Introduction to the Biosphere-Atmosphere system

Lecture Autumn 2023

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What is a system?

What is a system?

In most simple words:

A set of things - people, trees, molecules or whatever - that are interconnected in a way that they produce their own pattern of behaviour in time.

The Slinky experiment…

What made the Slinky bounce up and down?

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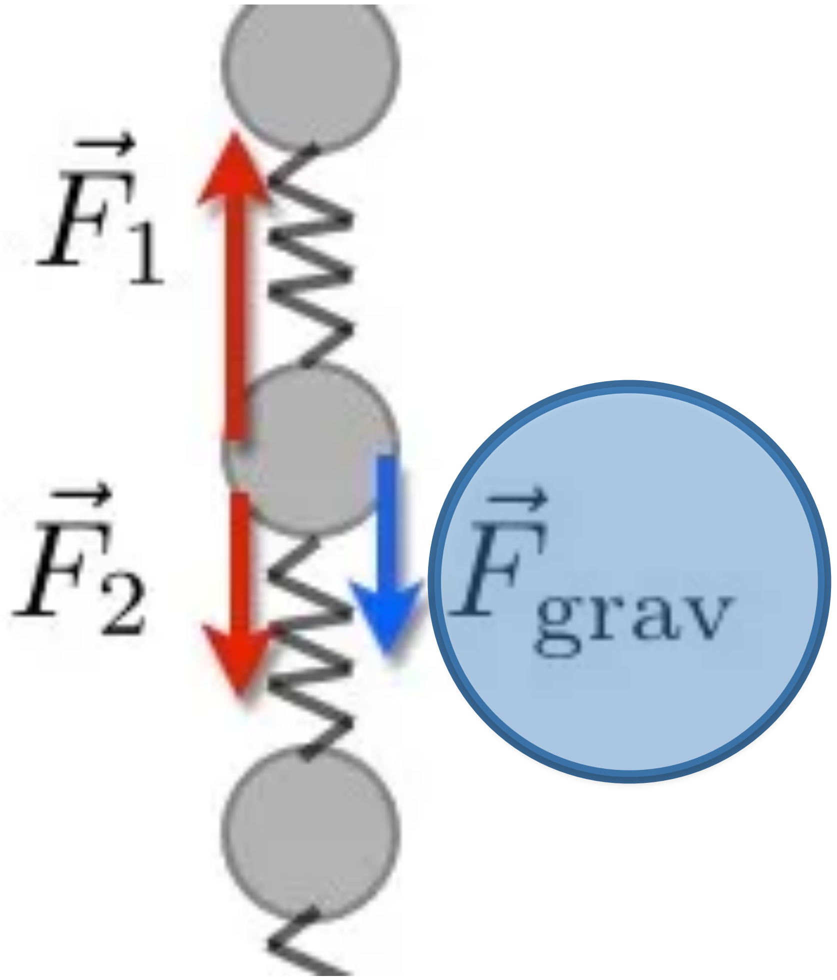
What made the Slinky bounce up and down?



On our planet, the outer gravitational force "pulls" the slinky towards the ground.

The forces "inside" the spring lead to the bouncing effect of the system.

The Slinky experiment…

What made the Slinky bounce up and down?

The answer lies within the Slinky itself. It is the behaviour of a spring in the gravitational field of Earth.

The behaviour can be suppressed or released!

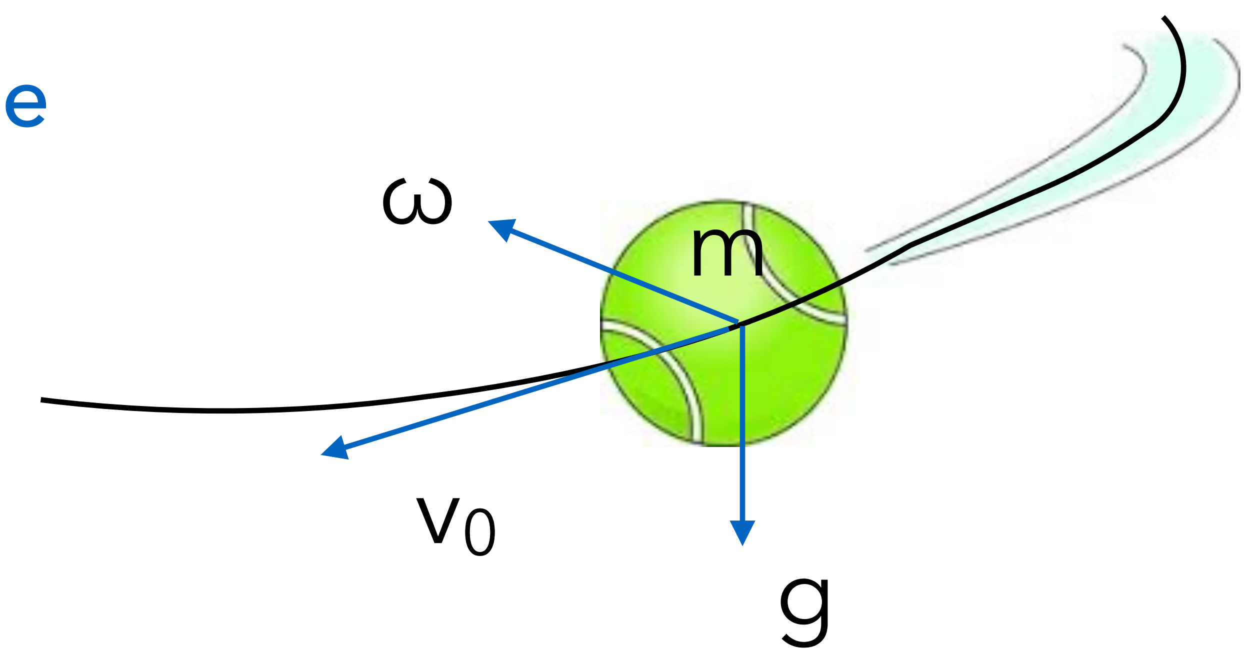
Another simple example…

We can calculate the flight trajectory of a tennis ball if we have its mass, initial speed v_0, and angular velocity ω.

We simplify that there is no resistance in air and the balls mass is just seen as a point.

If we want a very accurate estimate of the trajectory this simple “system” we learned at school will fail. Or if the ball is flying very fast (e.g. the trajectory where our GPS satellites are).

The “trick” is that we separated the ball from it’s surrounding and we ignored properties of the air.

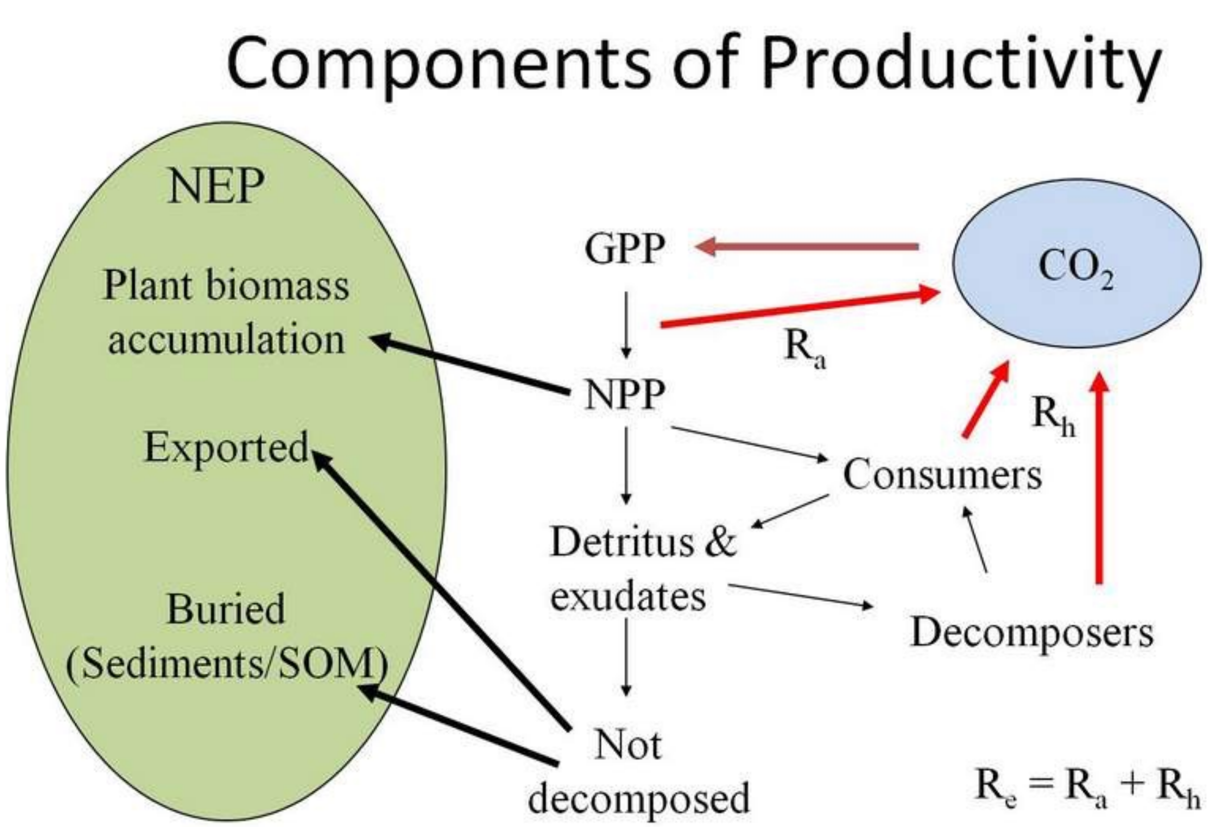


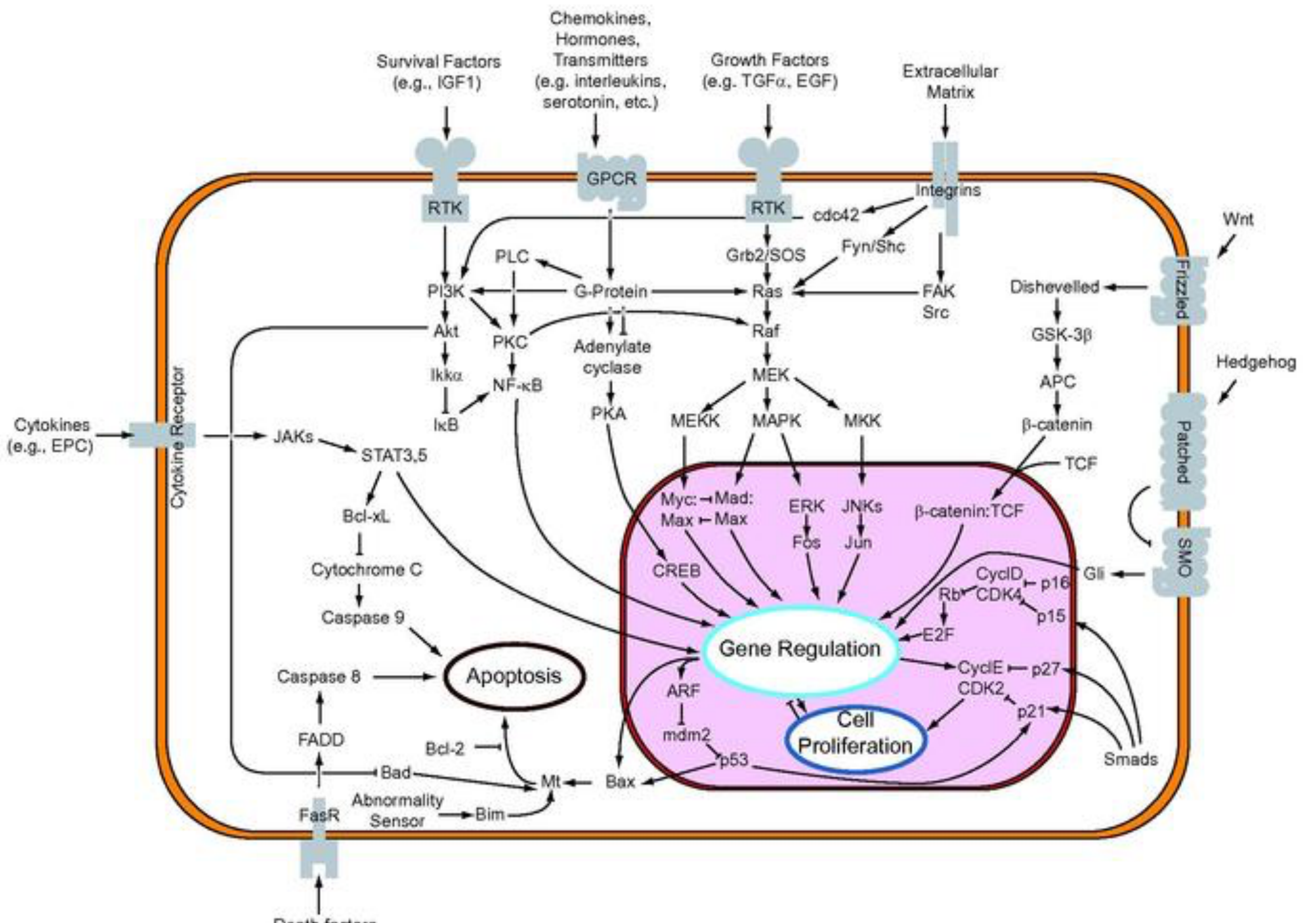
Systems have borders!

Biological systems

Biological systems are difficult to separate from the surrounding environment. An organism must interact with its environment in order to survive.

We call that an "open system"!



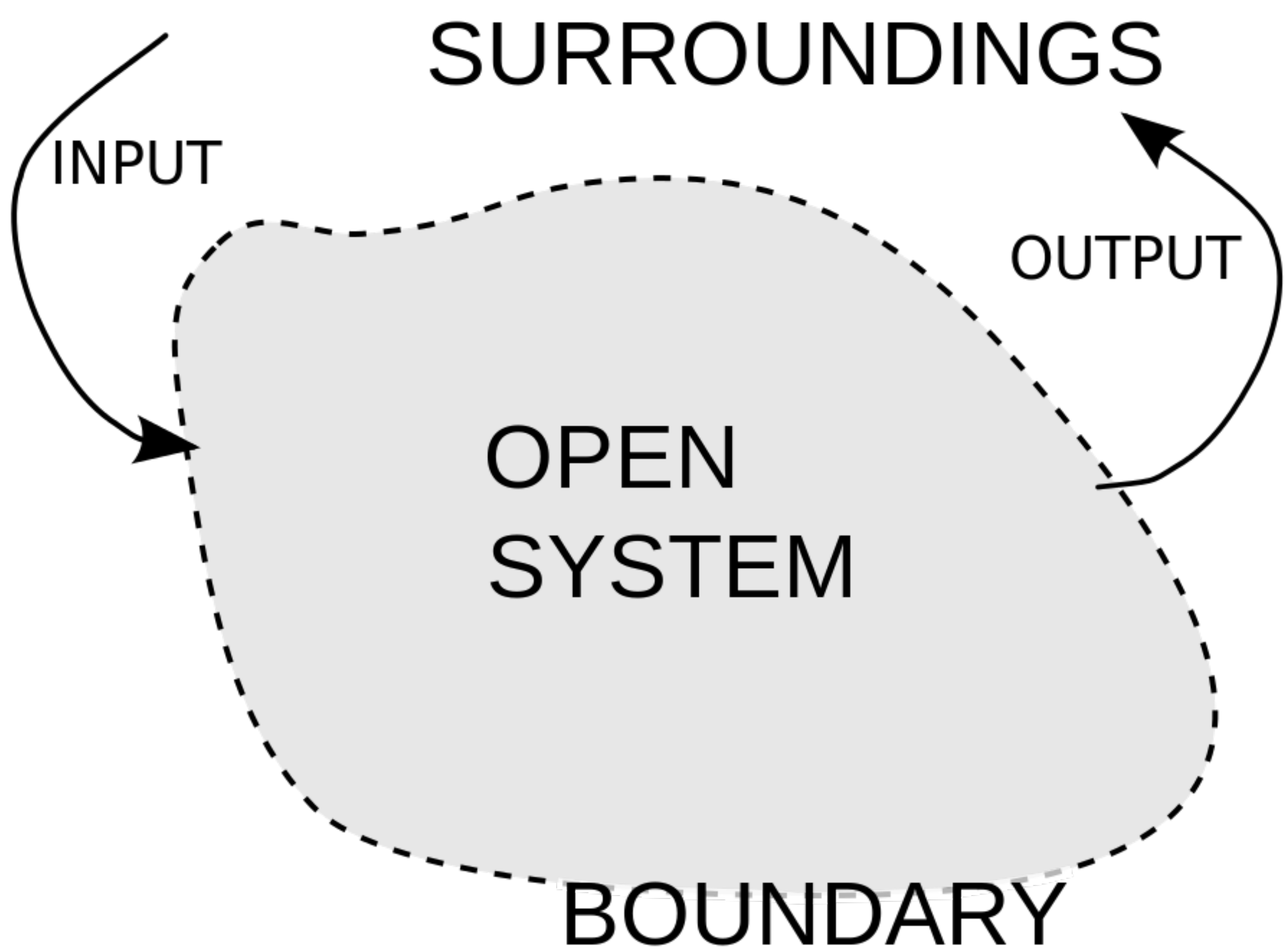


Ecosystems

Ecosystems usually consist out of different biological and non-biological systems. Atmospheric chemical reactions as example form a subsystem defining certain “environmental parameters” for the biological systems “plant” or “animal”as example.

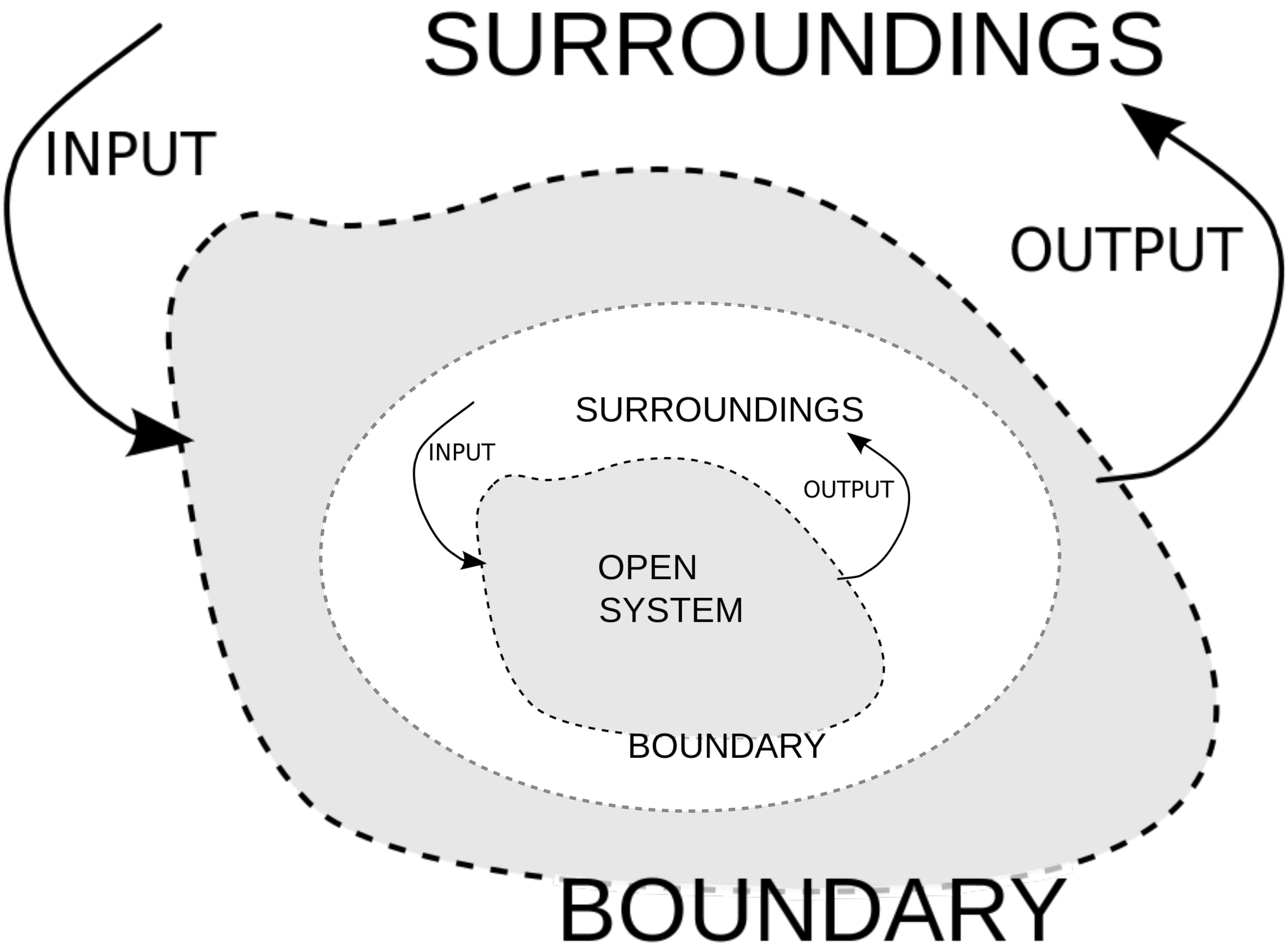
Open systems can contain other open systems!

An open system



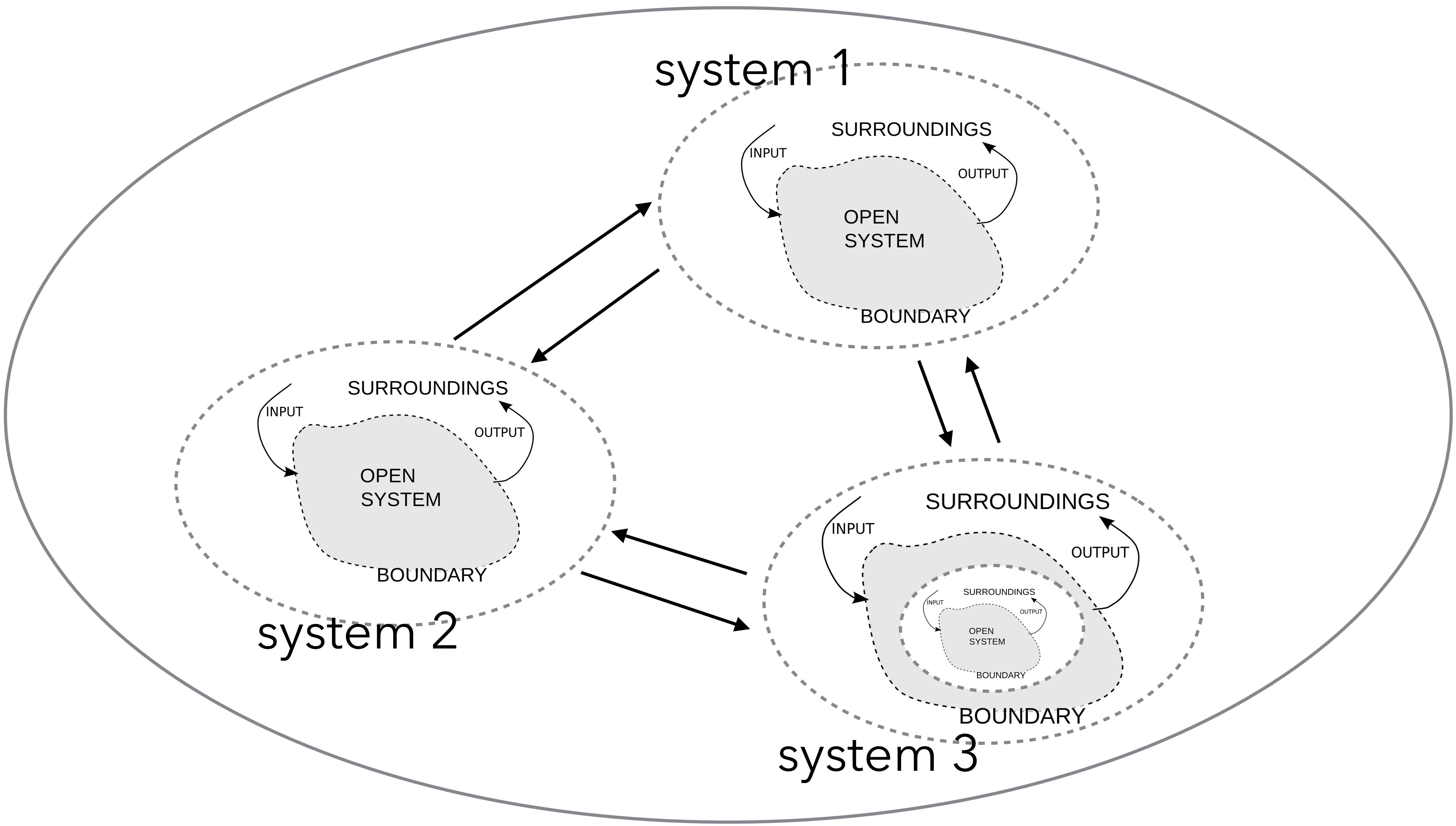
The open system has a boundary that was “chosen” according its purpose. It exchanges “things” with its surrounding environment.

Hierarchy of open systems



The closed system and subsystems

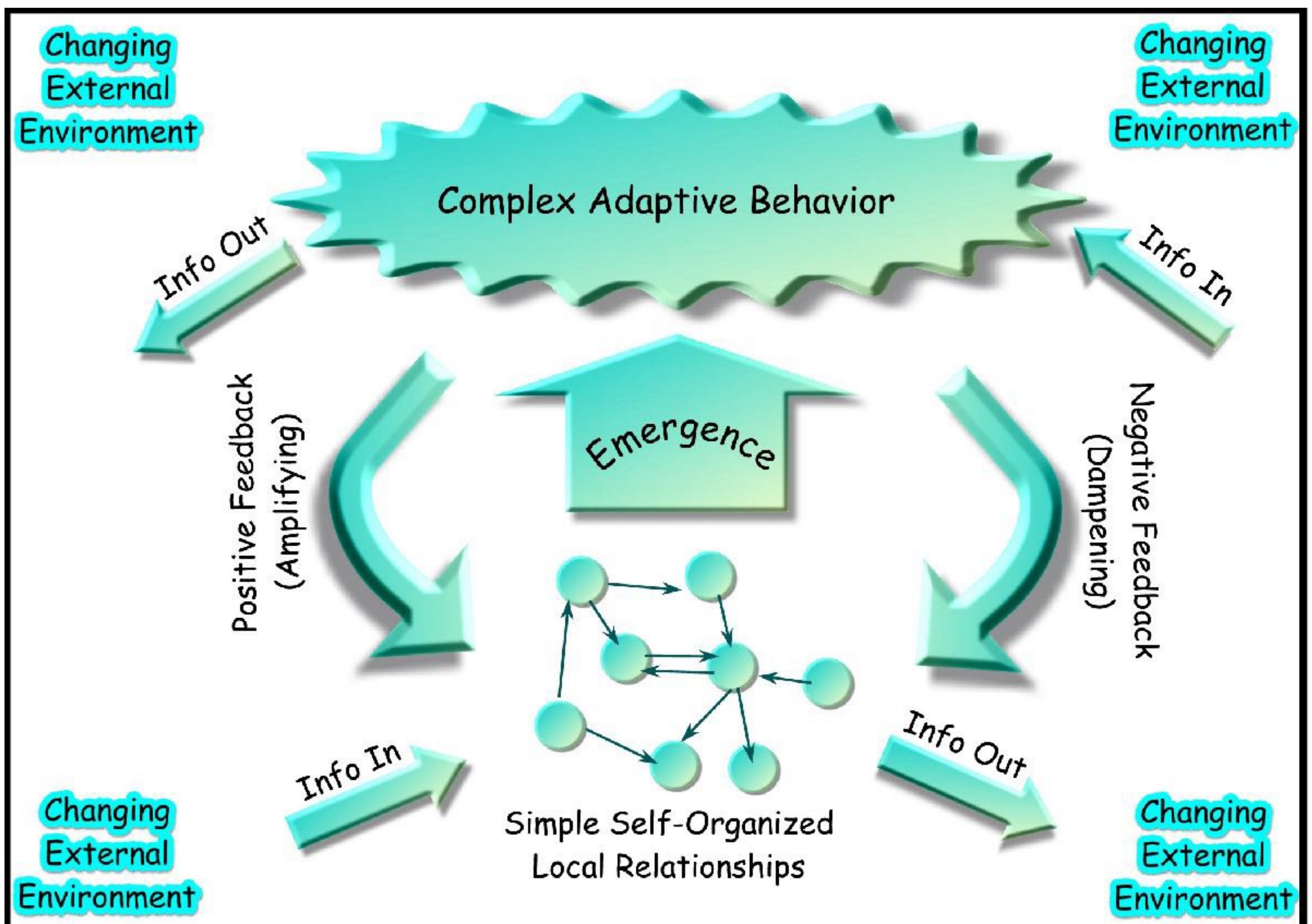
A theoretical example of a closed system is our cosmos!
We can have many subsystems!



Complex adaptive systems

Any system–engineering, natural, biological, or social–is considered adaptive if it can maintain its performance, or survive in spite of large changes in its environment or in its own components.

Black *et al.*, 2014, *Systems* 2014, *2*, 606-660; doi:10.3390/systems2040606



Steps to "construct" a system

Identify the **things** that participate.

We call the things also: Stock, pool, compartment,…

Problems: In most cases we do not know from the beginning all the things that should participate. It is trial and error process.

Identify the **relationships** between the things.

We call the relationships also: process, exchange, input, output, function,…

Problems: Again, we do not know all relationships from the beginning. But we need also to quantify them. Some may interact and change the surrounding environment not directly.

Steps to "construct" a system

Test the **structure** against **empirical measurements**.

Here, we need data. In the best case, these are continuously assessed long term datasets.

Problems: It is not easy to find the data to test the system. Sometimes they are too scarce. Sometimes their quality is of question.

All these steps impact on the structure of the systems we want to describe!

The problem of language

If we try to identify and describe the structure of a system we run into the **problem of language**.

Language can transport information only in a serial way, one sentence after another.

Many systems work in parallel! How can we describe it?

The problem of language

Our solution is so far to **simplify** and split into **subsystems**.

Doing so, we are able to work in parallel on these simpler parts and fit them together at another point in time.

Therefore, we need both the reductionistic viewpoint and the holistic viewpoint if we want to understand and use the systems paradigm.

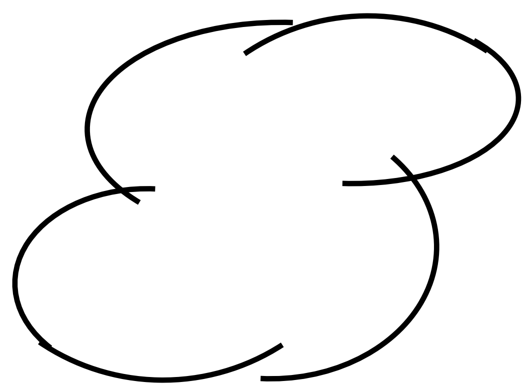
Using graphical representations

To deal with systems in an efficient way, it is beneficial to use a certain set of graphical symbols in combination with textual information.

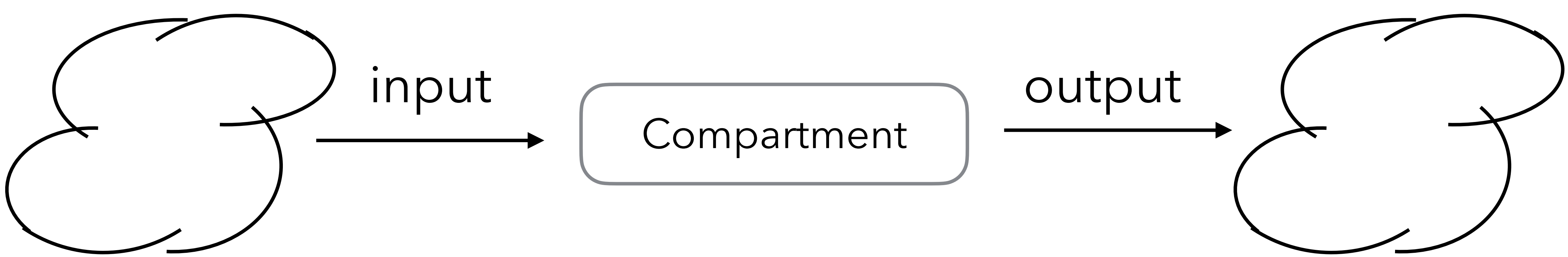
Boxes or Capsules: are used to represent compartments

Arrows: are used to represent linkages and processes.

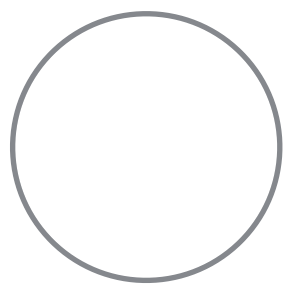
More graphical symbols



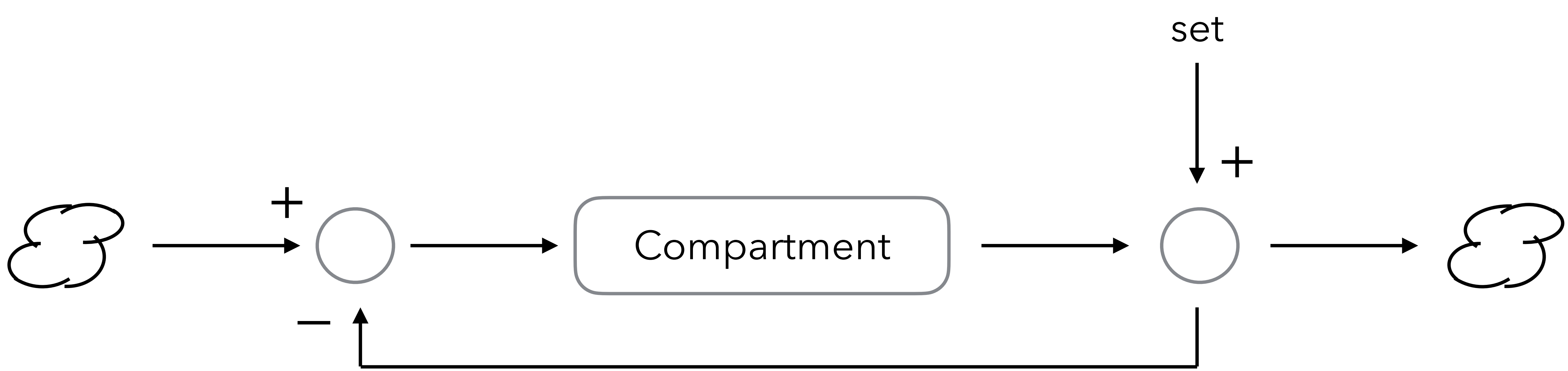
Clouds can be used to represent surroundings that do not change or to specify the removal of some thing from the system (drains to surrounding)



More graphical symbols

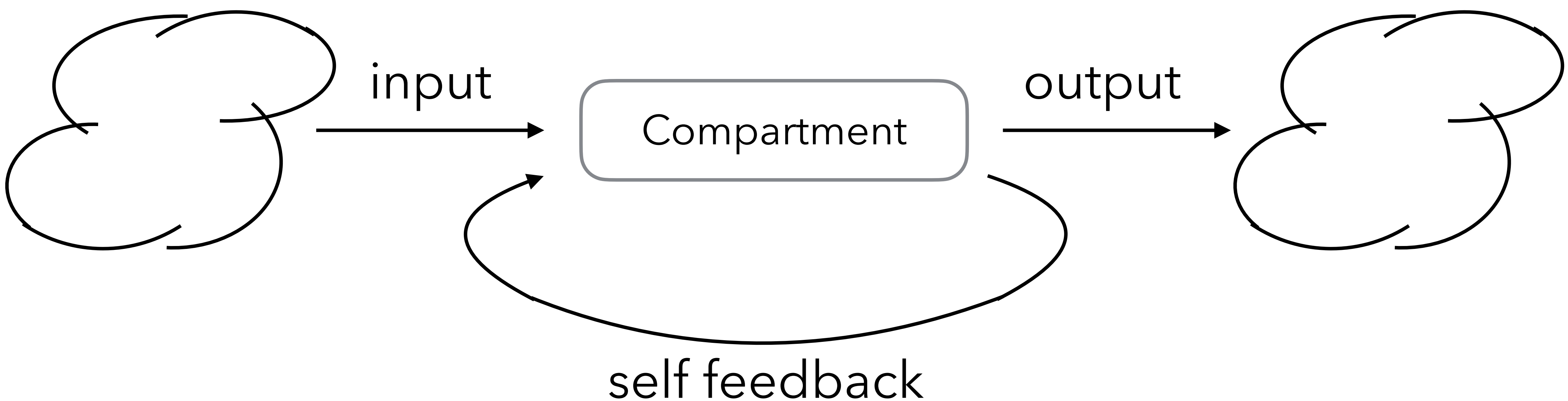


Circles can be used to indicate linking points. There can be also textual information such as + or – signs indicating a positive or negative relation or impact.



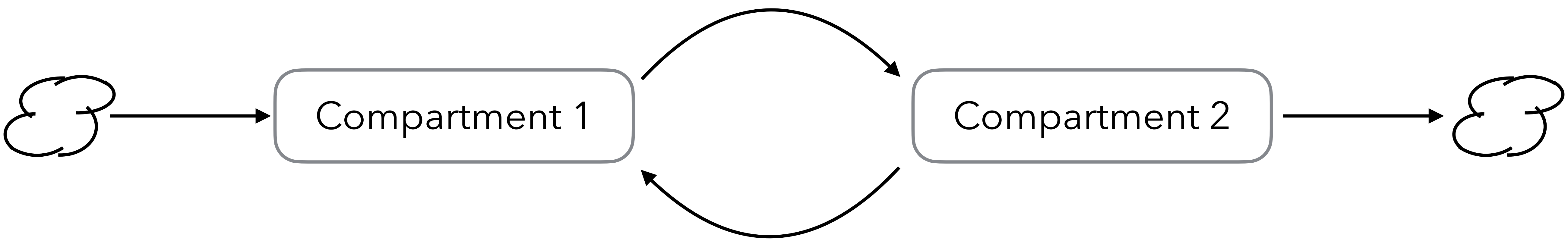
Regulation structures

Complex adaptive systems employ basic regulation structures. These are called feedback’s

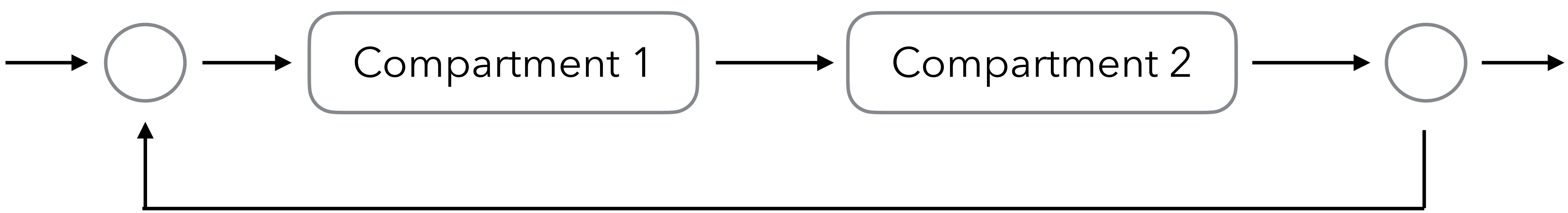


The output feeds back to the input of the same compartment.

Regulation structures

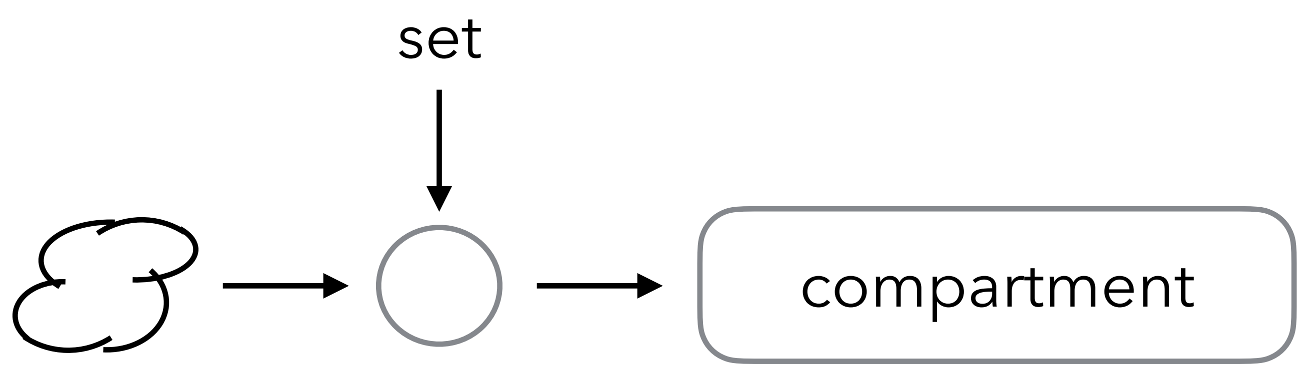


The state of compartment 1 influences on compartment 2 and vice-a-versa.

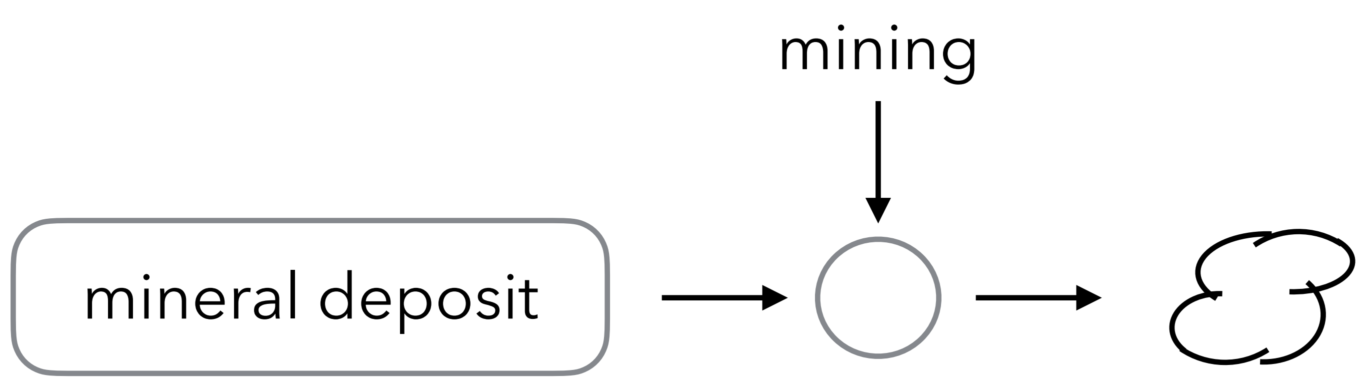


The output of compartment 2 influences on the input of compartment.

Some systems…



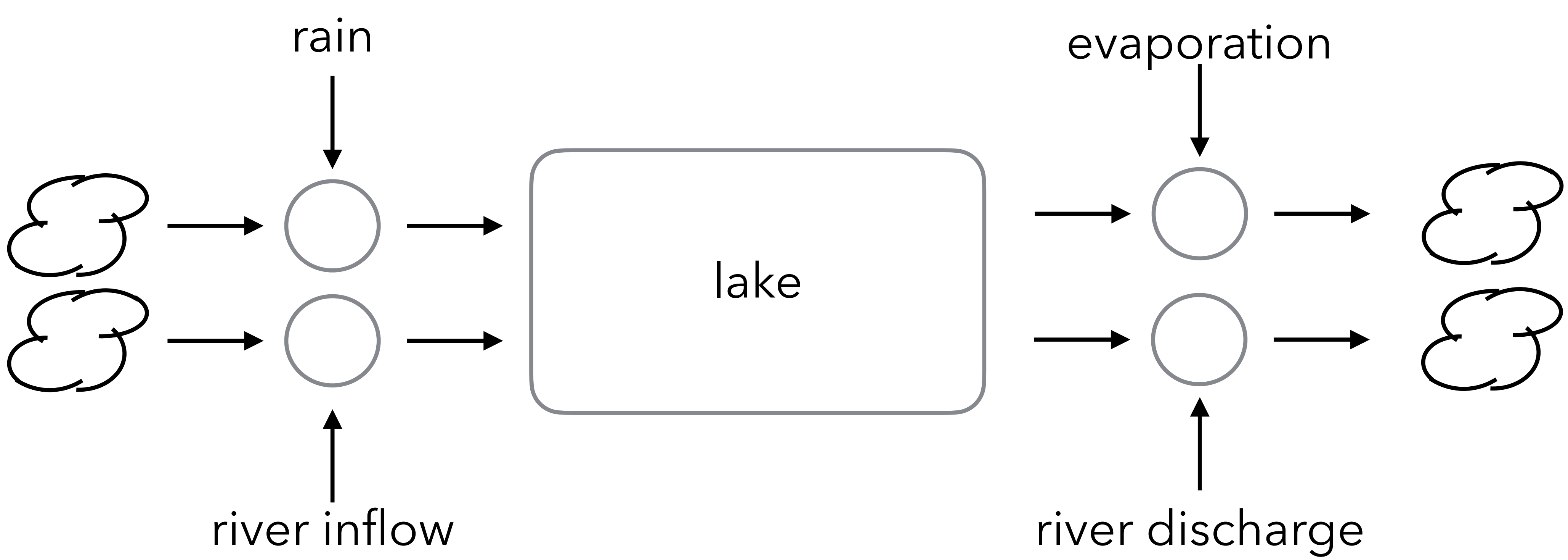
A reservoir that fills up depending on the set point.



A mine that gets depleted depending on the mining intensity.

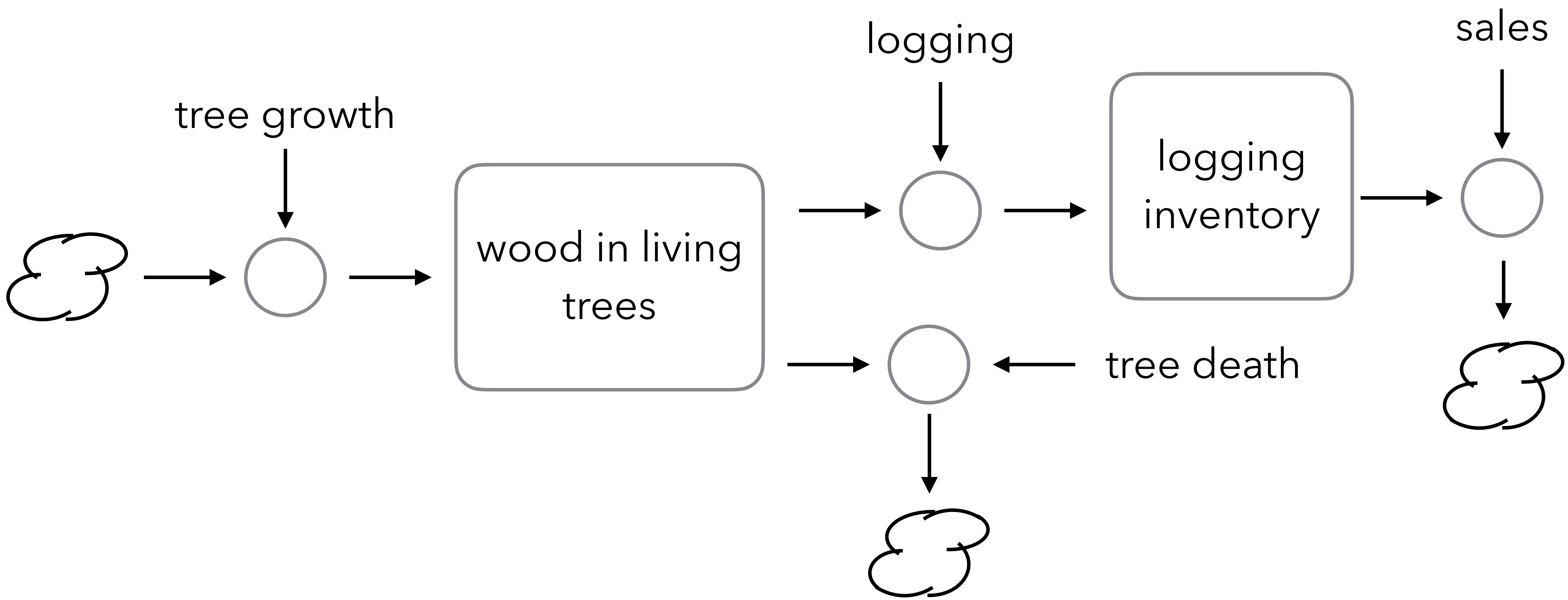
A bit more complicated system

The water level in a lake can be represented rather simple taking all possible water inflows and outflows into account.



And even more complicated…

Forest trees are the stock and the tree growth is the inflow, tree death and logging are the outflow of the resource. The logging fills another stock which is maybe a sawmill's log inventory and sales to customers reduce the amount of available logs for the sawmill.



Dynamics of systems

In the former examples, the dynamic behaviour of the stocks/reservoirs/compartments were rather straightforward.

Given that all the flows were seen as constant, we also can predict rather well how the stock will change over time once we have the numbers for the stock and the flows.

Some stocks might run out (mine), some grow (reservoir), Some change depending on the change in the sum of in/out flows (lake). Some stocks determine another stock (trees/logs).

How systems run themselves?

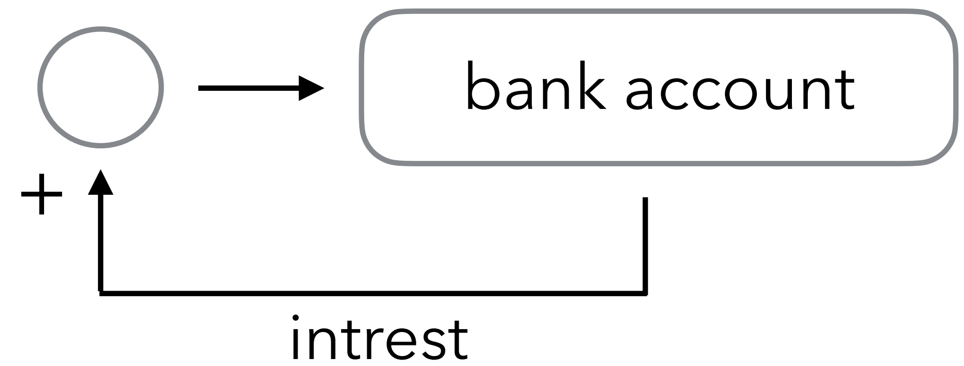
In many systems, the external drivers (sources/sinks) determine the dynamics of the stocks according the given structure (flow network).

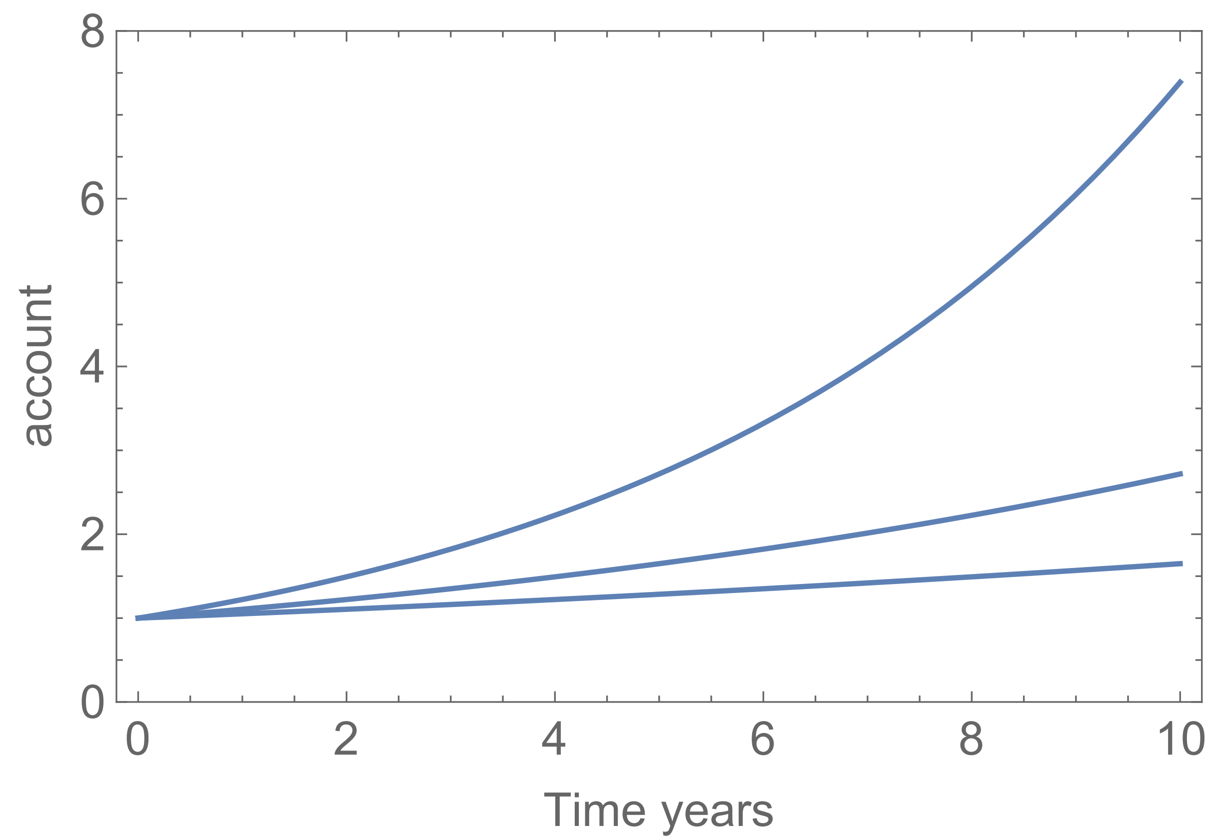
Some systems run themselves!

We see systems in nature that do not need any action from outside to keep a stock on a certain level. There has to be some sort of regulation mechanism!

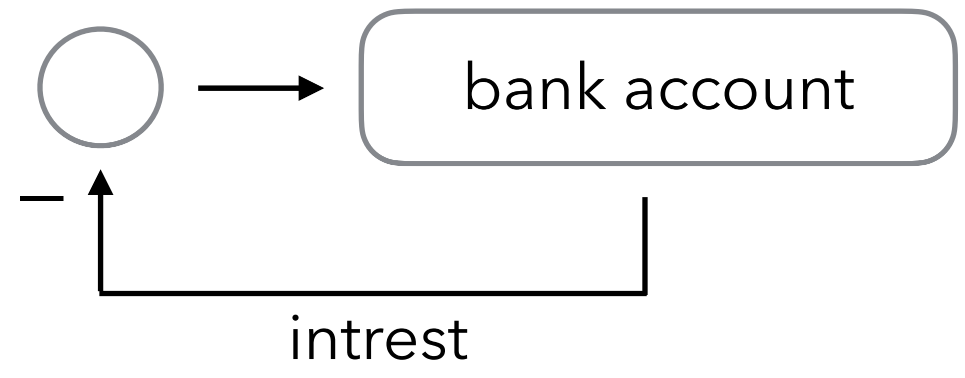
These regulation structures are called feedbacks!

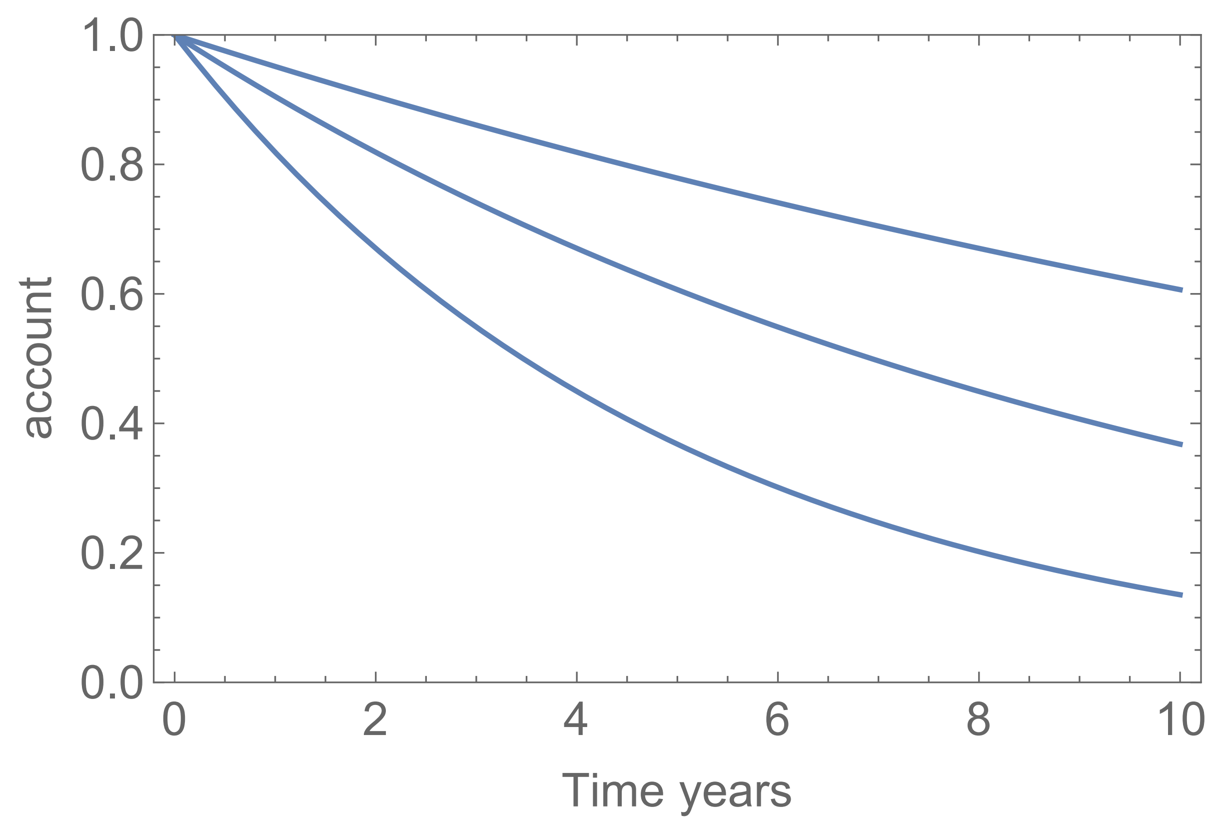
Positive feedback





Negative feedback





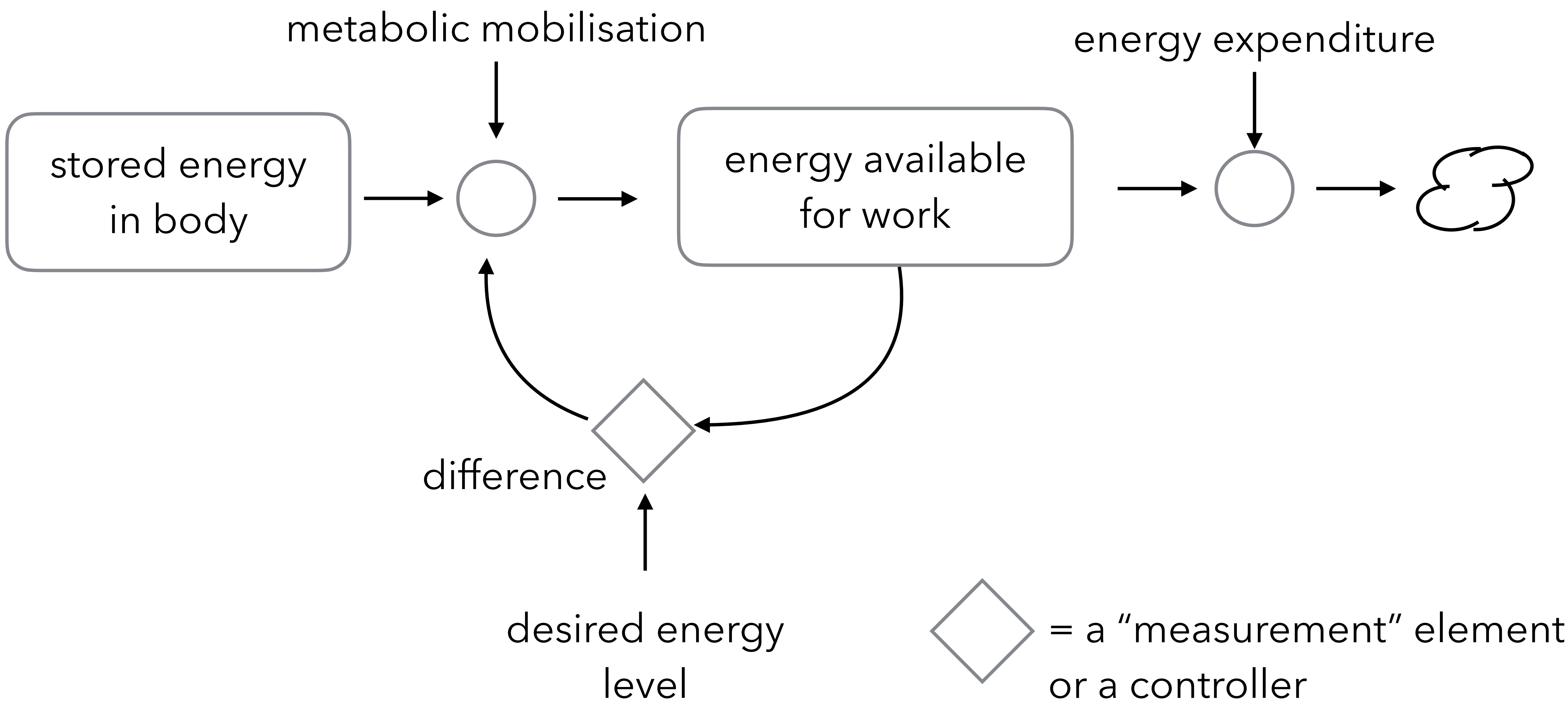
What happened to our bank account?

We generated a limitless growth (positive feedback or feed forward) and a limitless loss (negative feedback).

The systems dynamic was not linear anymore. The dependency on the size of the stock made the system acting with an exponential response.

Stabilising loops

In case we want a system to “hit a goal”, we need to control that the system gets stable “around” that goal.



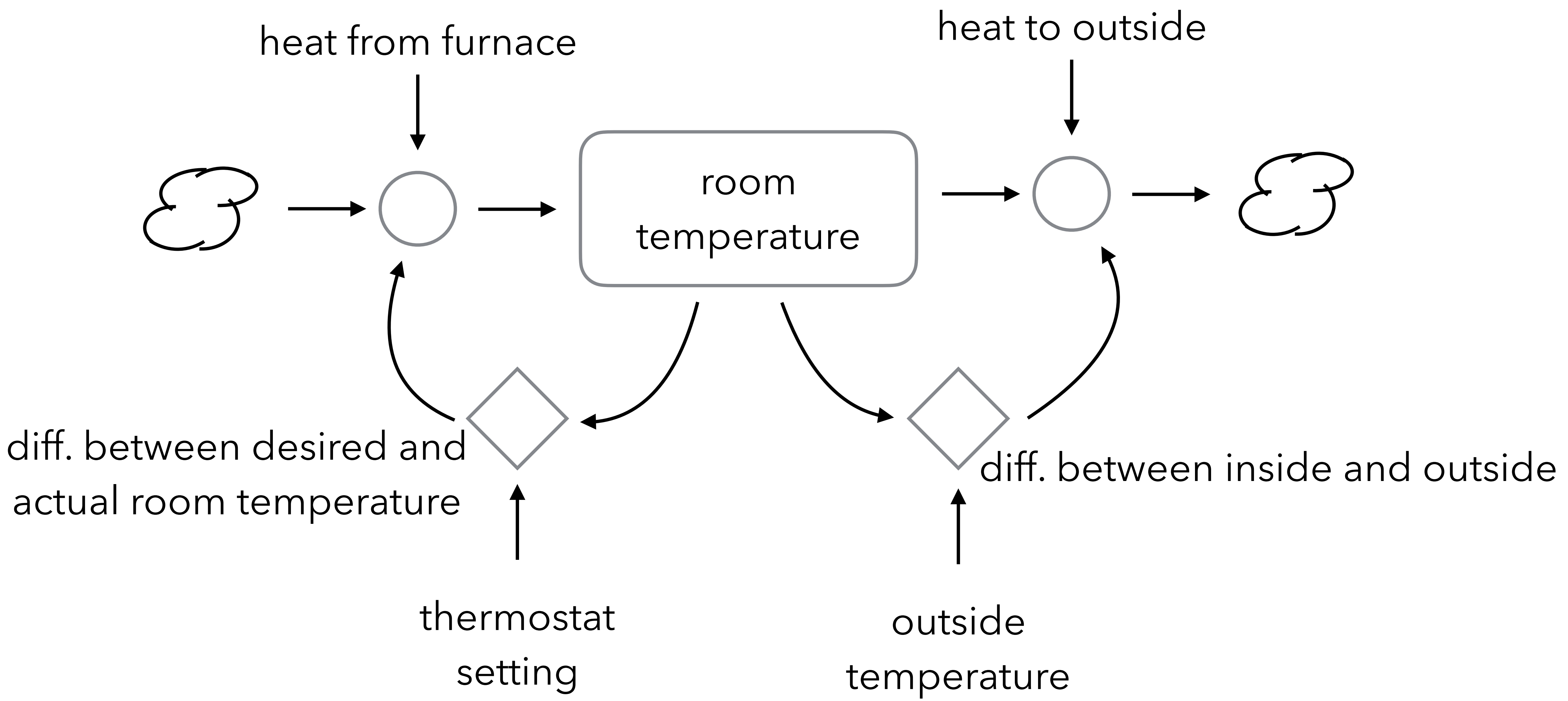
Stabilising loops

The example before includes a controller that uses the function “difference” to change the rate of metabolic mobilisation of stored energy.

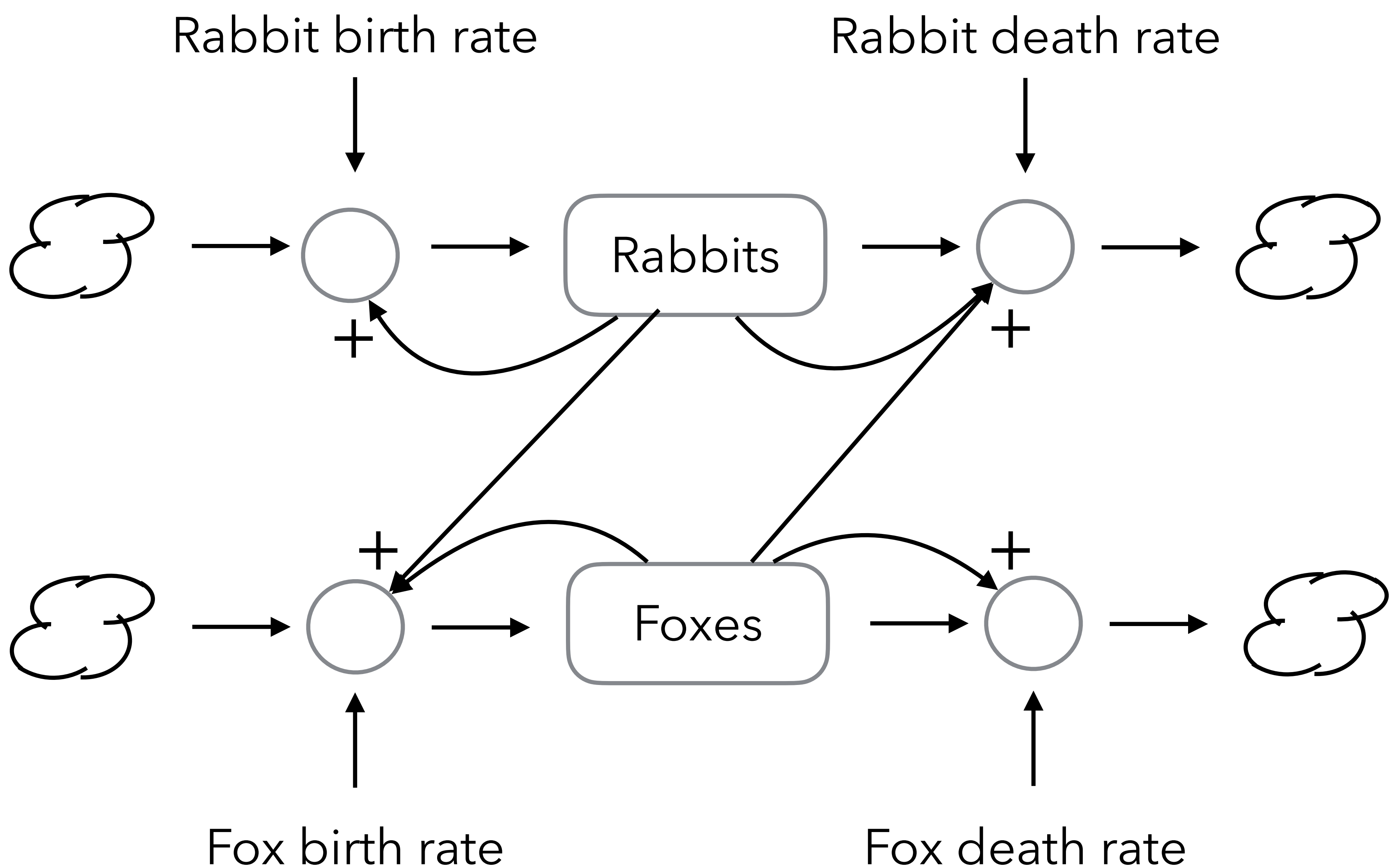
The “desired level” determines that there is enough energy available to keep up with the energy expenditure.

Controlling loops occur frequent

Controlling a stock is mostly done by combinations of stabilising feedback and reinforcing feedforward loops acting together. Here we have two concurrent stabilising loops!



A two compartment system



Interdependency

In the Rabbit–Fox system (aka Lotka–Volterra) the stock of Rabbit influences on rabbits birth and death rate positive but also the amount of foxes increase the rabbits death rate.

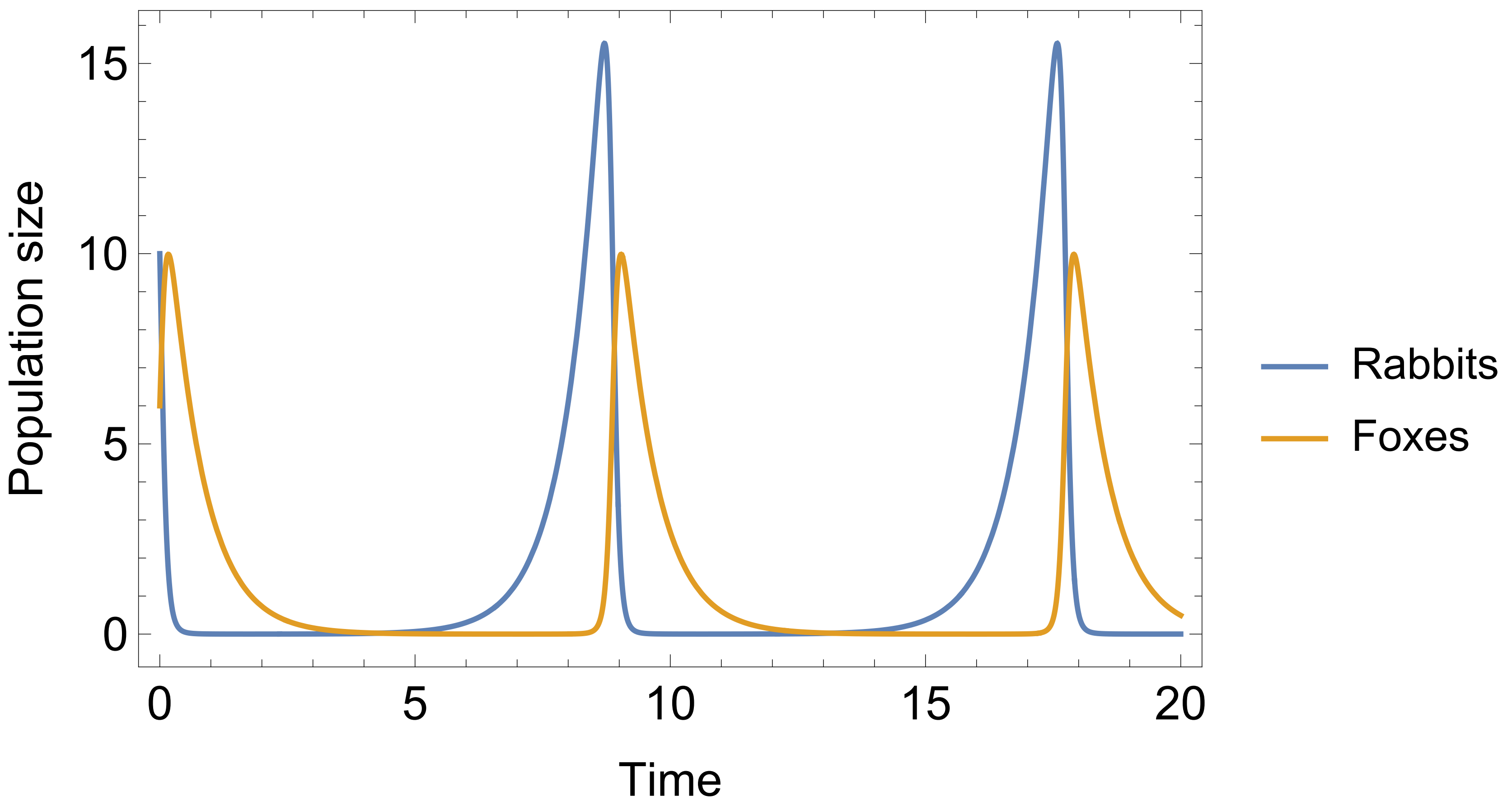
On the other hand, the number of rabbits has a positive influence on the birth rate of foxes. While the stock of foxes also has positive impact on the birth and death rate of foxes.

Assumptions:
Rabbits have endless food resource, exponential growth, predation is proportional to number of foxes.

Foxes always find rabbits, growth is proportional to predation, but not necessarily at the same rate as the death of rabbits, death of foxes lead to exponential decay.

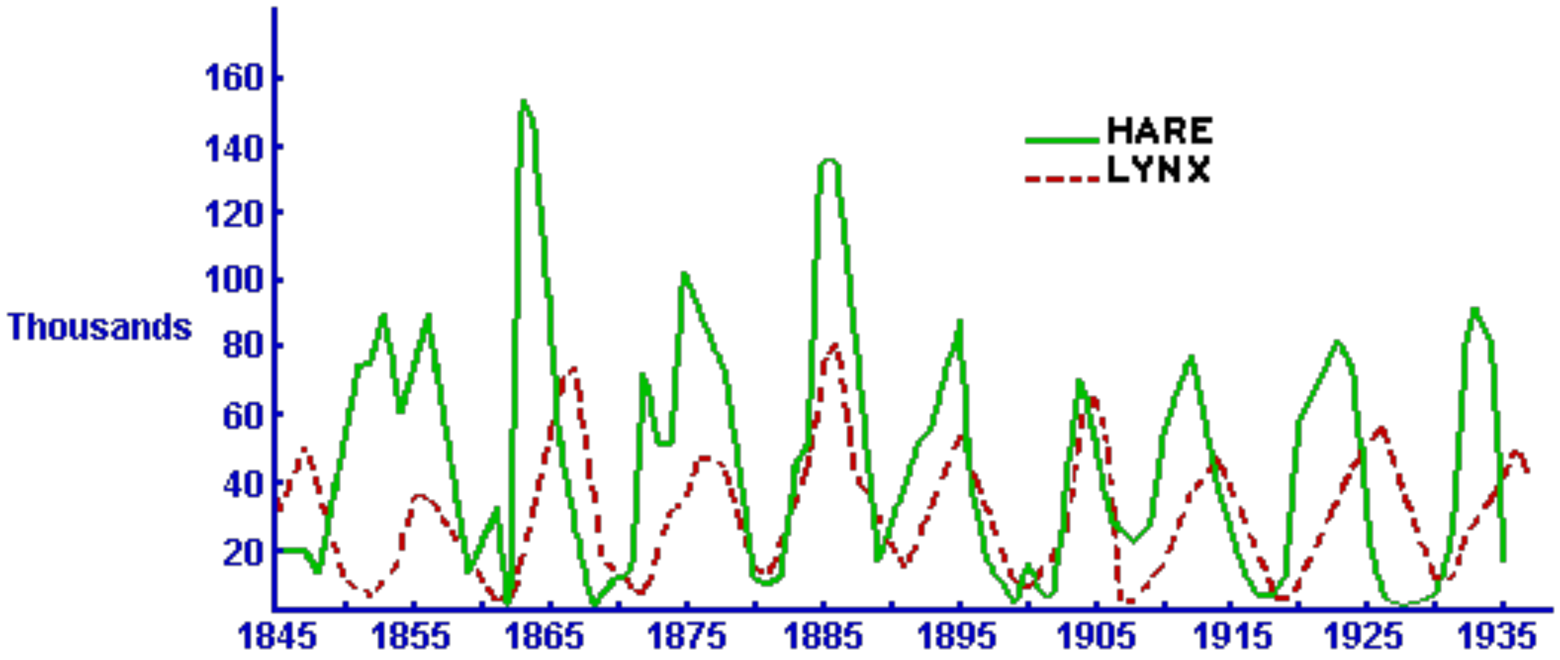
Oscillations

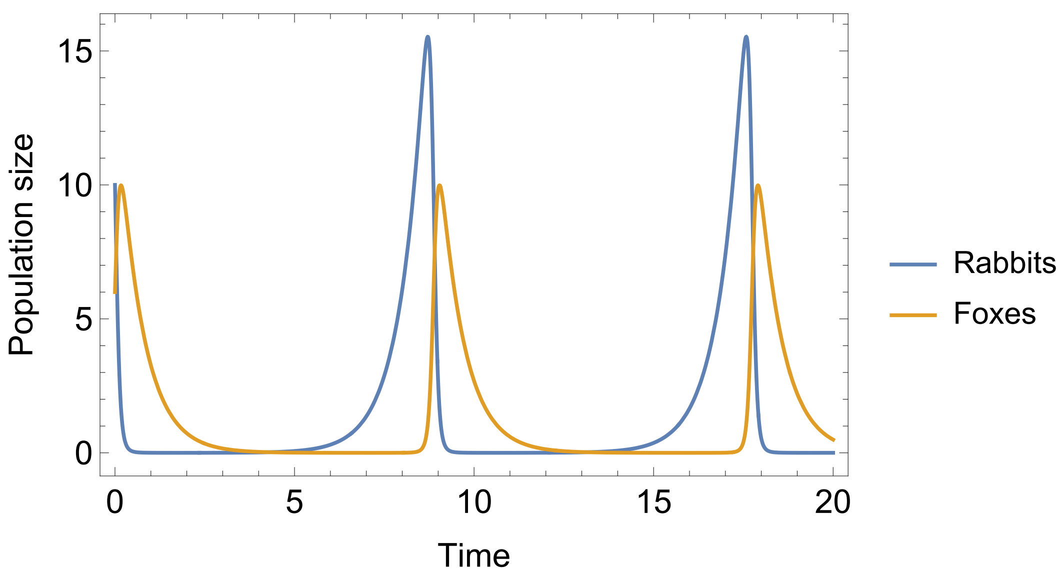
The system is controlled by a time lag, once the stock of foxes grows too high, the rabbits stock falls very low and subsequent the foxes population declines. Rabbits then grow again and the fox population is following with a time lag.



Oscillations

The Hudson Bay company data of hunted pelts is a classical dataset that shows the oscillating behaviour in a predator-prey system between Canadian lynx and snowshoe hare.





What we learned so far…

A system is not just some collection of things. It is an interconnected set of elements. Organised in a coherent way to achieve some goal.

The systems behaviour lies in its structure.

Graphical symbols help us to describe systems in a very intuitive way.

We can simplify and split larger systems into “better” understandable portions.

The Earth system

- formed 4.5 billion years ago, by gravitational accretion out of a dust and gas cloud!
- There are 92 major chemical elements present!
- They have almost all been here since the formation of earth!
- Extraterrestrial sources (eg. meteorites) are relatively unimportant!
- Escape of atoms is prevented by gravity and extremely slow!

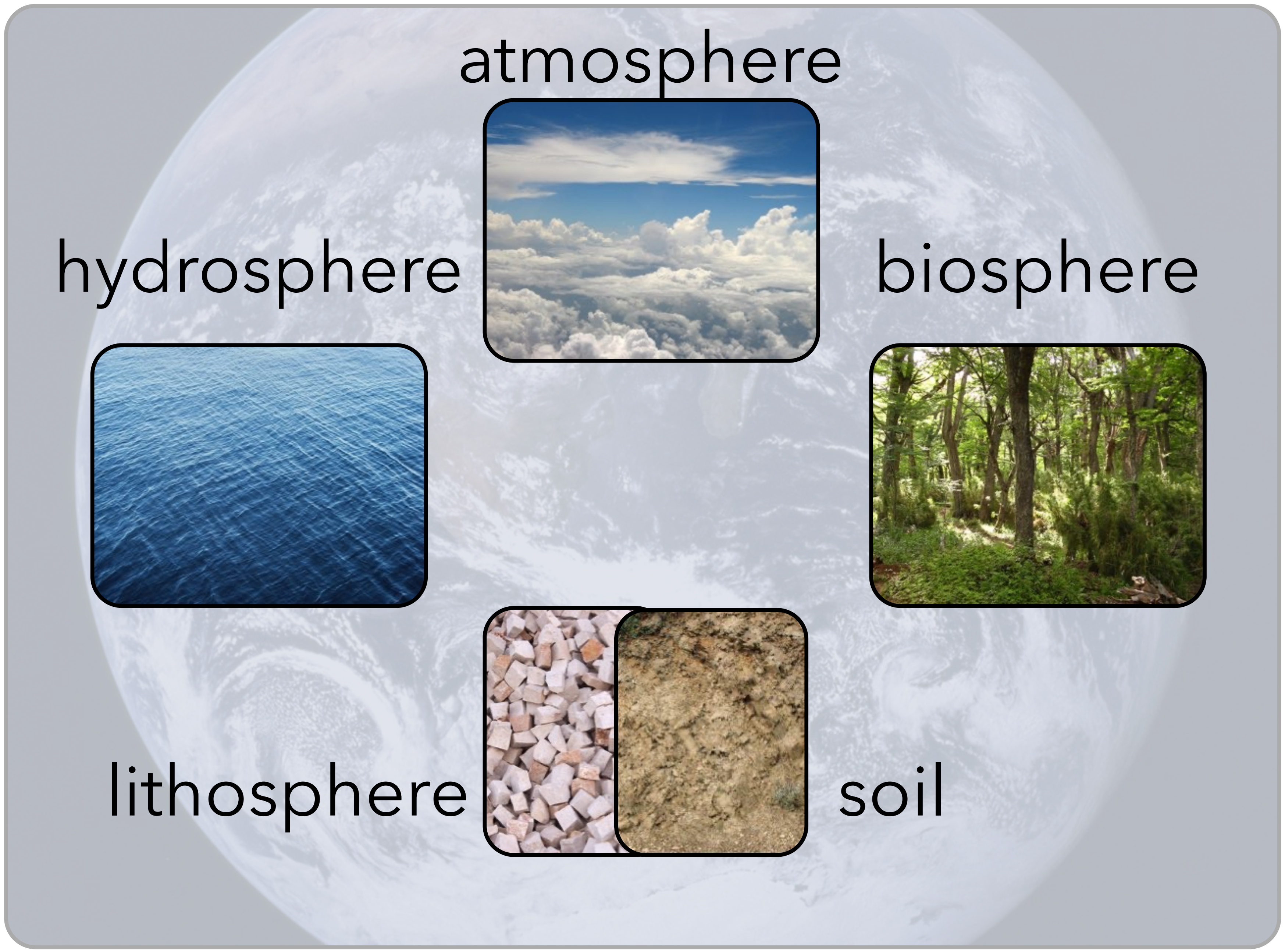
Earth system is roughly conserved since that time!

The atoms in form of various molecules are constantly migrating between several reservoirs!

The biogeochemical cycle!

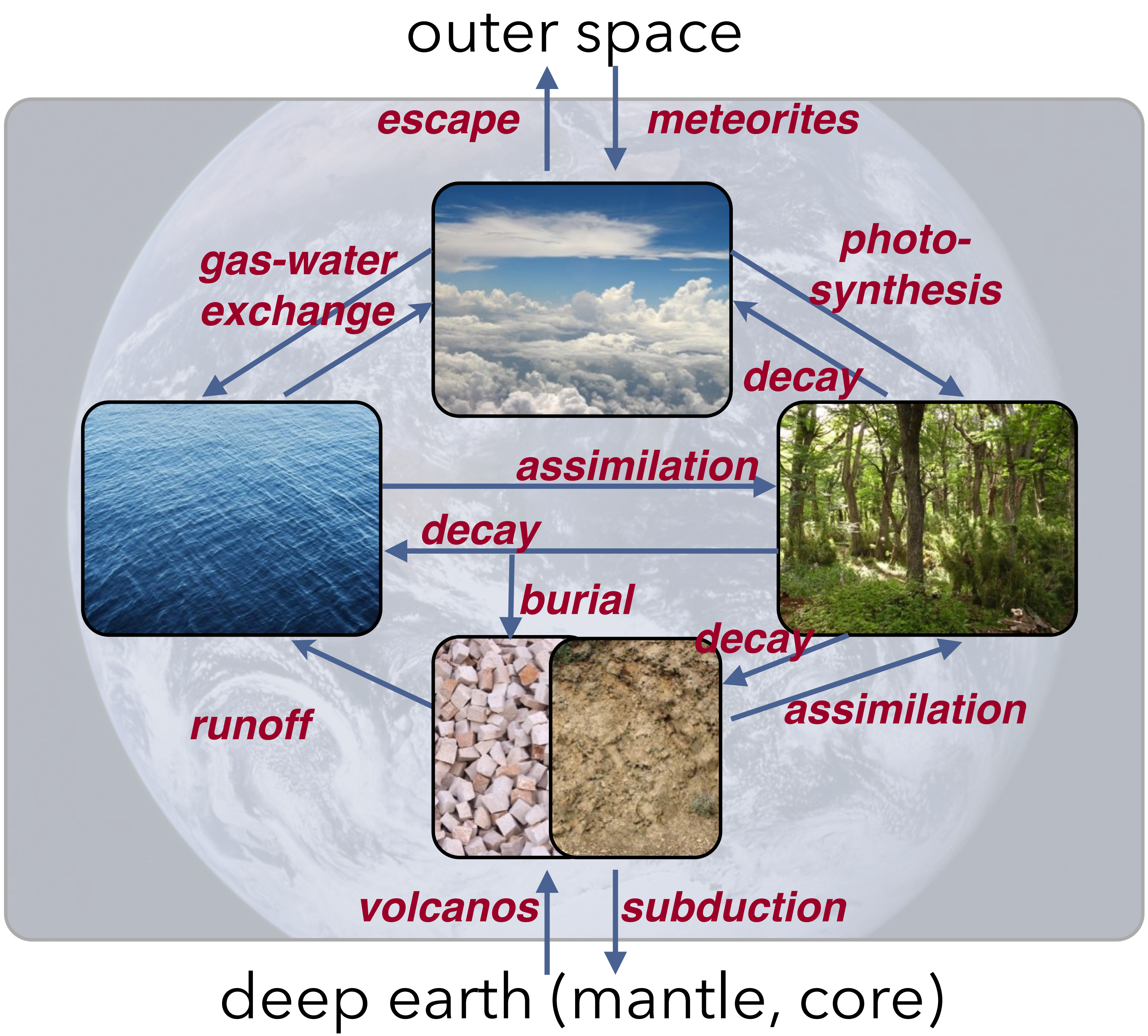
The reservoirs in the Earth system

outer space

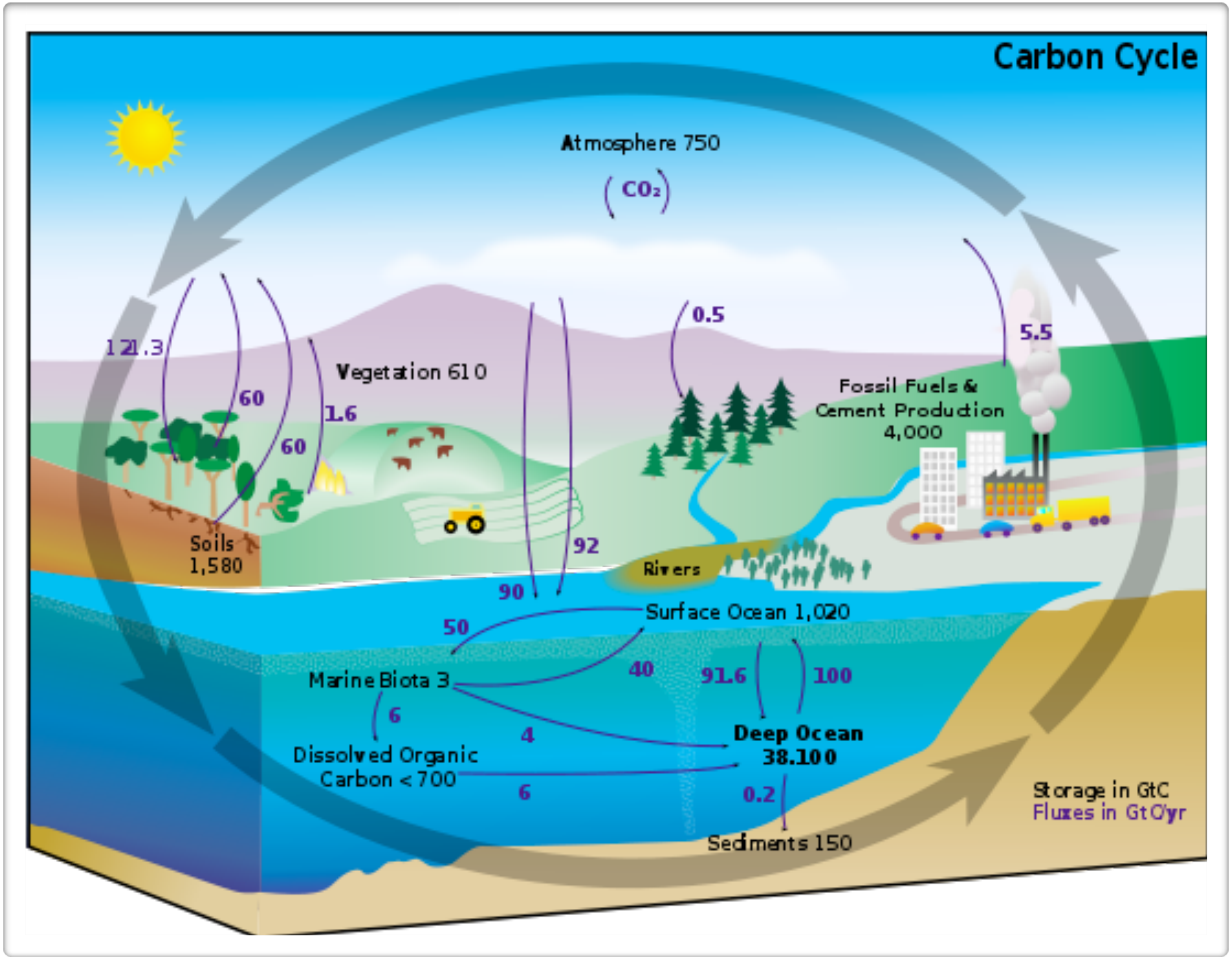


deep earth (mantle, core)

The fluxes between the reservoirs

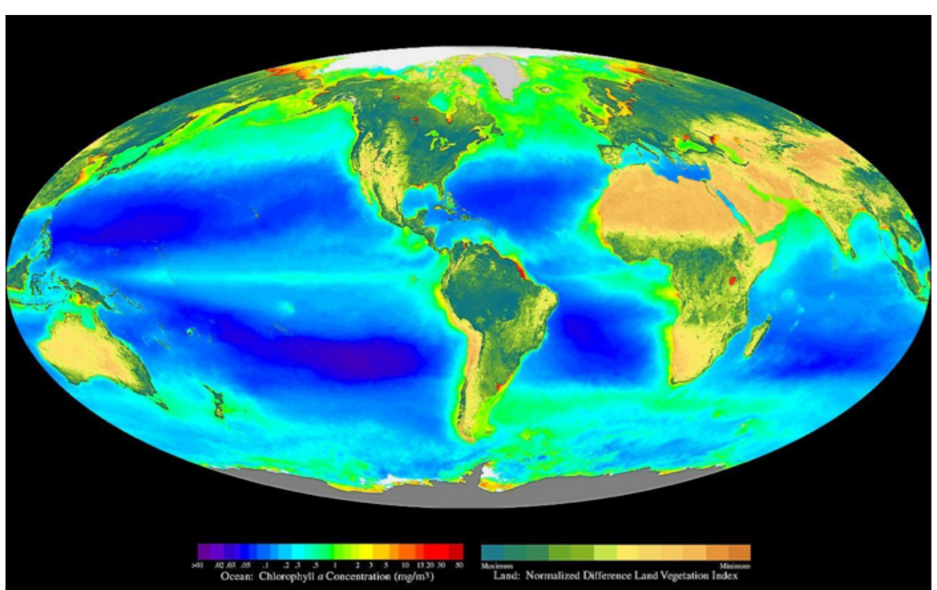


The carbon cycle as example



Some assumptions on these cycles

- There are several reservoirs such as **atmosphere** (air), **hydrosphere** (water), **lithosphere** (rock), **pedosphere** (soil), and the **biosphere** (living organisms)
- **Reservoirs have not to be strictly spatially separated.** Biosphere overlaps with pedosphere, atmosphere and biosphere are also overlapping
- **Matter** (C, N, O, P, H_2O, ...) and **energy** are **transported between** the reservoirs
- The total amount of **matter** stays constant, thus the earth system is seen to be a **closed system** to matter
- Energy is assumed to be not constant in time and space (eg. solar radiation is a variable source for the planet), **energy** operates on an **open system**



How to describe that system?

- We are far from being perfect in understanding and describing it!
- It’s an **interdisciplinary task**, to understand and define the “reaction chambers” and transitions in and between them we will need the help of mathematics, physics, chemistry, biology, geology, economy, social sciences, computer sciences, agriculture, forestry, oceanography, glaciology, ...
- The system is a **complex adaptive system**.


The Biosphere-Atmosphere system

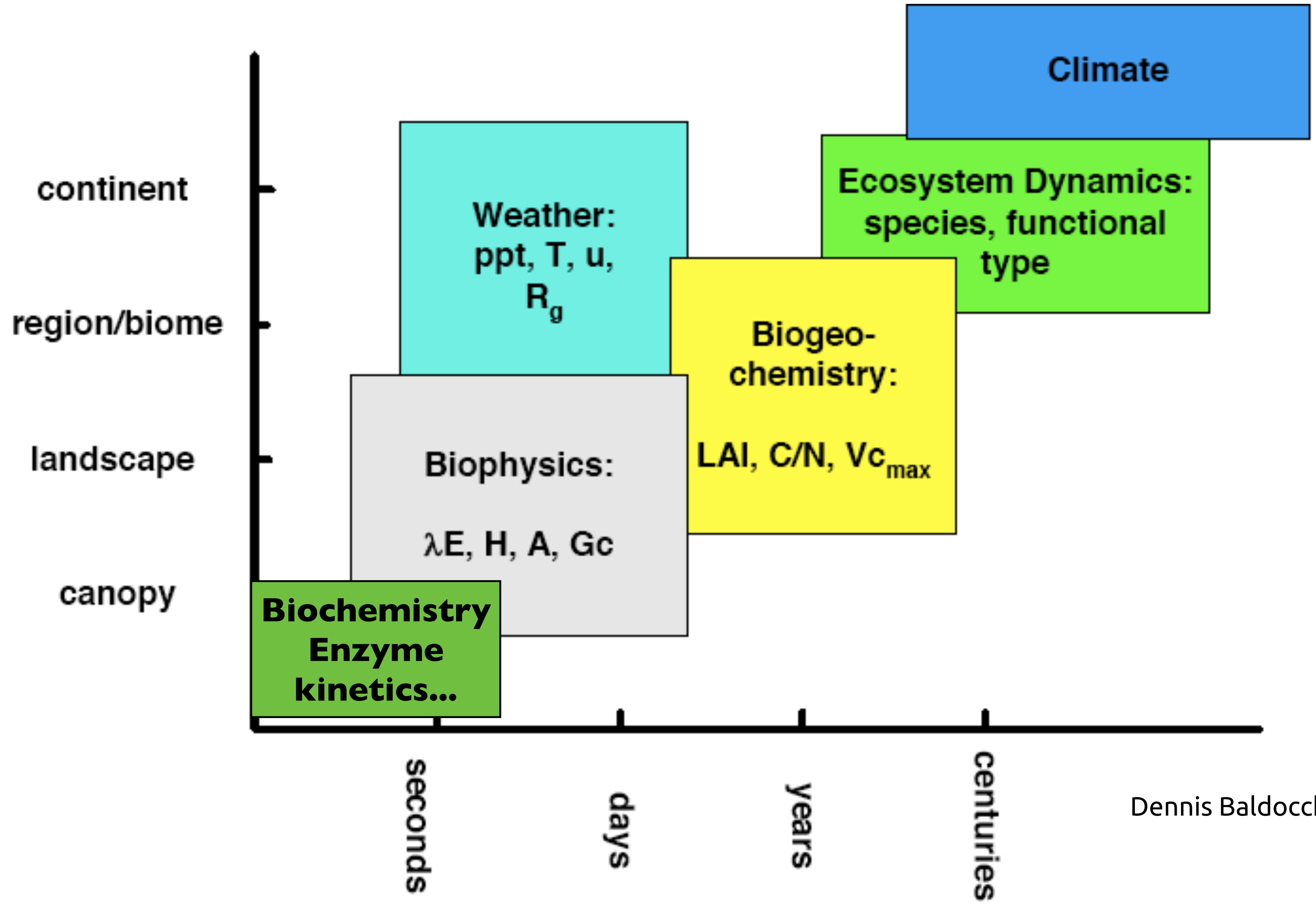
- Ranges -

nanometers - globe

femtoseconds - millennium

- a system of connected cycles from molecules to space

Spatial and temporal scaling of processes



Dennis Baldocchi, Biometeorology

Are there things in nature that are not systems?

The answer is yes.

Think of some sand on the road. The sand has no particular interconnection. We can add some, remove some, it stays just sand on the road.

We call that a conglomeration.

Lecture