Systems Analysis for Sustainable Development

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Lecture 2, Tuesday 22 Jan

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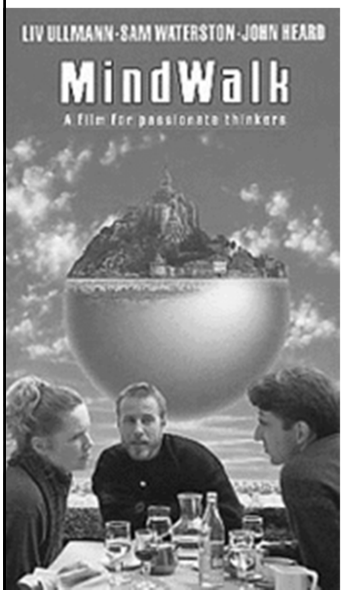


Mindwalk is based upon the work of physicist **Fritjof Capra**, and his book ***The Turning Point***, specifically. Capra is a **Systems Theorist**, and in this film he tries to explain his perspective in a language that filmgoers may find most accessible and applicable to their own lives. To set up his **theory of systems**, Capra uses the film to discuss how the revolution of **modern science** corresponds with the transformation of **world views and values in contemporary society** – working from the infinitely small to the infinitely large and back again. In order to better illustrate this abstract concept, the writers and director of this film have staged an evolving conversation between three distinctly different personalities: Jack, a "conservative democrat" politician on holiday after failing in his run for president in the primaries (Sam Waterston); Tom, an expatriate poet dealing with his "mid-life crisis" (John Heard); and Sonia, an ex-physicist with a strong sense of ethics willfully living in exile in Mont St. Michel (Liv Ullmann).

Problem examples

- Energy transformations
  - Renewable energy resources
- Energy transport and consumption
- Climate change
  - Greenhouse gases
- Dispersion of pollutants
  - In air, ground and water
- Ecosystems
  - Biodiversity
  - Stability
  - Disturbances
  - Habitat loss
  - Fragmentation

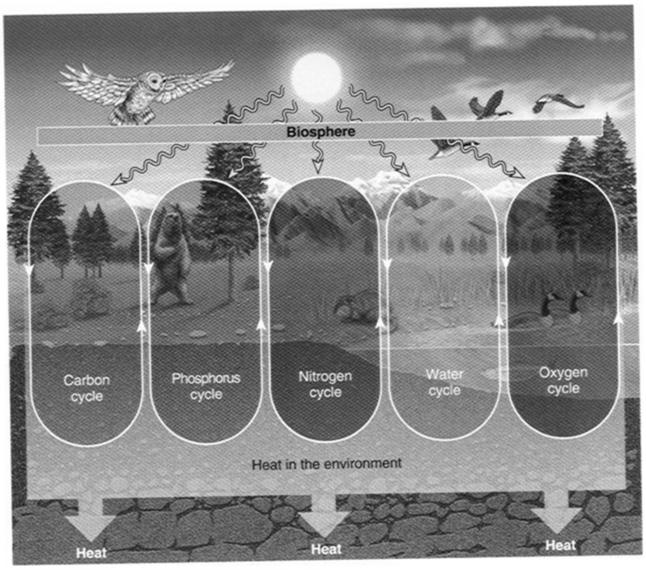
Problem solutions

It is a matter of

1) describing
2) analysing
3) attacking

the environmental problems in an objective and insightful way.

This belong to the most important tasks for science for a sustainable development.



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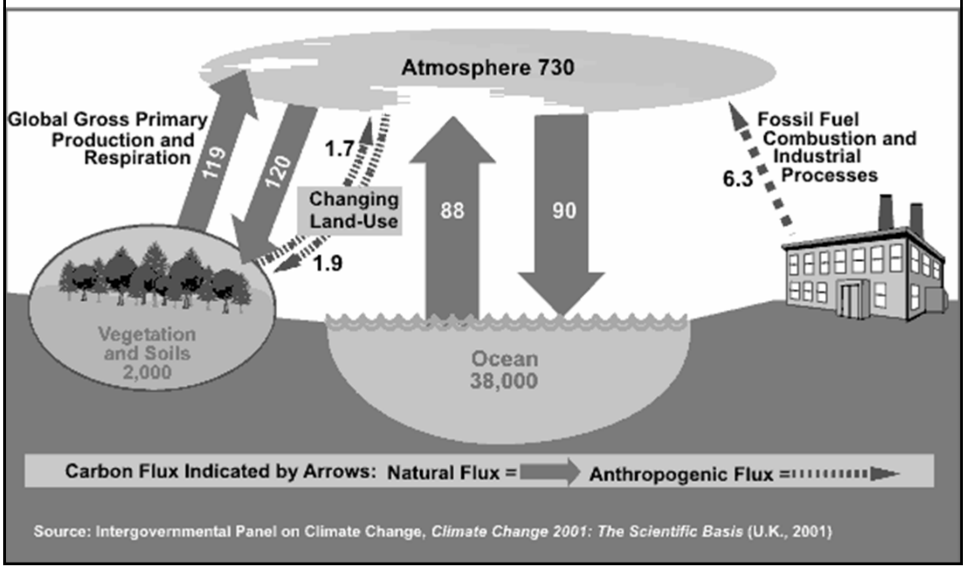
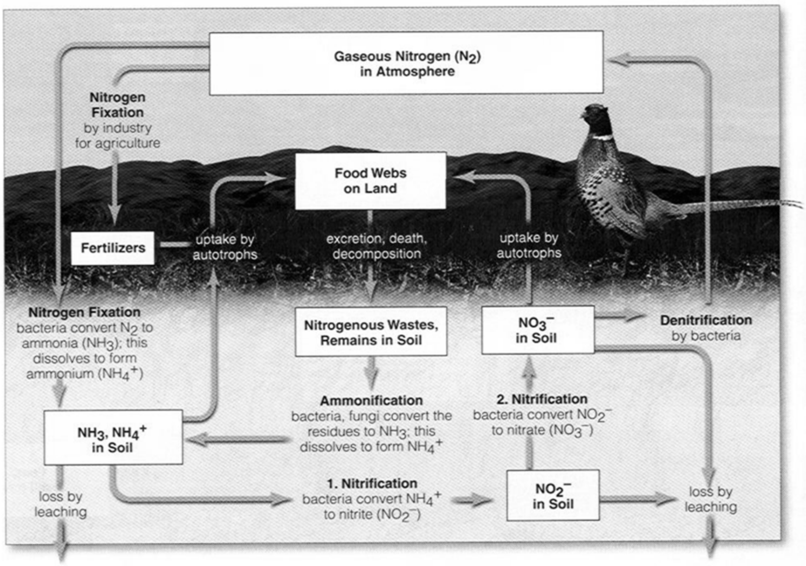
Active Figure 3-6 **Natural capital:** life on the earth depends on the *one-way flow of energy* (wavy arrows) from the sun through the biosphere, the *cycling of crucial elements* (solid lines around ovals), and *gravity*, which keeps atmospheric gases from escaping into space and enables chemicals to move through the matter cycles. This simplified model depicts only a few of the many cycling elements. *See an animation based on this figure and take a short quiz on the concept.*

Carbon cycles





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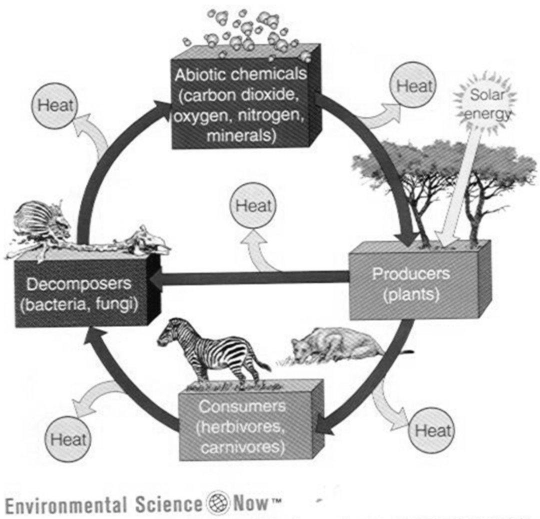
Active Figure 3-27 **Natural capital:** simplified model of the *nitrogen cycle* in a terrestrial ecosystem. Nitrogen reservoirs are shown as boxes; processes changing one form of nitrogen to another are shown in boxed print. *See an animation based on this figure and take a short quiz on the concept.* (Adapted from Cecie Starr and Ralph Taggart, *Biology: The Unity and Diversity of Life*, 9th ed., Belmont, Calif.: Wadsworth, © 2001)



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Active Figure 3-13 **Natural capital:** the main structural components of an ecosystem (energy, chemicals, and organisms). Matter recycling and the flow of energy—first from the sun, then through organisms, and finally into the environment as low-quality heat—links these components. *See an animation based on this figure and take a short quiz on the concept.*

Ecological energy flow

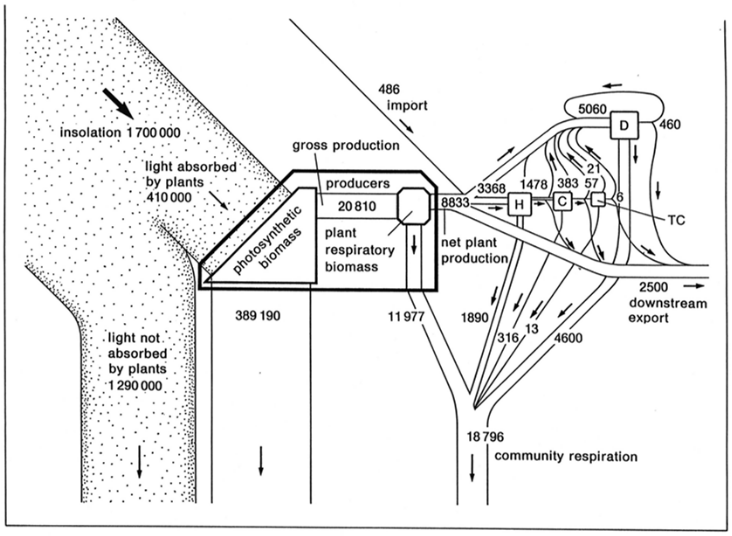
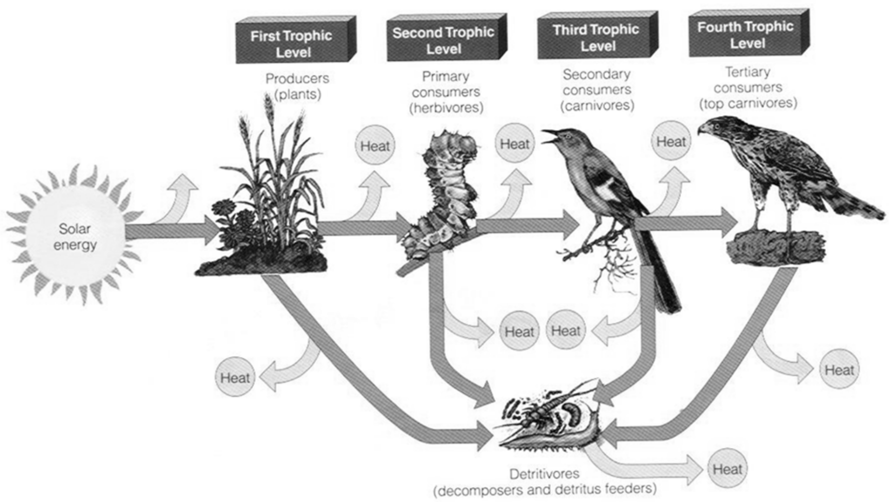


Figure 12.6 The energy flow in the Silver Springs community. The units are kcal/m²/yr (1 kcal = 4.2 kJ). H = herbivores; C = carnivores; TC = top carnivores; D = decomposers. (From Odum, 1957.)



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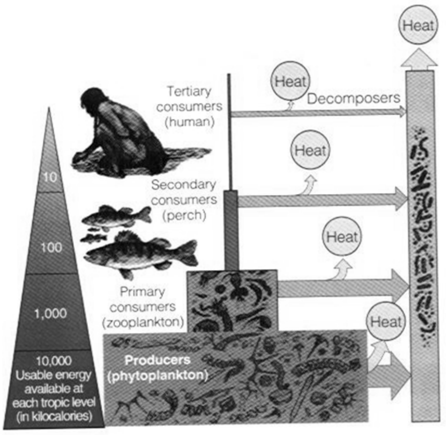
Active Figure 3-16 Natural capital: a *food chain.* The arrows show how chemical energy in food flows through various *trophic levels* in energy transfers; most of the energy is degraded to heat, in accordance with the second law of thermodynamics. *Critical thinking: food chains rarely have more than four trophic levels. Can you figure out why? See an animation based on this figure and take a short quiz on the concept.*



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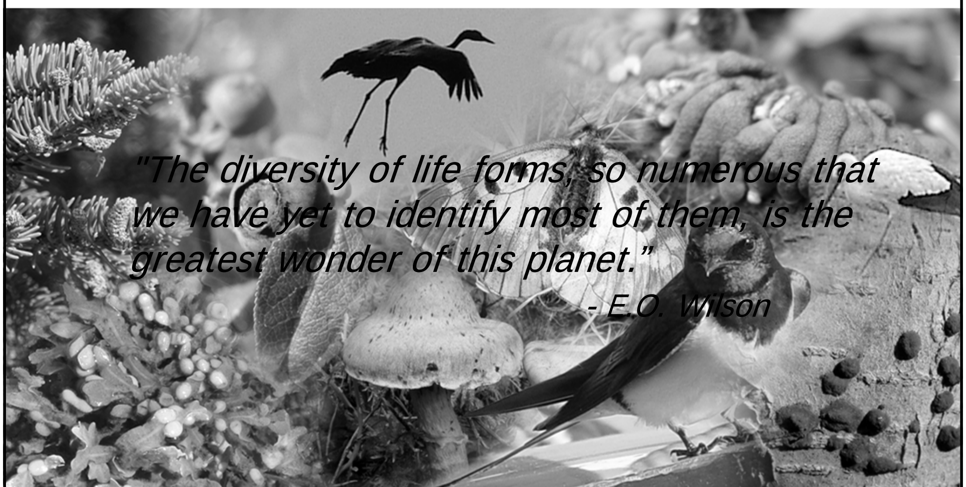
Active Figure Figure 3-18 **Natural capital:** generalized *pyramid of energy flow* showing the decrease in usable energy available at each succeeding trophic level in a food chain or web. In nature, ecological efficiency varies from 2% to 40%, with 10% efficiency being common. This model assumes a 10% ecological efficiency (90% loss in usable energy to the environment, in the form of low-quality heat) with each transfer from one trophic level to another. *See an animation based on this figure and take a short quiz on the concept.*

Biodiversity

Obvious economical values

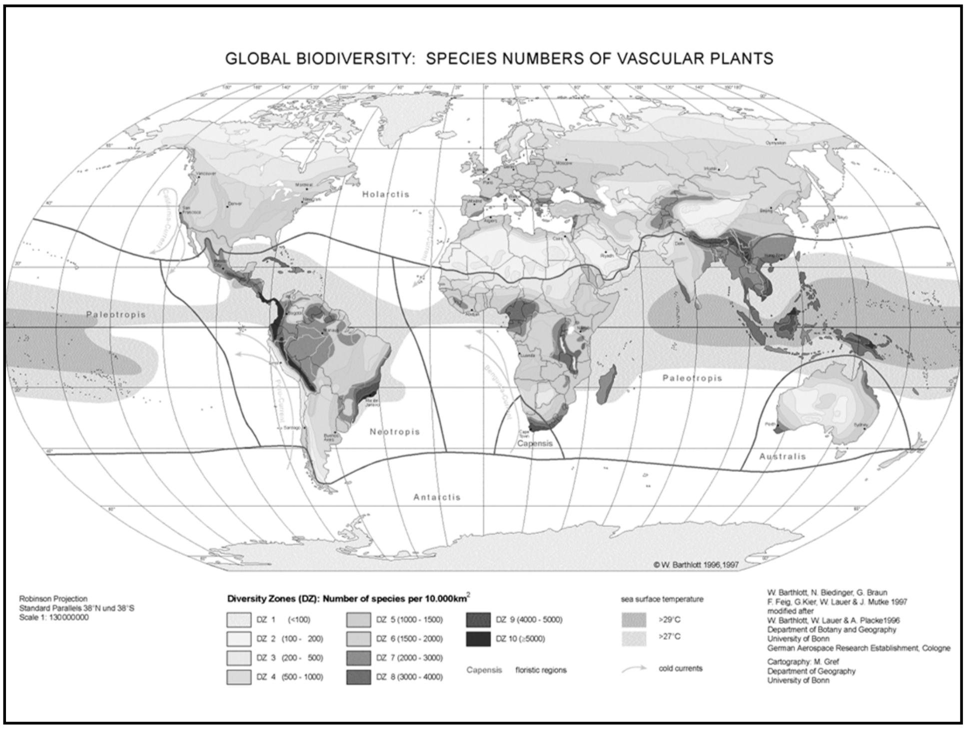


No obvious economical values

Biodiversity

How does Man fit into the web of Life?

Escher



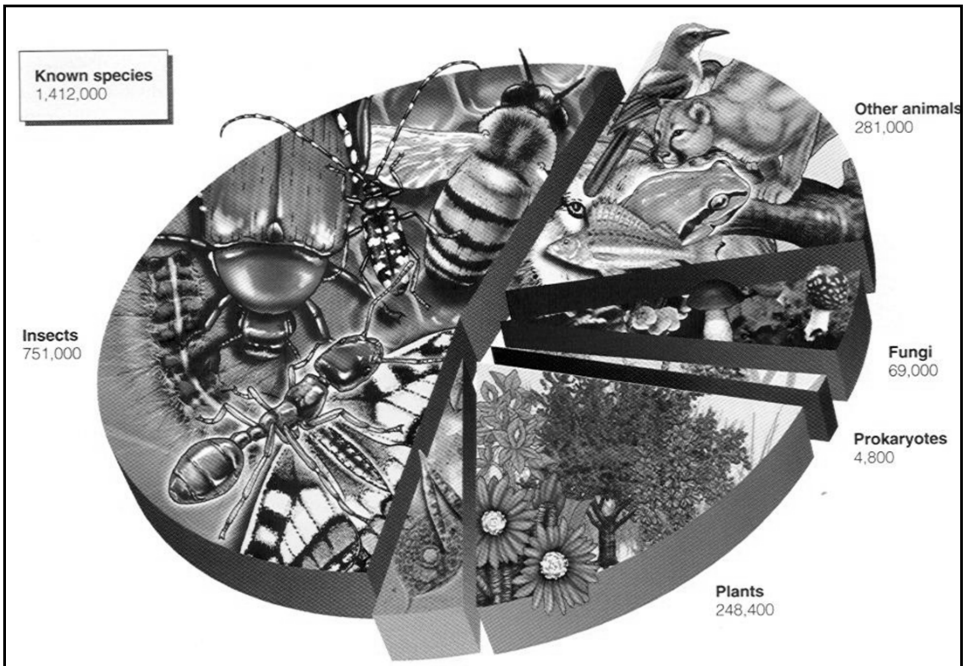


Figure 3-2 Natural capital: breakdown of the earth's 1.4 million known species.

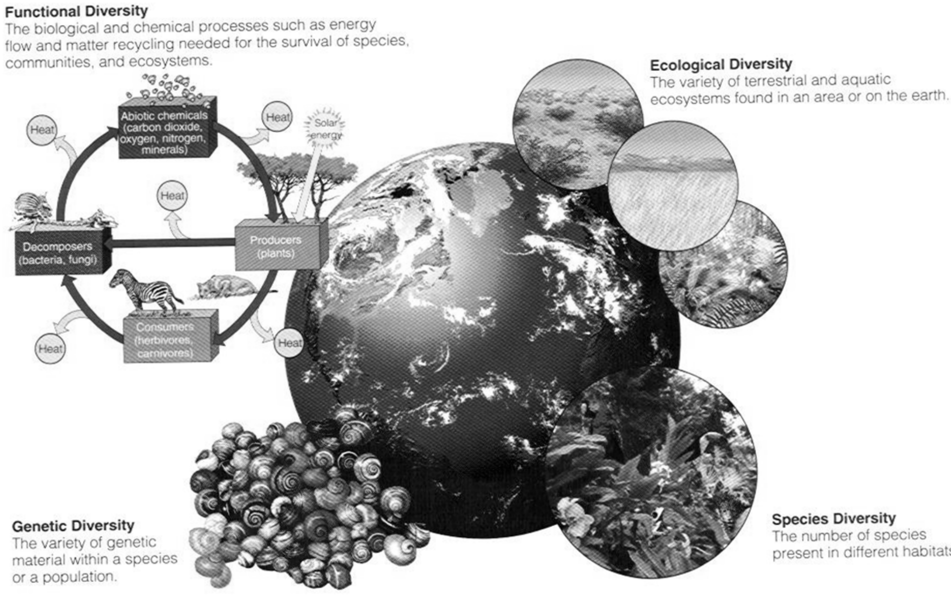
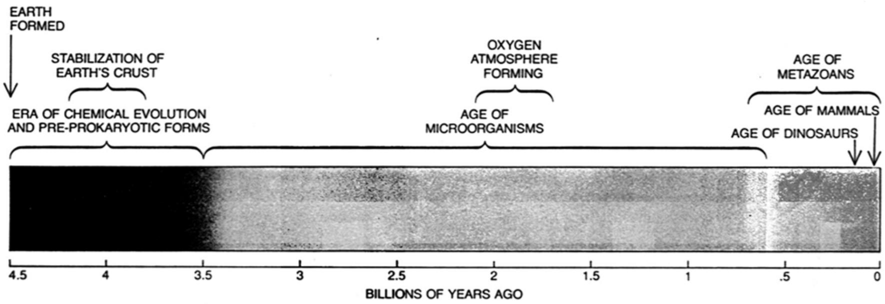


Figure 3-14 Natural capital: the major components of the earth's *biodiversity*—one of the earth's most important renewable resources.

Life history on Earth



Evolution of biodiversity

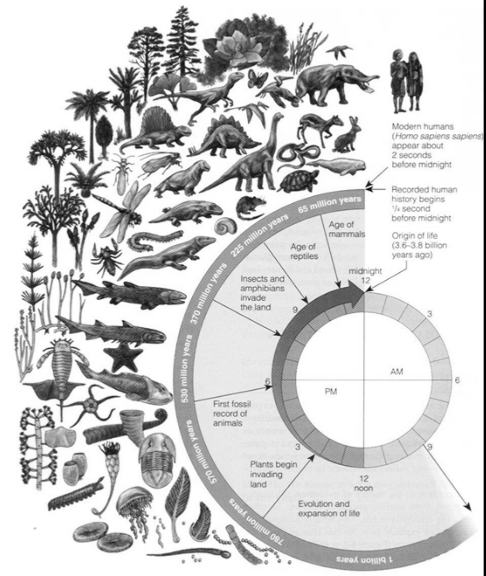
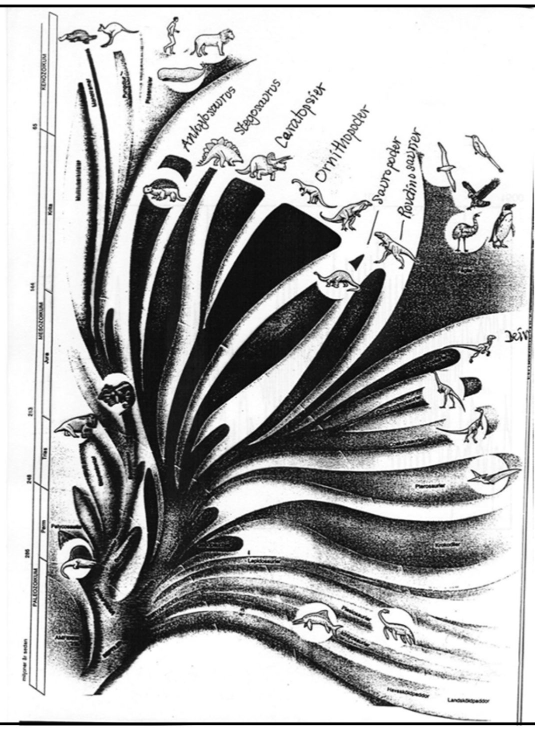


Figure 4-3 Natural capital: greatly simplified overview of the biological evolution of life on the earth, which was preceded by about 1 billion years of chemical evolution. Microorganisms (mostly bacteria) that lived in water dominated the early span of biological evolution on the earth, between about 3.7 billion and 1 billion years ago. Plants and animals evolved first in the seas. Fossil and recent DNA evidence suggests that plants began invading the land some 780 million years ago, and animals began living on land about 370 million years ago. Humans arrived on the scene only a very short time ago. We have been around for less than an eye blink of the earth's roughly 3.7-billion-year history of biological evolution. Although we are newcomers, humans have taken over much of the planet and now have the power to cause the premature extinction of many of the other species that travel with us as passengers on the earth as it hurtles through space.

The tree of Life



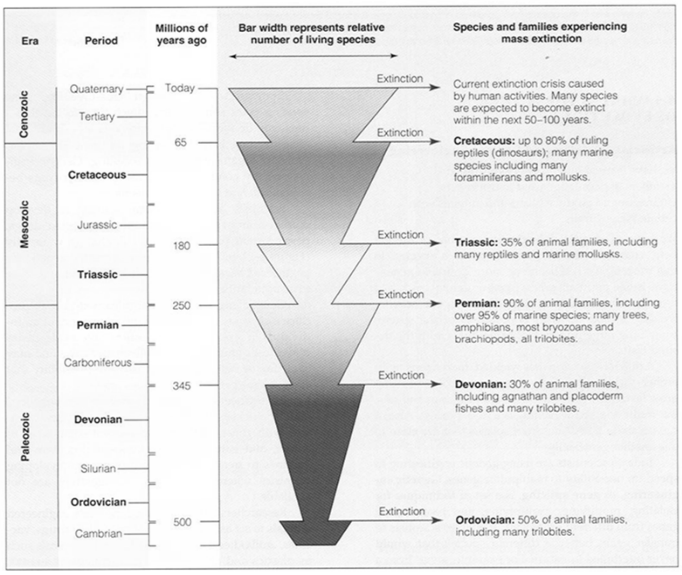
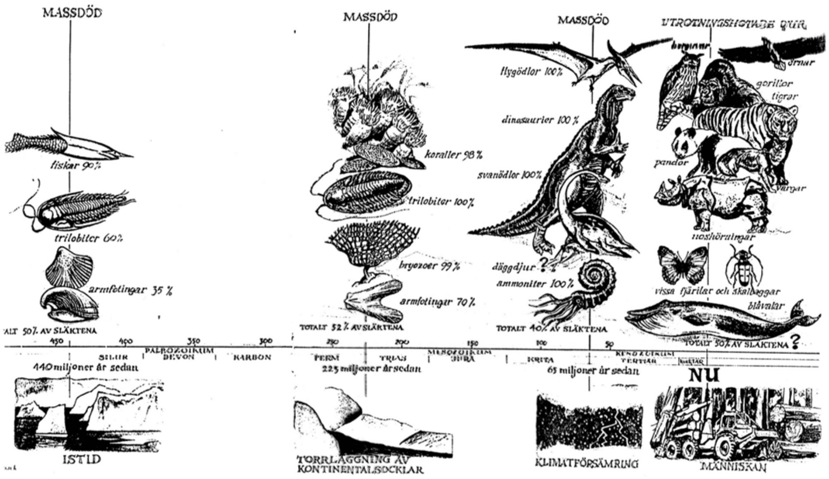
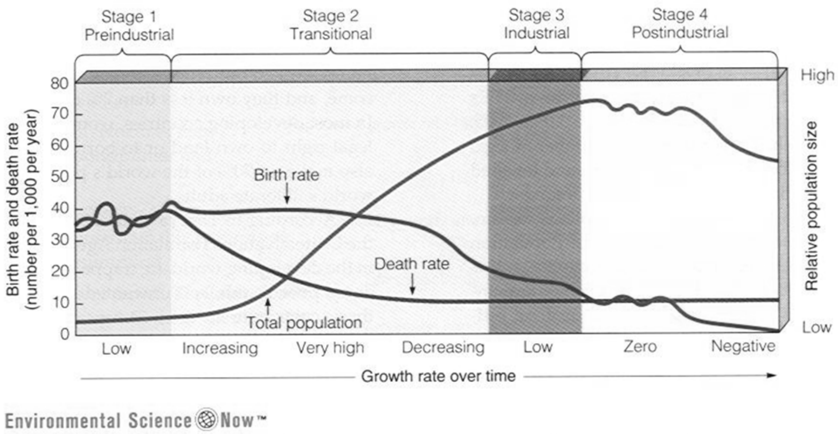


Figure 4-9 Fossils and radioactive dating indicate that five major *mass extinctions* (indicated by arrows) have taken place over the past 500 million years. Mass extinctions leave many organism roles (niches) unoccupied and create new ones. As a result, each mass extinction has been followed by periods of recovery (represented by the wedge shapes) called *adaptive radiations*. During these periods, which last 10 million years or longer, new species evolve to fill new or vacated ecological roles. Many scientists say that we are now in the midst of a sixth mass extinction, caused primarily by human activities.

Current mass extinction is of human origin



Demographic transition



Active Figure 7-11 Generalized model of the *demographic transition*. There is uncertainty over whether this model will apply to some of today's developing countries.

Systems thinking for a sustainable development

A sustainable development requires that Man (and his technical and socio-economic systems) can co-exist with Nature (and its biogeo-chemical and ecological systems).

In order to harmonise these different types of systems requires a deeper understanding of the system properties and what make them more or less stable.

We must find a balance between stability and flexibility.

Systems thinking for a sustainable development

Which kind of science and which technology promotes a sustainable development?

What can science and mathematics contribute with?

Can systems analytical models give us a greater understanding of natural and artificial systems and be guiding for how we can make these systems function more efficiently together?

Specifically, how can science and systems thinking aid us to attain a more sustainable use and management of the natural resources?

What is systems thinking?

System = a collection of elements that are connected together to form an ordered whole

Systems thinking implies that emphasis is put on the whole, the structure and the relationships between the parts of a complex problem area.

The structure of the system, i.e. the relations between the parts, is crucial for the system properties and behaviour.

The Whole > the sum of the parts
(*Emergence*)

Sciences and systems

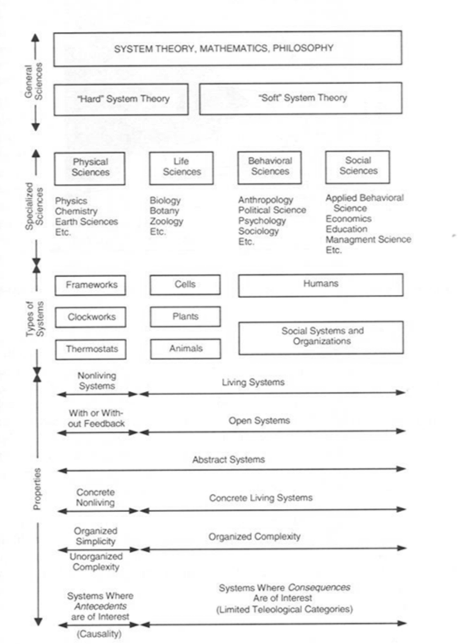


Figure 2.1: A taxonomy of sciences and systems. (Source: van Gigch, 1991:66)

What is systems analysis?

Systems theory is the basis for modeling complex systems, which are broken down into **three basic components**: units, processes, and structures. Once these three components can be identified, a mathematical model can be produced. This model is then run through a simulation.

What is systems analysis?

Systems analysis is the science dealing with analysis of complex, large scale systems and the interactions within those systems. This field is closely related to operations research.

The systems discussed within systems analysis can be within any field such as: industrial processes, management, decision making processes, environmental protection processes, etc.

Systems analysis researchers apply mathematical methodology to the analysis of the systems involved, trying to form a detailed overall picture.

What is systems analysis?

Systems analysis is a discipline that gives scientific theory, methods and techniques for:

- description
- experiments
- analysis
- planning
- control

of complex systems.

Systems analysis involves:

- a systems ”world view” and concepts
- a project methodology
- a number of powerful tools and techniques

What does Systems Analysis imply?

All analysis and problem solving in connections with a systems analytical study is made with the aid of a model of the studied problem area.

A model is a simplified picture, an abstraction, of the relevant aspects on the problem area.

The model can be more or less formalised depending on the nature of the studied problems.

The purpose of a systems analytical study must always be clearly defined before the problem solving work can begin.

The result of a systems analytical study should not be seen as a complete answer, but as a part of a decision making.

Some central concepts

- Model – system – purpose
- Deterministic process
- Stochastic (random) process
  - Throwing dice, radioactive
- Linear
- Non-linear
- Fluctuations
- Predictability

Some additional concepts

- Complexity – between order and disorder; ’the more information that is needed to describe a system, the more complex it is’
- Self-organization – ordered solutions (e.g. oscillations, or solitary waves) arise from the non-linear equations
- Chaos – irregularities/randomness that arises in a deterministic system, more structured than noise

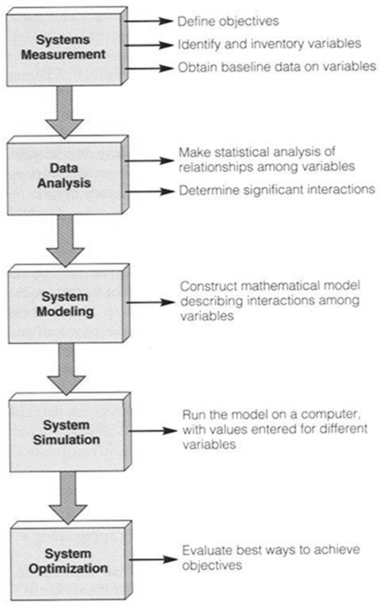


Figure 3-32 Major stages of systems analysis. (Modified data from Charles Southwick)

Purpose, system, and model

1. **Purpose** (objective): You decide what to study!
2. **System**: A set of objects together with relationships between the objects and between their attributes.
3. **Model**: A simplified reproduction/abstraction of the system.

Holistic thinking: Systems philosophy and techniques focus on the *whole* system

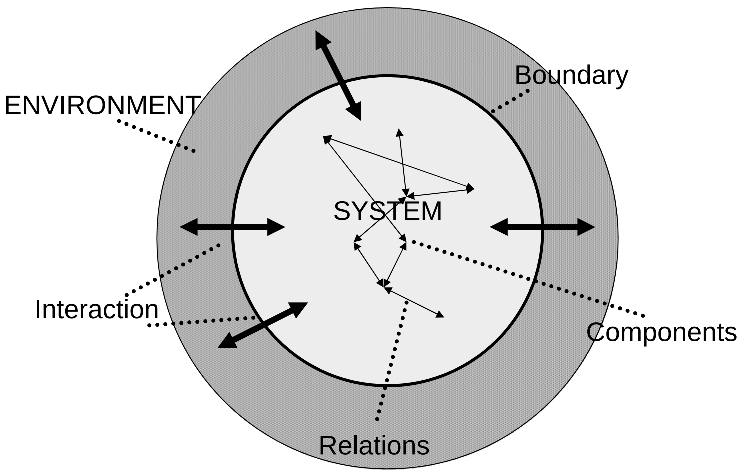
1. Purpose

- You have to choose what to study, and why.
- You have to formulate the goal in operative terms:
  - Which data/information to collect?
  - System boundaries?
  - Model building
  - Validation
  - Analysis
  - Evaluation of results
  - Presentation of results

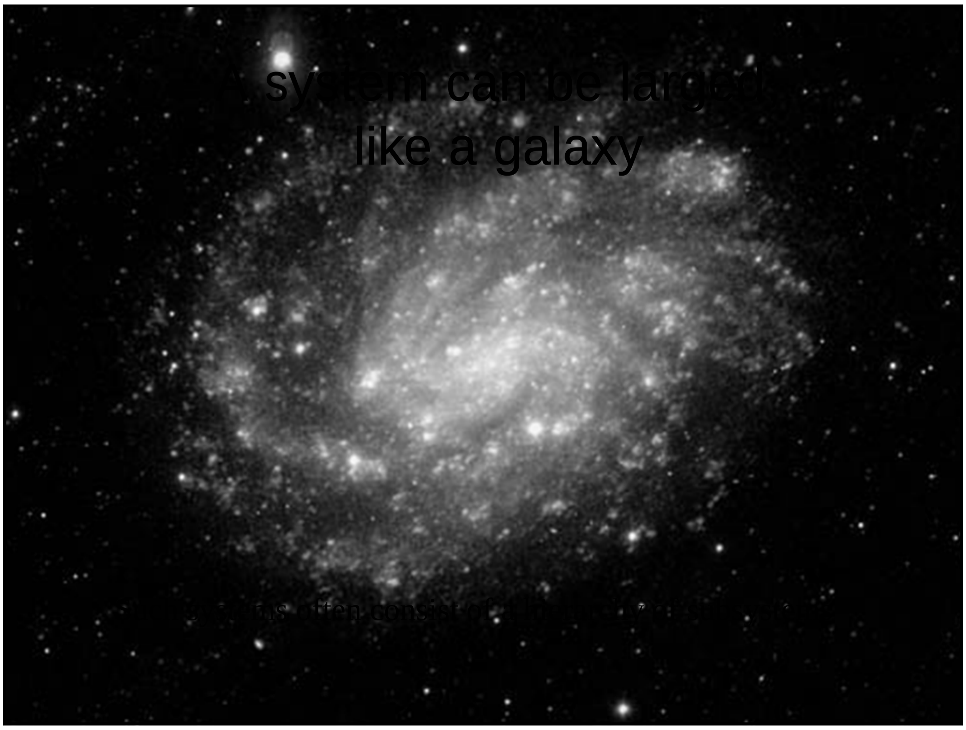
2. System

- A system consists of two types of entities:
  1. some kind of components, and
  2. the relationships between them
- The set of components and relations chosen should form some kind of whole.
- There must be some system boundary that separates the system from the rest of the world.
- The rest of the world, outside the system is called its surround, or environment.

Basic concepts in systems theory

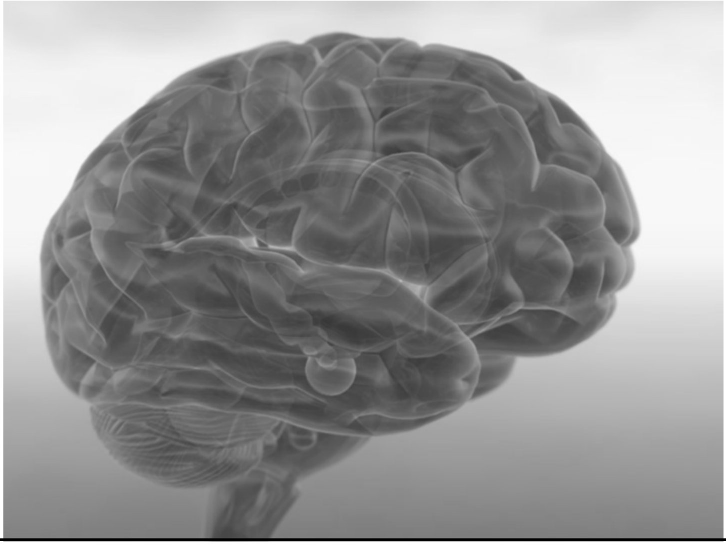


A system can be large
like a galaxy

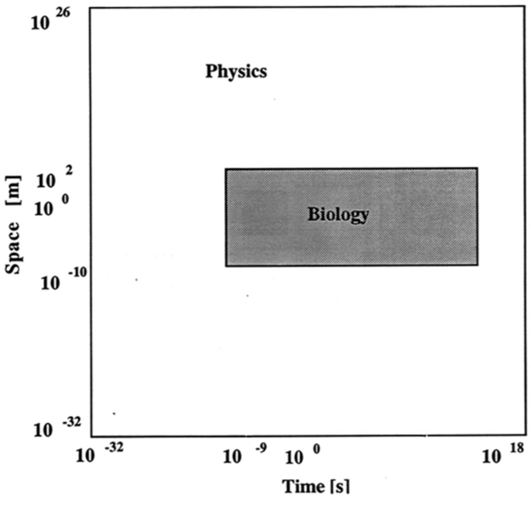


...or a system can be a farm,
or a tractor...

...or a human brain

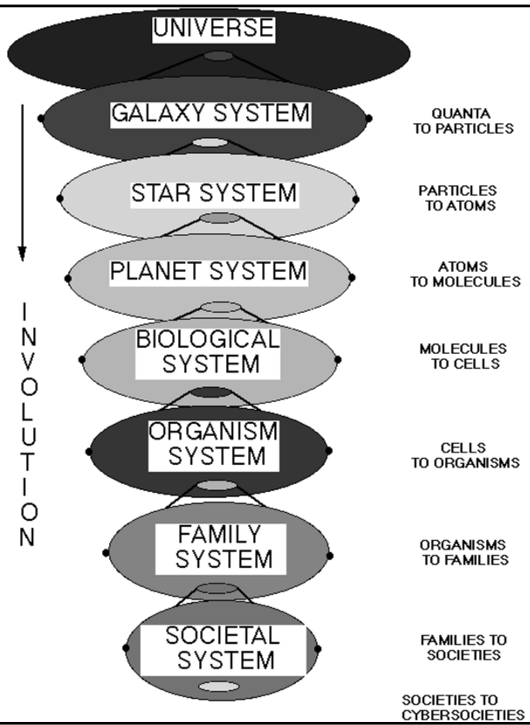


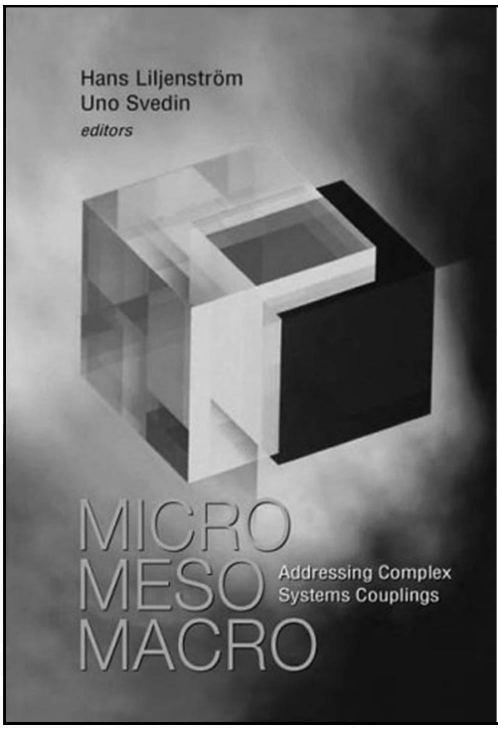
Spatial and temporal scales



Micro-meso-macro

with Man in the middle





Contents

Micro-meso-macro in social systems

Local – regional - global

- Village
- City
- County
- Region
- Country
- Continent/Union

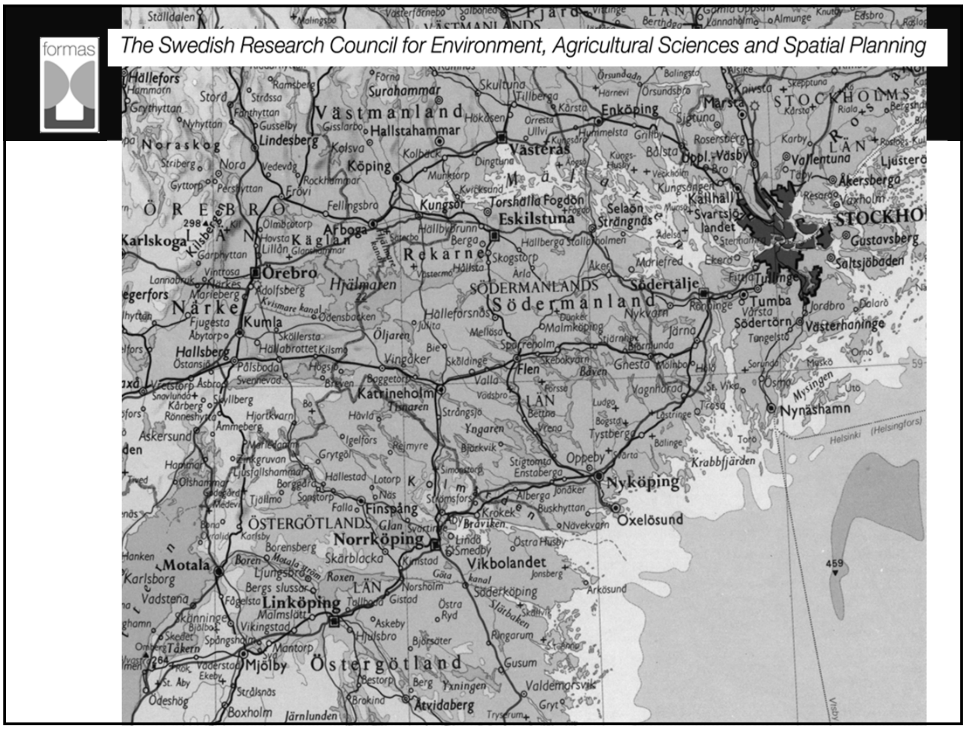
Micro-meso-macro in social systems

But these concepts are relative, not fixed.

For example, the concept of region may refer to an area larger than a city but smaller than a country,

or

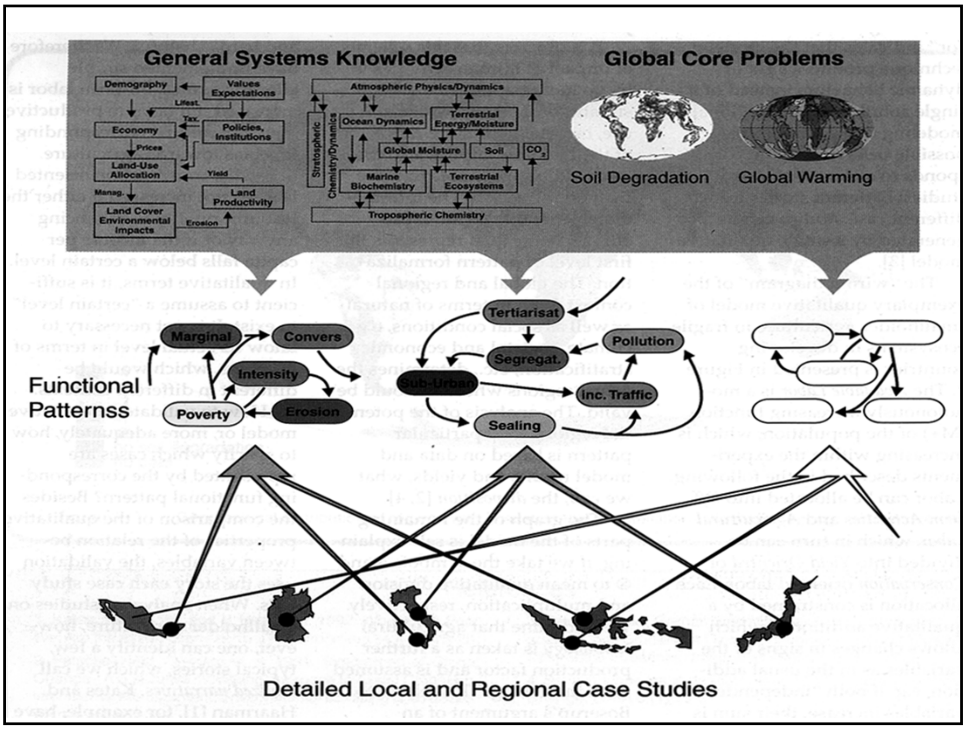
it could include several countries, such as the South-East Asia region.



Baltic Sea Region

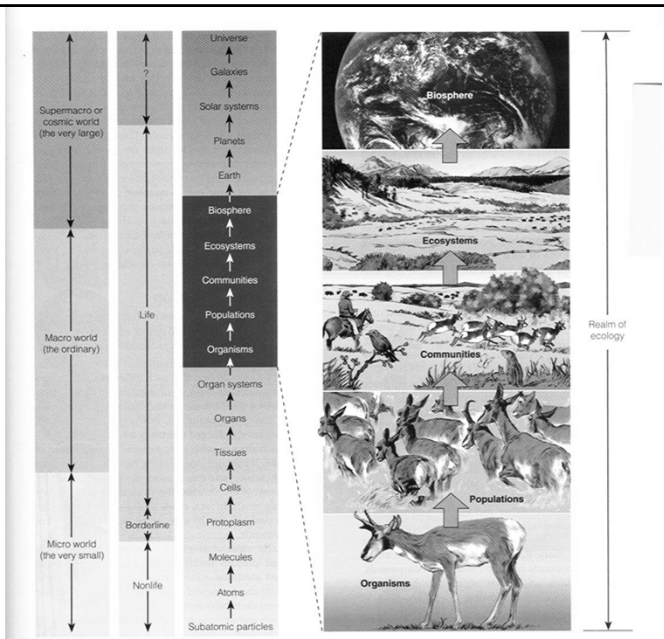
What is the boundary?

For example, the Baltic Sea Drainage Basin



Micro-meso-macro in biological systems

- Biomolecules
- Cells
- Multicellular systems
  - cell populations
  - organs
  - networks
- Ecological systems
- Evolution



Environmental Science Now™
Active Figure 2-3 **Natural capital:** levels of organization of matter in nature. Ecology focuses on five of these levels. *See an animation based on this figure and take a short quiz on the concept.*

Micro – Meso - Macro

Example:

Molecular motion - temperature, pressure

Stat. mechanics thermodynamics

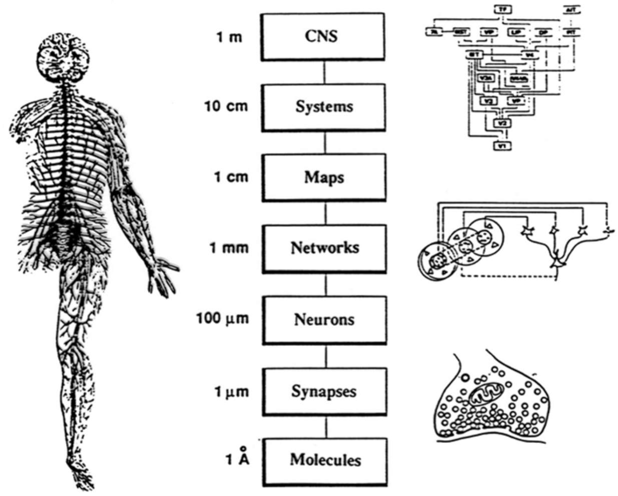
Micro – Meso - Macro

Also:

Individual - group - population

Single - few - many

Hierarchy: also the parts are sub-systems, composed of parts, etc



There are also different temporal scales

- Molecular dynamics — $10^{-12} – 10^{-9}$ sec
- Ion channel openings — $10^{-6} – 10^{-3}$ sec
- Neurodynamics — $10^{-3} – 10^{-1}$ sec
- Protein synthesis — $10^{1} – 10^{2}$ sec
- DNA replication (cell cycles) — $10^{3} – 10^{5}$ sec
- Physiological rhythms — min - days
- Learning — min – years
- Life spans — hours – 10^{3} years
- Evolution — $10^{2} – 10^{9}$ years

Complex systems

- Could be very simple, e.g. a double pendulum, chemical clocks
- Often consists of a large number of components, e.g weather, a cell, a brain, an ecosystem

Characteristics of complex systems

- non-linear
- feedback loops
- self-organizing
- emergent
- behaviour often unpredictable
- often have large number of components
- often hierarchical
- often open

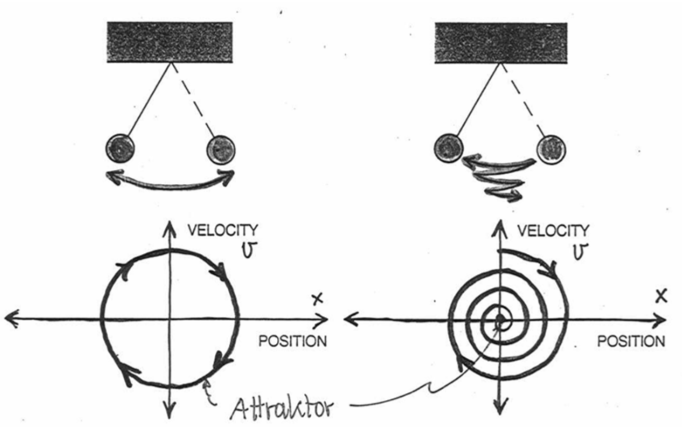
Complex behaviour

- Often appears abruptly, unpredictably
- Complex global patterns can be generated by repeatedly applying simple local procedures
- Above a certain threshold of complexity, new qualities arise (emerge)

Linear (”simple”) systems

- Linearity – a sum of solutions to a linear equation is also a solution, e.g. a harmonic oscillator
- Many problems in physics (science) are expressed by linear equations, e.g. potential theory, wave propagation, quantum mechanics etc.

Regular and irregular motion

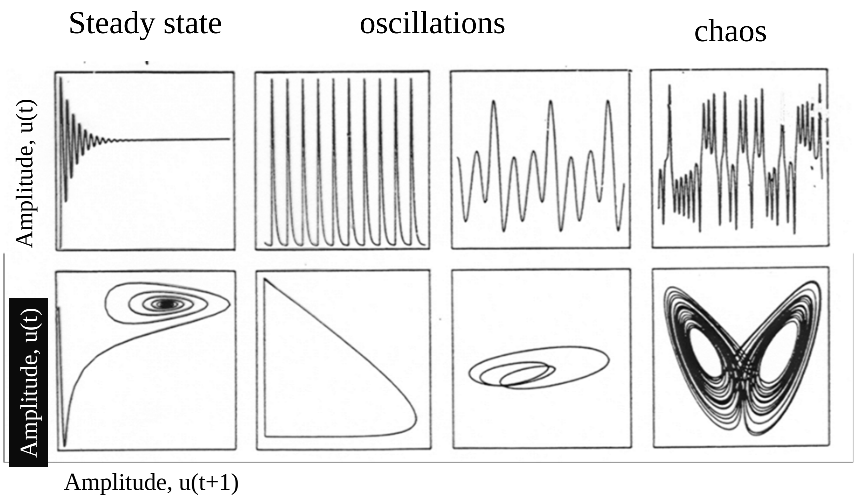


Dynamical systems

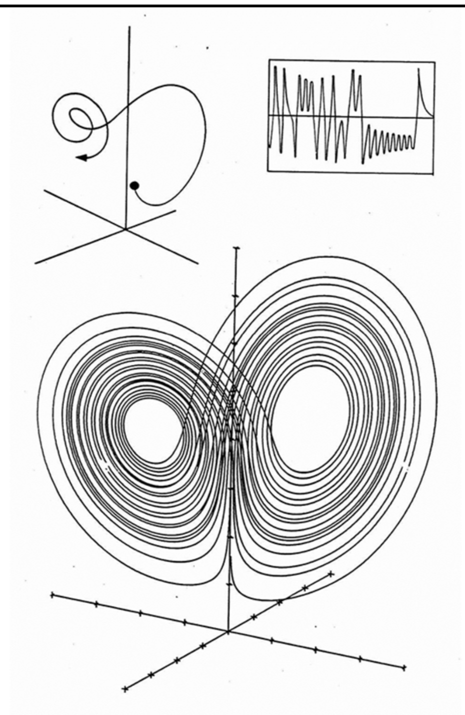
Four main mathematical ideas have been developed to characterize time series:

- steady states (equilibrium, fixed point)
- oscillations (limit cycle)
- chaos (strange attractor)
- noise

Non-linear dynamics

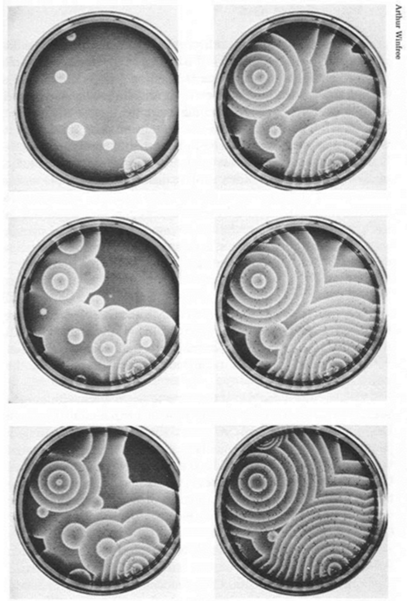


The Lorenz attractor



Chemical chaos

Beluzov-Zhabotinsky reaction



CHEMICAL CHAOS. Waves propagating outward in concentric circles and even spiral waves were signs of chaos in a widely studied chemical reaction, the Beluzov–Zhabotinsky reaction. Similar patterns have been observed in dishes of millions of amoeba. Arthur Winfree theorized that such waves are analogous to the waves of electrical activity coursing through heart muscles, regularly or erratically.

Chaos

- irregular, random
- deterministic, but unpredictable
- sensitivity to initial conditions

Charcteristics of ”chaos”

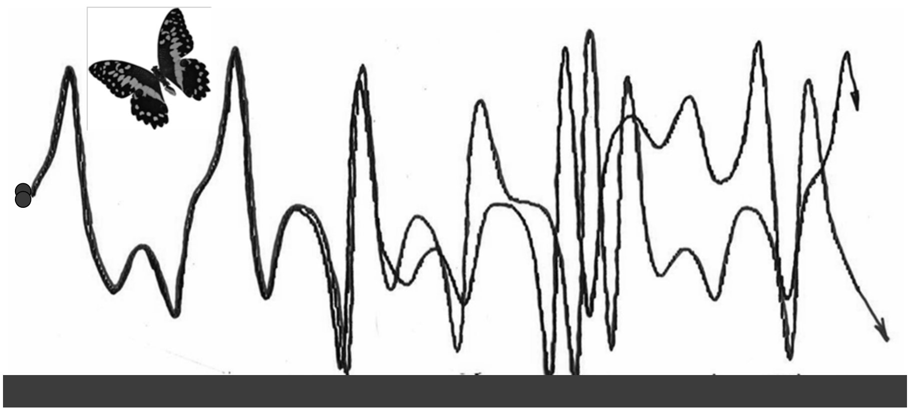
- Solutions are very sensitive to initial conditions, i.e. they provide positive Lyapunov exponents
- The pattern of the solution shall have some, completely irregular features which can be characterized by a sequence of two symbols (e.g. 0, 1) that is as irregular as a sequence of tosses of a coin
- The solutions should have a fractal character

Examples of ”chaotic” behaviour

- turbulence (e.g. smoke, cream in coffee)
- dripping water tap
- water heated in container
- traffic jams
- brain-waves
- the stock market
- certain growth of populations

The butterfly effect

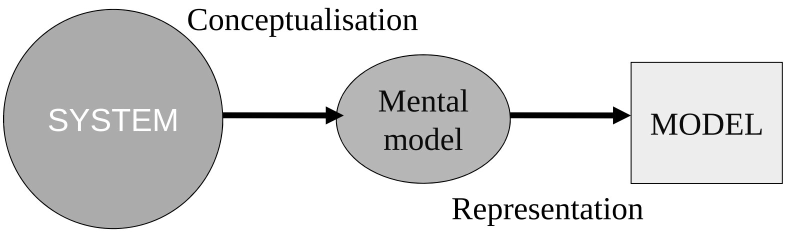
sensitivity to initial conditions



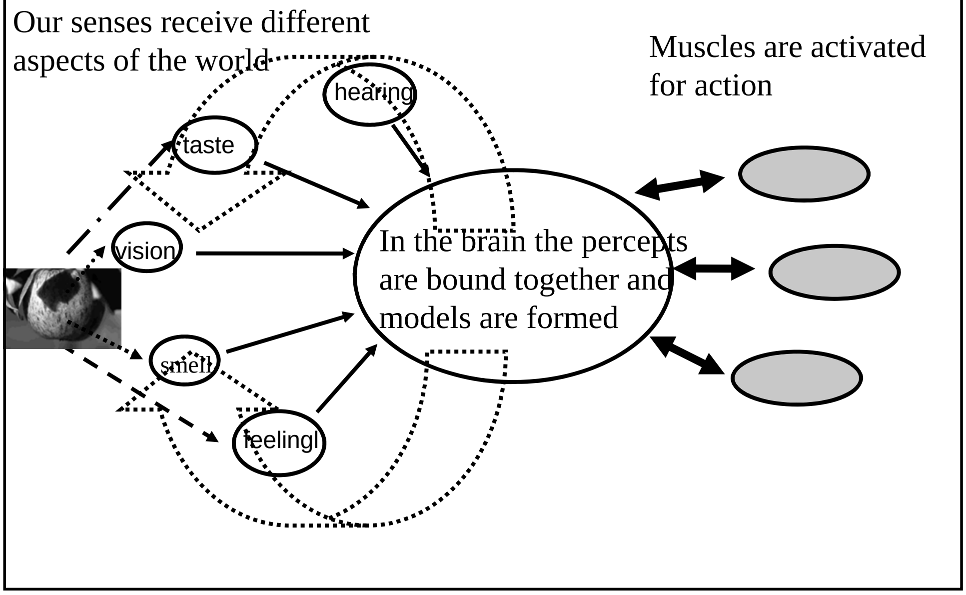
”The flaps of the wings of a butterfly in Amazonas may cause a snow storm in Uppsala”

3. Model

A model is a simplified reproduction of a real system, an abstraction, which we use to better describe, understand and predict our complex world



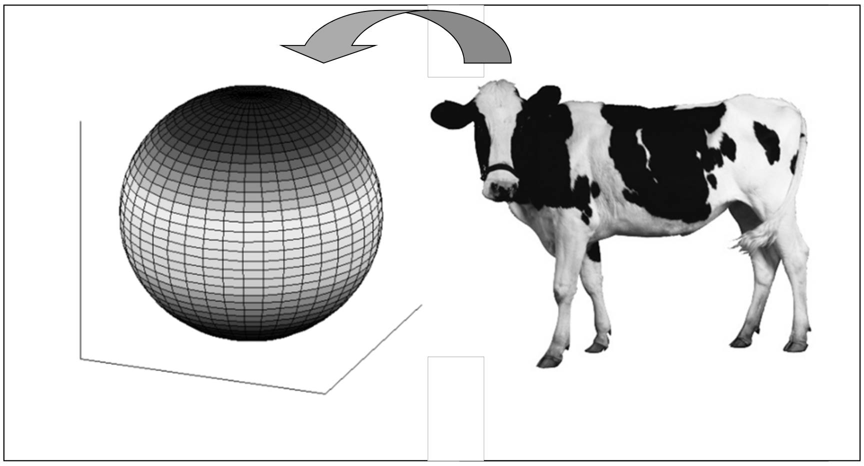
Perception - model



Why use a model?

- We cannot avoid it. Our thinking deals with models!
- Models are simplified descriptions
- Model building brings knowledge and insight
- A formalised model can be discussed and criticised
- You can make experiments (simulations) with some
- When it is too expensive, time-consuming or dangerous to make experiments with the real system
- When we plan to make a real system
- Models have pedagogic merits
- ….

Is a sphere a good model of a cow?



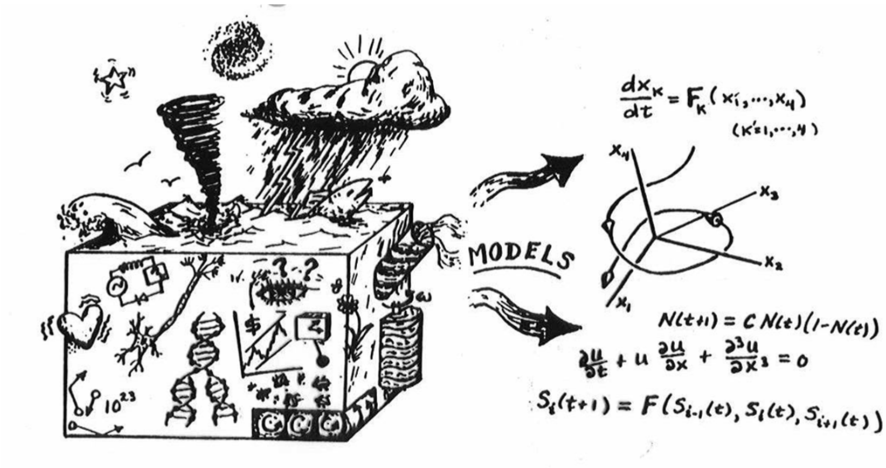
That depends on what you are asking

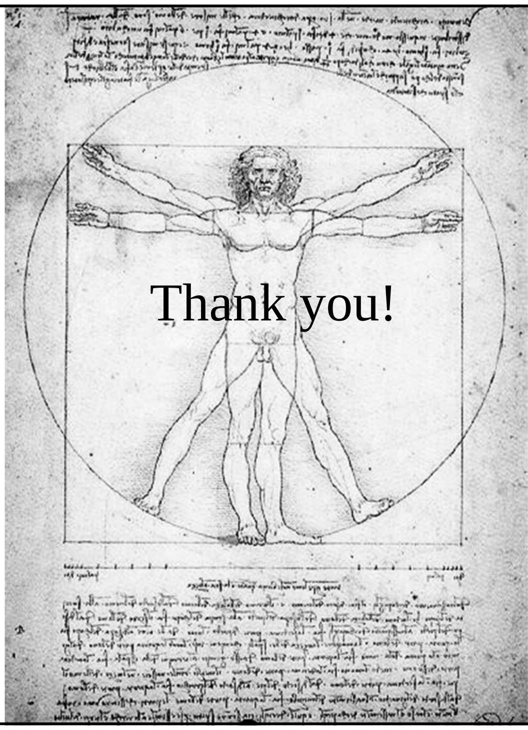
Spherical cows

"For evaluating thermal radiant exchange between a cow and her surroundings, the cow can be represented by an equivalent sphere....."

(Perry, R.L., and Speck, E.P. "Geometric Factors for Thermal Radiation Exchange Between Cows and Their Surroundings", American Society of Agricultural Engineers Paper #59-323.)

Mathematical models of complex (natural) systems





Thank you!