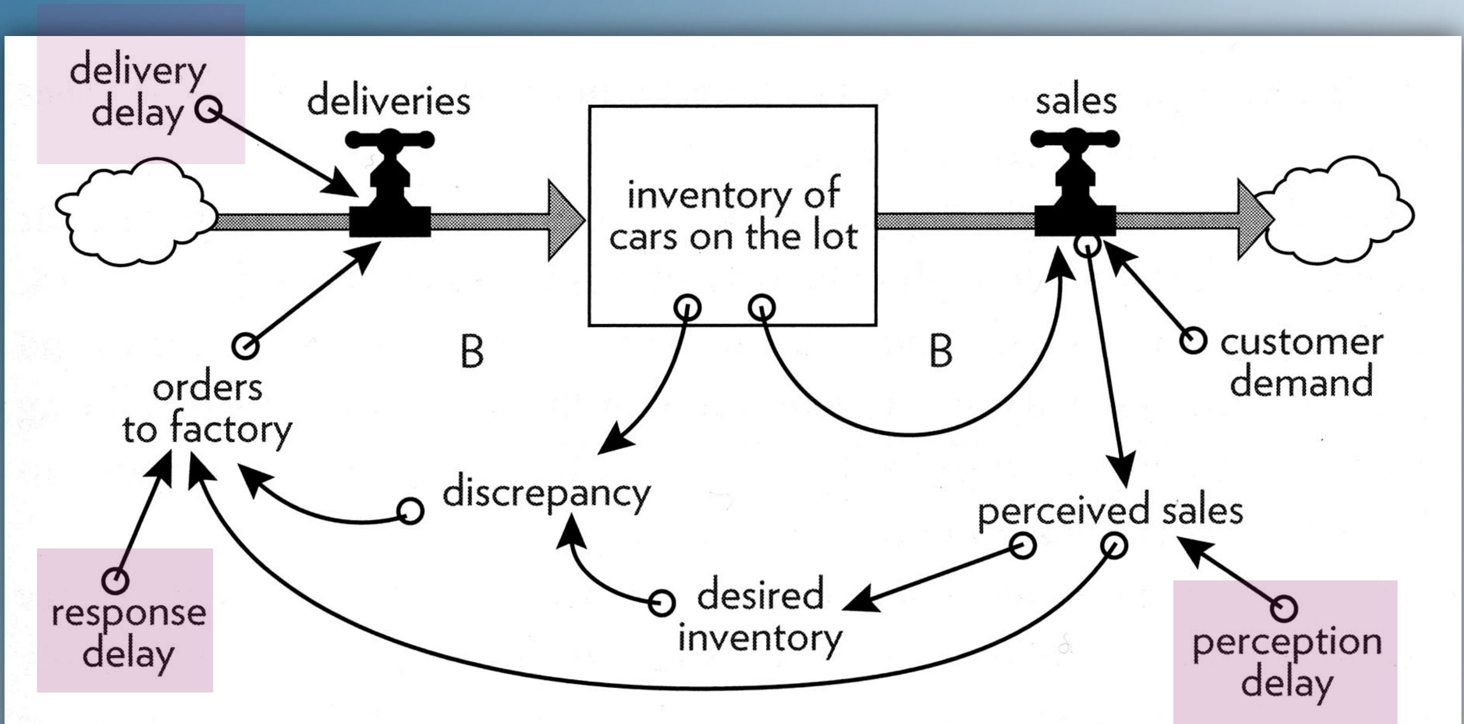

Figure 31. Inventory at a car dealership with three common delays now included in the picture—a perception delay, a response delay, and a delivery delay.

Meadows, *Thinking in Systems*, 2008

Response to a 10% increase in customer demand starting on day 25 when three delays are present in the system: Oscillations

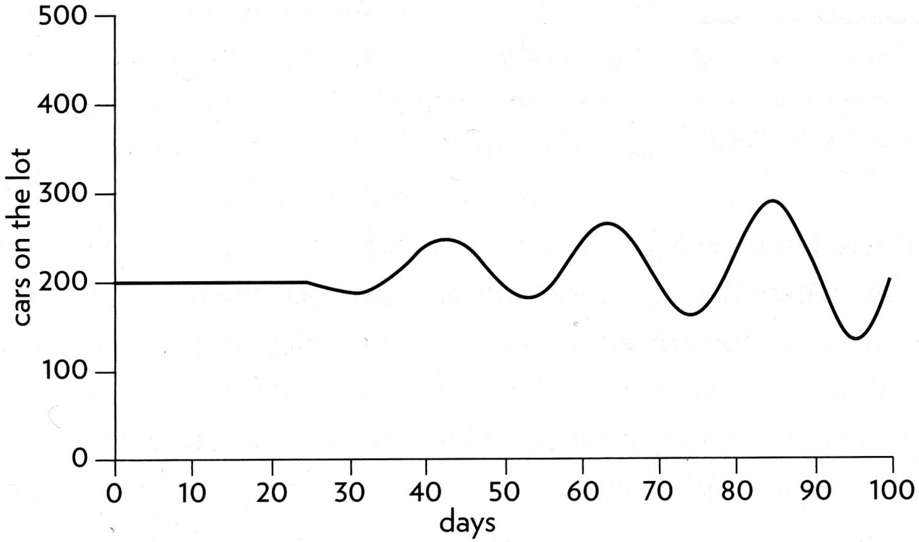

Figure 32. Response of inventory to a 10-percent increase in sales when there are delays in the system.

Meadows, *Thinking in Systems*, 2008

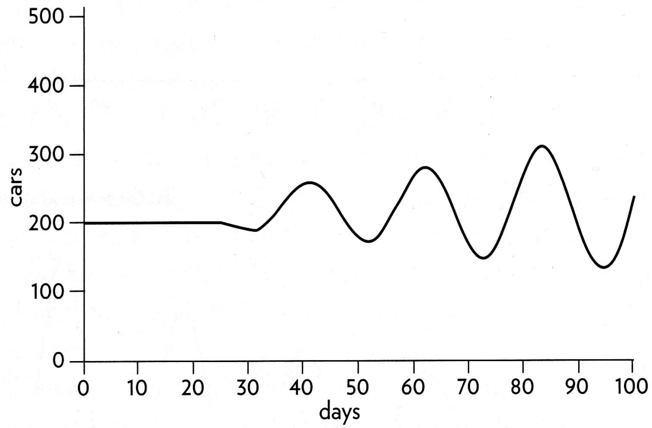

Figure 34. The response of inventory to the same increase in demand with a shortened perception delay.

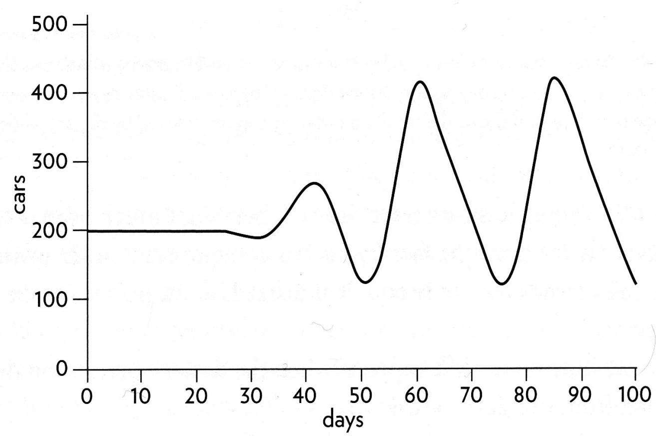

Figure 35. The response of inventory to the same increase in demand with a shortened reaction time. Acting faster makes the oscillations worse!

Effect of shortening the perception delay

Effect of shortening the reaction time: Acting faster makes the oscillations worse.

Meadows, *Thinking in Systems*, 2008

The effect of lengthening the reaction time: the oscillations are damped (counter-intuitive!)

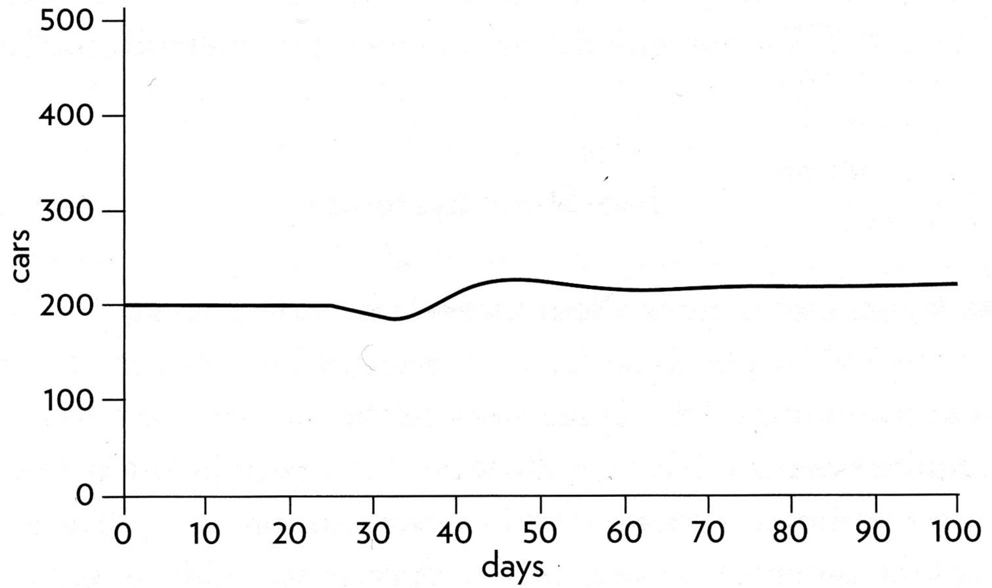

Figure 36. The response of inventory to the same increase in demand with a slowed reaction time.

Meadows, *Thinking in Systems*, 2008

Delays are pervasive in systems and are strong determinants of behavior. Changing the length of a delay may or may not make a large change in the behavior of a system depending on the type of delay and the relative lengths of other delays.

Meadows, *Thinking in Systems*, 2008

In physical, exponentially growing systems, there must be at least one reinforcing loop driving the growth and at least one balancing loop constraining the growth, because no physical system can grow forever in a finite environment.

Meadows, *Thinking in Systems*, 2008

Two-stock systems

A two-stock system

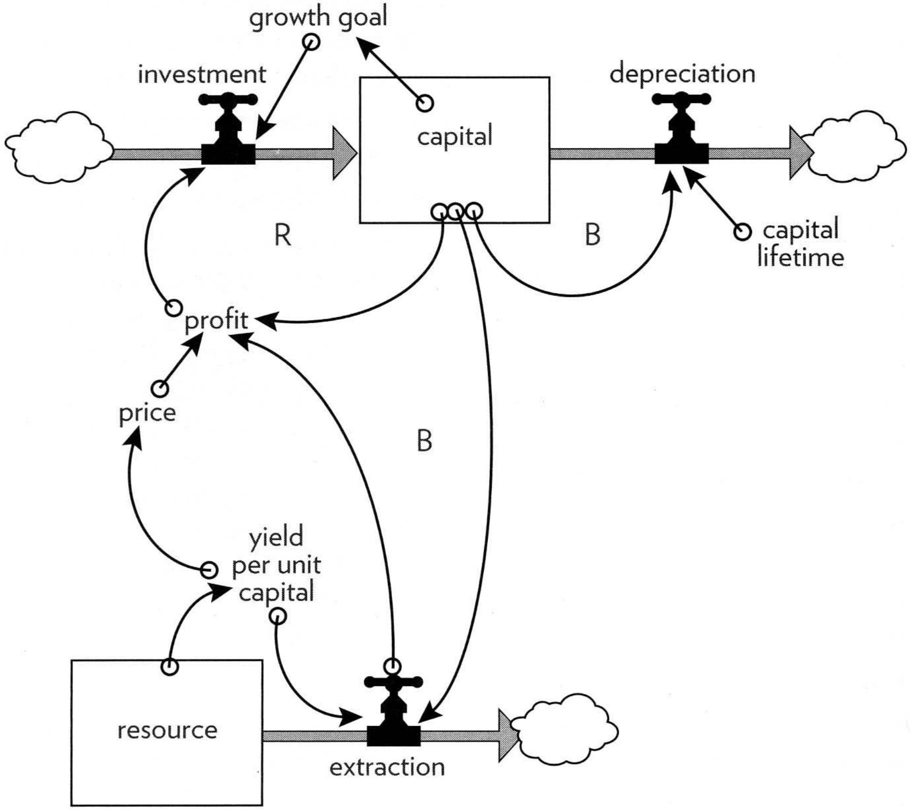

Figure 37. Economic capital, with its reinforcing growth loop constrained by a nonrenewable resource.

This model might pertain to an oil company that has discovered a new oil field. Note the lack of an input to the resource stock.

In this case, the yield per unit capital is not constant. As this non-renewable resource is depleted, the more it costs to extract it.

Let's assume a 5% annual growth in business capital and a 20-year depreciation of capital.

Meadows, *Thinking in Systems*, 2008

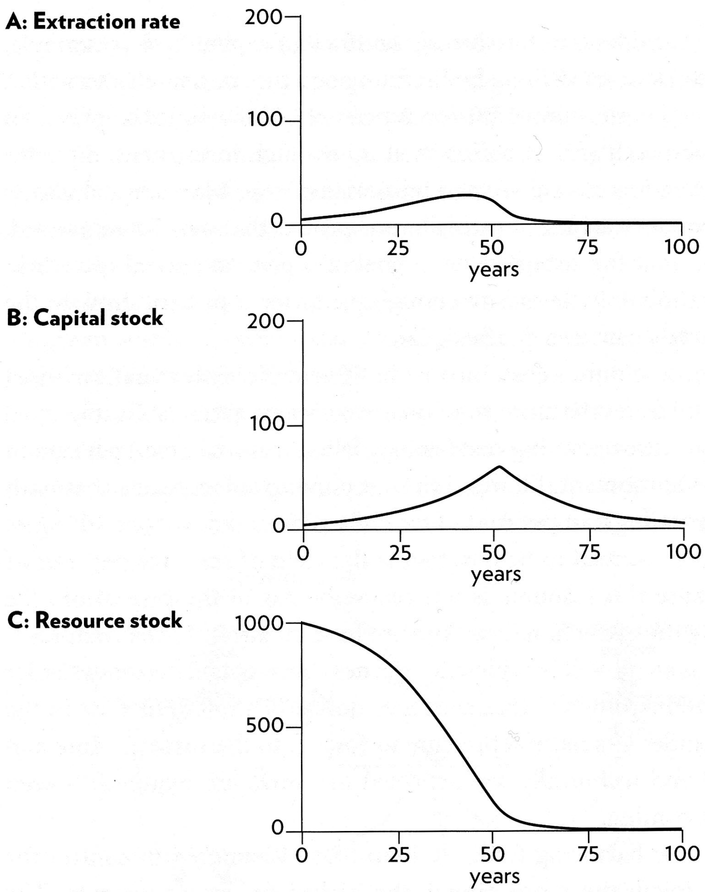

Figure 38. Extraction (A) creates profits that allow for growth of capital (B) while depleting the nonrenewable resource (C). The greater the accumulation of capital, the faster the resource is depleted.

The extraction rate peaks at ~40 y because of the effect of exponential growth.

Annual investment rate = 10%.

Annual capital stock and extraction rates are each 5%, and both double in the first 14 years.

After 28 years, the capital stock has quadrupled and extraction lags. By year 50, maintaining capital stock overwhelms income from extraction, and the operation shuts down.

Meadows, *Thinking in Systems*, 2008

A two-stock system

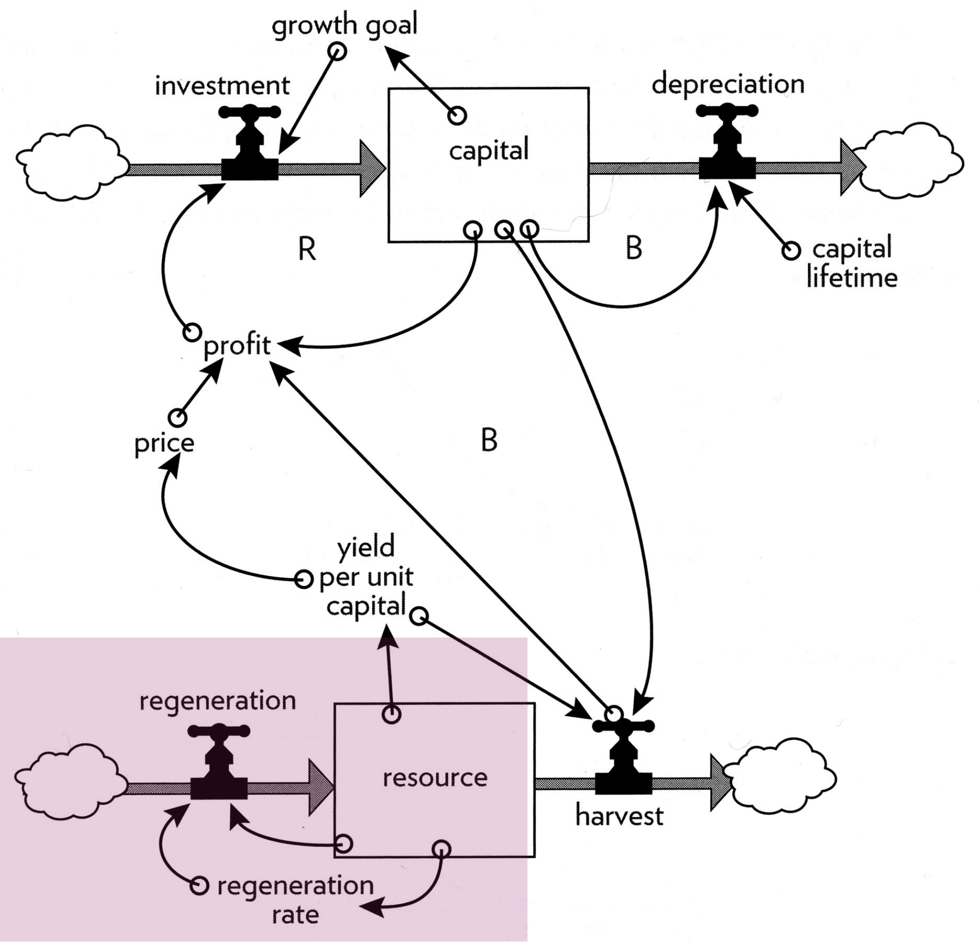

Figure 42. Economic capital with its reinforcing growth loop constrained by a renewable resource.

This model might pertain to a company developing a renewable resource. Note the presence of an input to the resource stock.

Meadows, *Thinking in Systems*, 2008

Good Scenario

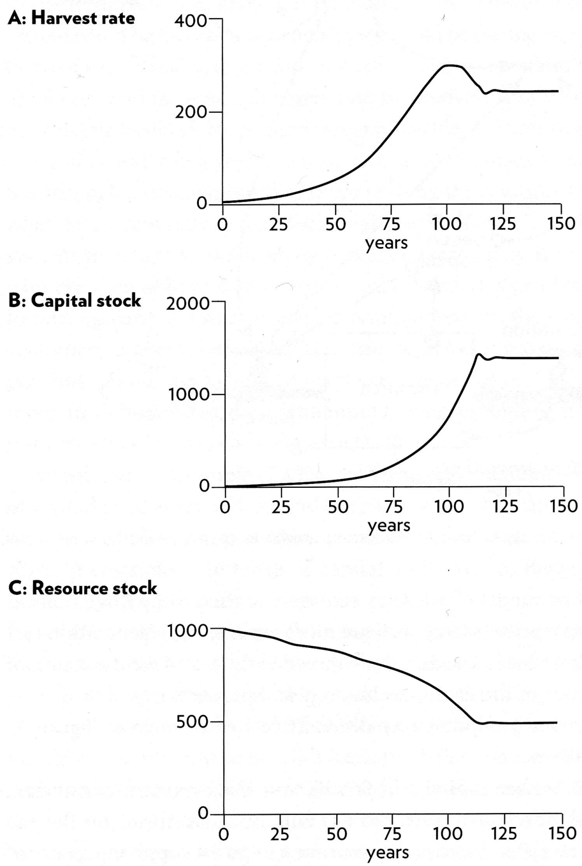

Figure 43. Annual harvest (A) creates profits that allow for growth of capital stock (B), but the harvest levels off, after a small overshoot in this case. The result of leveling harvest is that the resource stock (C) also stabilizes.

Over time, harvest rate, capital stock and resource stock stabilize. Manageable steady-states are reached and maintained.

The balancing feedback loops constrain the effects of the reinforcing loop.

Meadows, *Thinking in Systems*, 2008

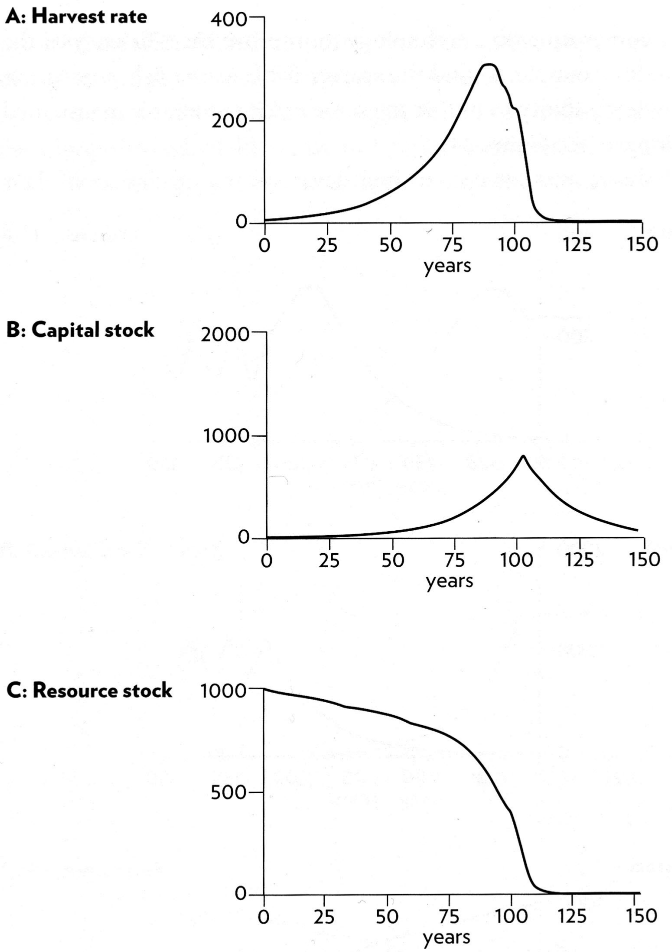

Figure 45. An even greater increase in yield per unit of capital creates a patterns of overshoot and collapse in the harvest (A), the economic capital (B), and the resource (C).

Bad Scenario

A new technology allows serious depletion of the renewable resource without a concomitant major decrease in yield per unit capital.

Meadows, *Thinking in Systems*, 2008

Non-renewable resources are stock-limited. The entire stock is available at once, and can be extracted at any rate (limited mainly by extraction capital). Since the stock is not renewed, the faster the extraction rate, the shorter the lifetime of the resource.

Renewable resources are flow-limited. They can support extraction or harvest indefinitely, but only at a finite flow rate equal to their regeneration rate. If they are extracted faster than they regenerate, they may eventually be driven below a critical threshold and become, for all practical purposes, nonrenewable.

Meadows, *Thinking in Systems*, 2008

Some reasons why systems behave in unexpected ways

1. Non-linear behavior
2. Ubiquitous delays
3. Non-existent boundaries (“clouds”)

Meadows, *Thinking in Systems*, 2008

Where can clouds be placed and still model the system correctly?

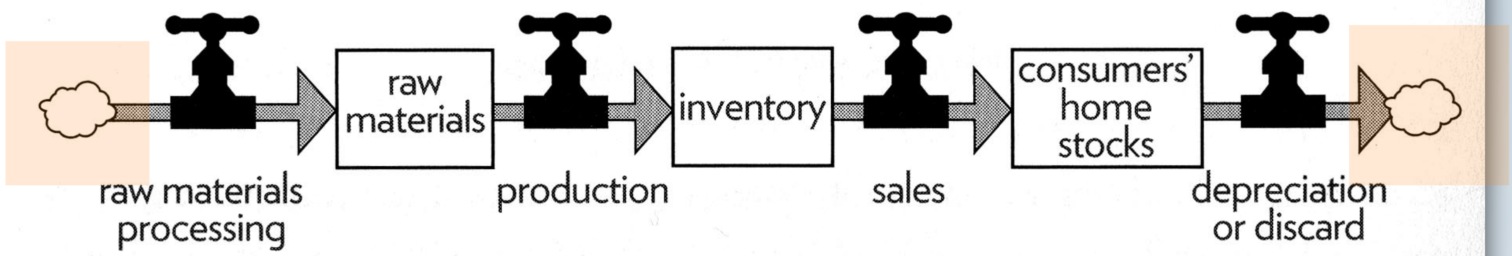

Figure 47. Revealing some of the stocks behind the clouds.

Meadows, *Thinking in Systems*, 2008

How to change systems - Some leverage points

1. Manage delays

2. Strengthen balancing feedback loops

3. Control reinforcing feedback loops

4. Insure optimal information flow

5. Awareness of who makes the rules

Meadows, *Thinking in Systems*, 2008

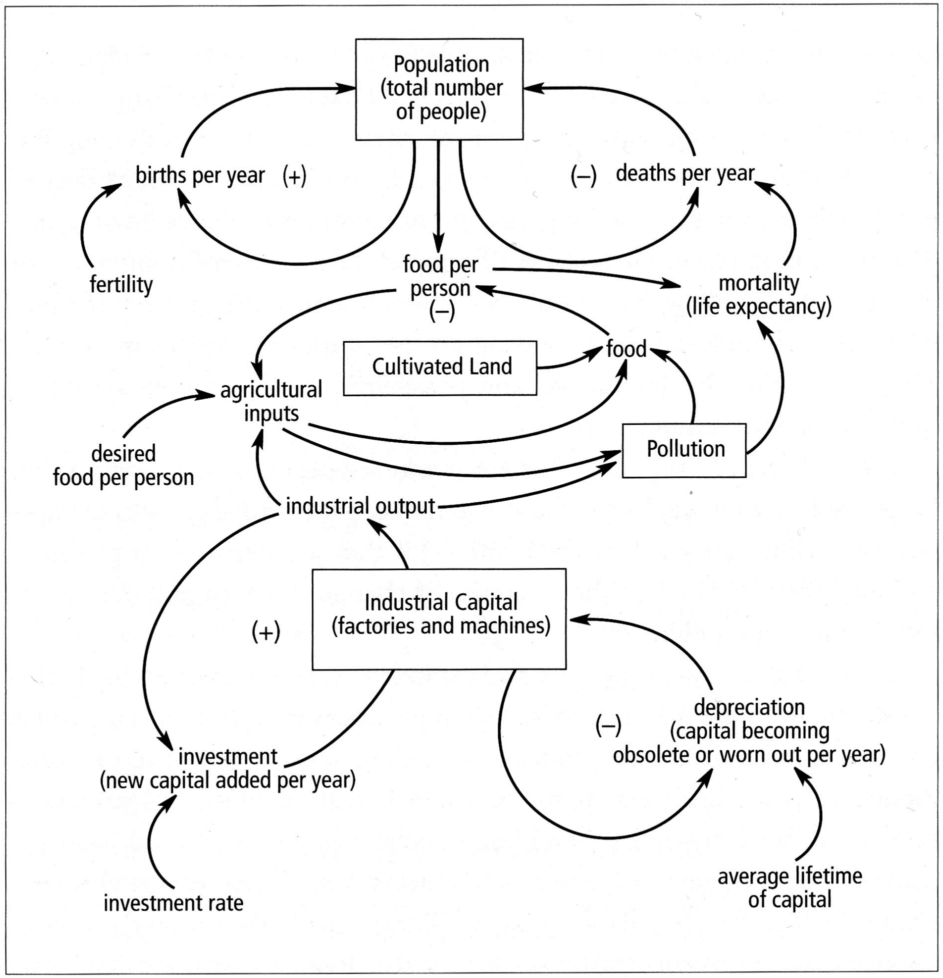

FIGURE 4-5 Feedback Loops of Population, Capital, Agriculture, and Pollution
Some of the interconnections between population and industrial capital operate through agricultural capital, cultivated land, and pollution. Each arrow indicates a causal relationship, which may be immediate or delayed, large or small, positive or negative, depending on the assumptions included in each model run.

Some factors influencing human population

A system approach
(four stocks)

Meadows, *Thinking in Systems*, 2008