Rencontres de la Chaire Modélisation mathématiques et biodiversité – 15/9/2015, Paris

Modelling the ecosystem as a hierarchical system

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Ecology is an « integrative » or « synthetic » science

pedology

[bio]geography

systematics

geology

genetics

hydrology

demography

[bio][geo]chemistry

ecology

physiology

[micro]meteorology

cell biology

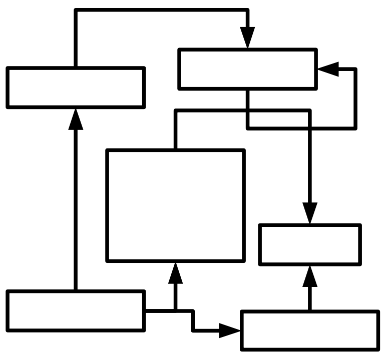
climatology

graph theory

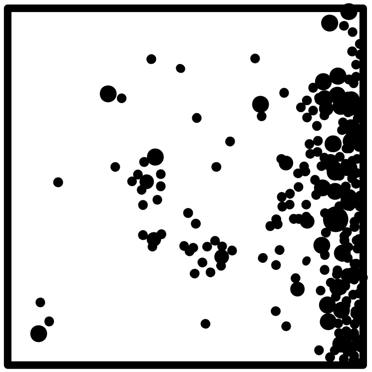
thermodynamics

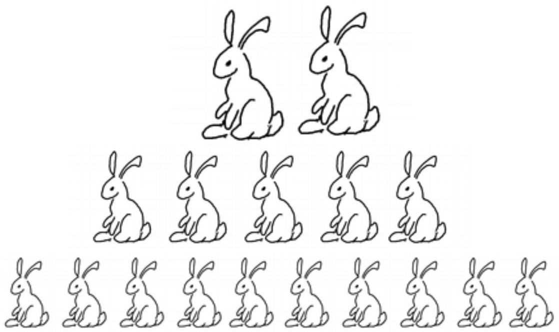
game theory

system dynamics

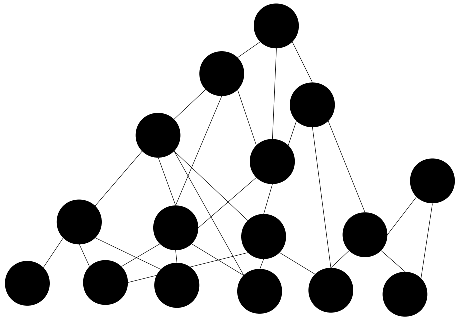


As a result of this « integration », ecological modelling is far from united
- PDE type models
- cellular automata
- individual-based models / multi-agent systems





Consequences:
- incompatible time and space representations
- problems with model comparisons
- and « the scaling problem » : changing from one type of model to another *for the same real-world system* is costly – when possible.



Can ecological concepts help us designing a broadly applicable framework for ecological modelling ?

Which concepts used in ecology are truely 'ecological', i.e. were not borrowed from another scientific field ?

?

Which concepts used in ecology are truely 'ecological', i.e. were not borrowed from another scientific field ?

The ecosystem

...

What can we build upon the ecosystem definition ?

Problem: 'conceptual drift'

The ecosystem was defined in 1935 and has undergone many transformations since then.

Jax K., 2007. Can We Define Ecosystems? On the Confusion Between Definition and Description of Ecological Concepts. *Acta Biotheoretica*, 55:341-355.

*« A major problem, which impedes the solution to these questions, is a common confusion between **definitions** and **additional descriptions** of concepts »*

example:

O'Neill R.V., 2001. Is it time to bury the ecosystem concept? (with full military honors, of course). *Ecology*, 82:3275-3284.
“There is no proof of ecosystem showing stability, resilience, etc.”
These properties were never part of the initial definition.

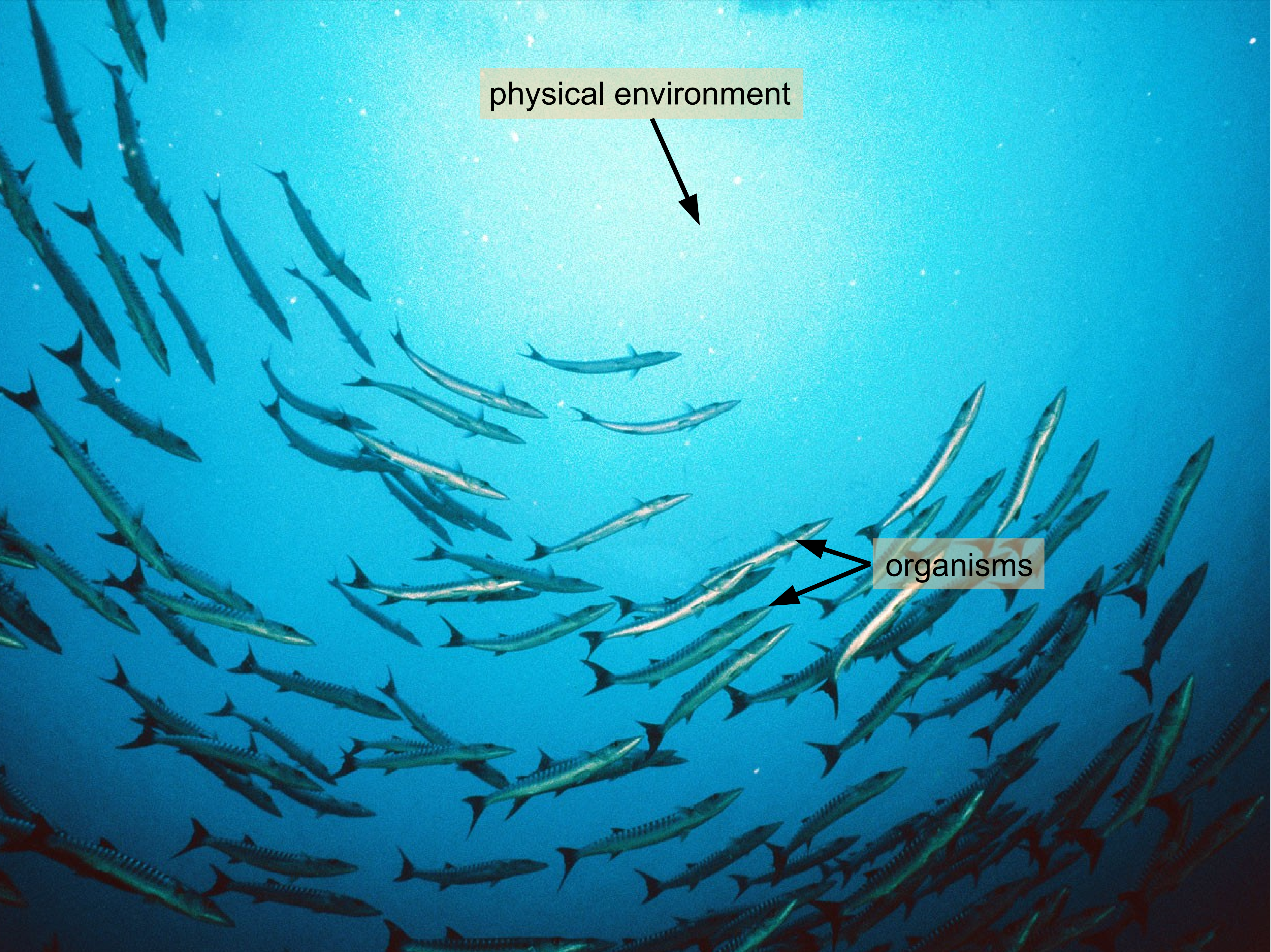
Back to the roots!

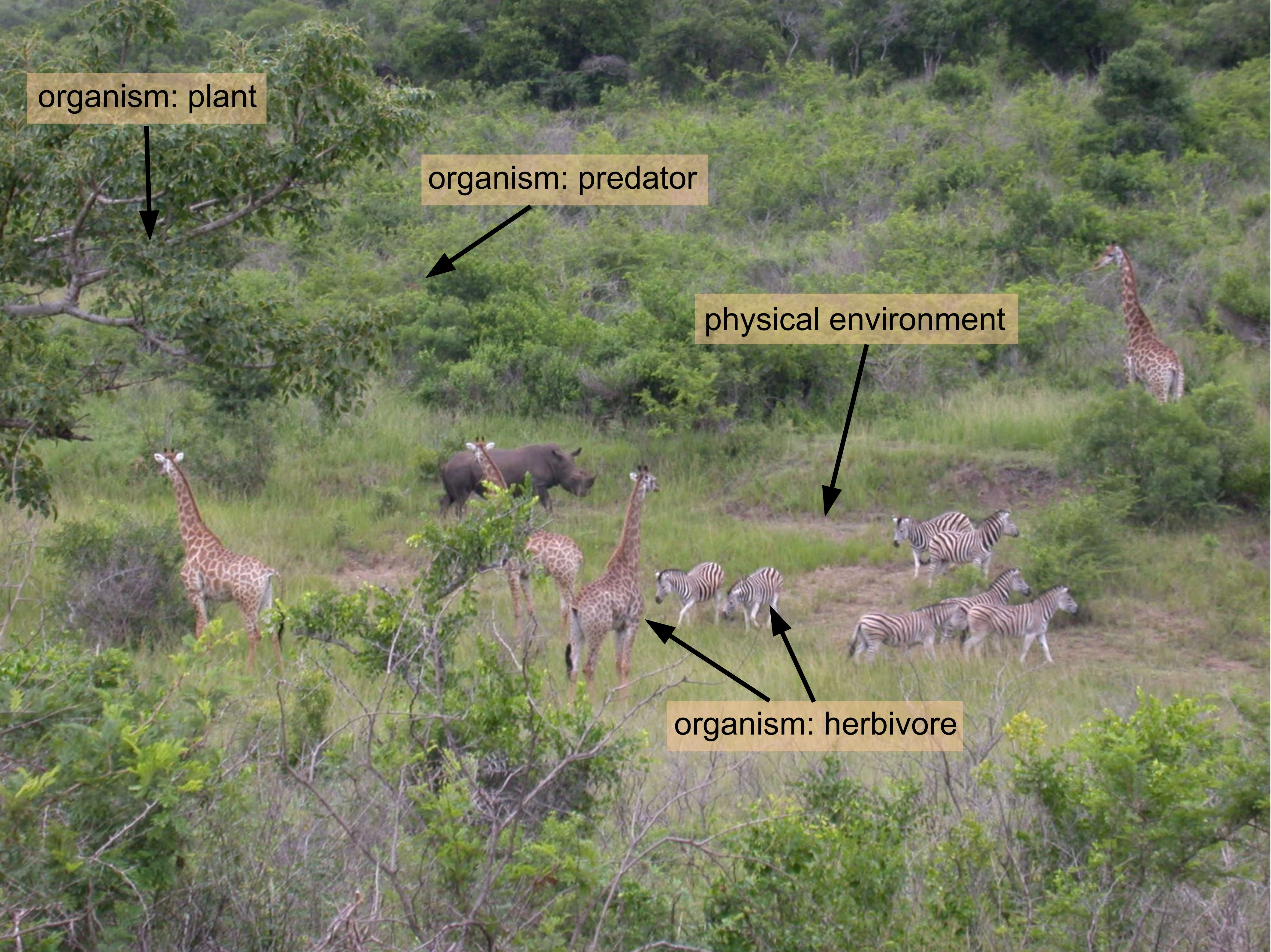
The ecosystem

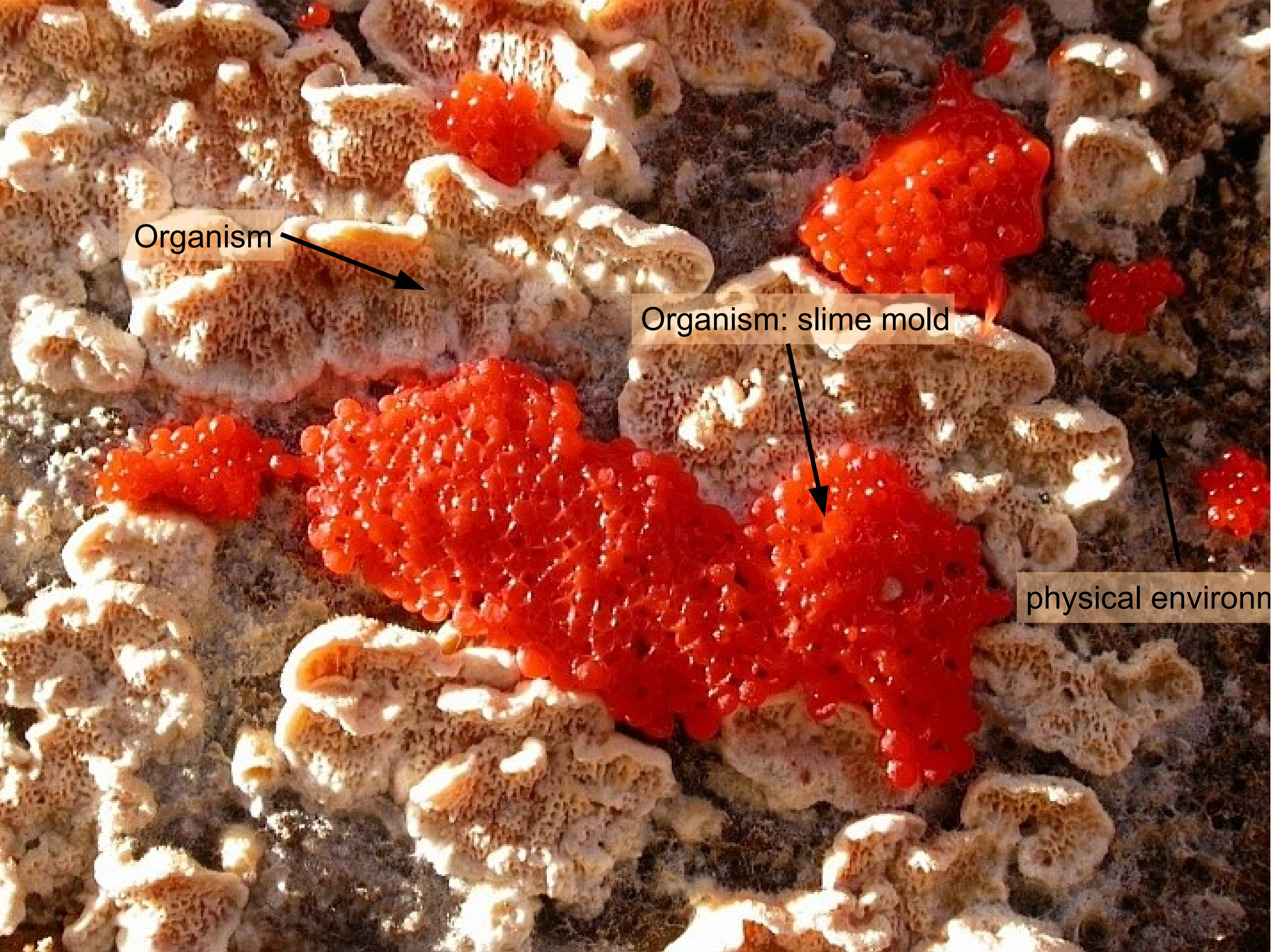
Tansley (1935) The use and abuse of vegetational concepts and terms. *Ecology* **16**:284-307:

[...]
But the more fundamental conception is, at is seems to me, the whole *system* (in the sense of physics), including not only the organism-complex, but also the whole complex of physical factors forming what we call the environment of the biome – the habitat factors in the widest sense. Though the organisms may claim our primary interest, when we are trying to think fundamentally we cannot separate them from their special environment, with which they form one physical system.

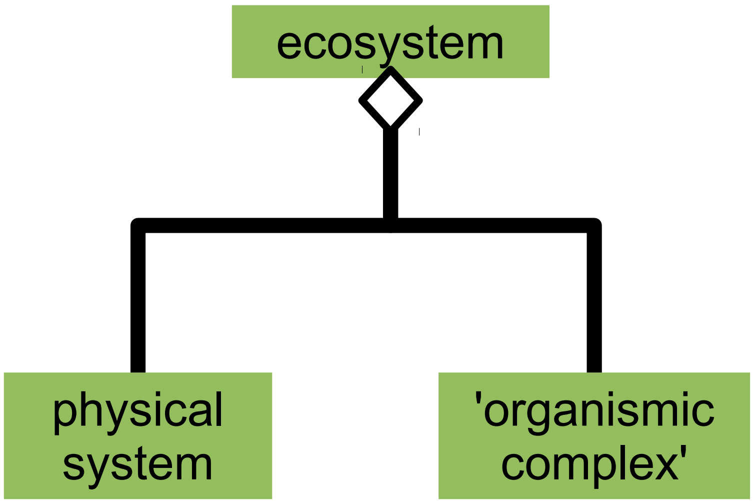
1. Ecosystem = biological system + physical system


physical environment
organisms


organism: plant
organism: predator
physical environment
organism: herbivore


Organism
Organism: slime mold
physical environn

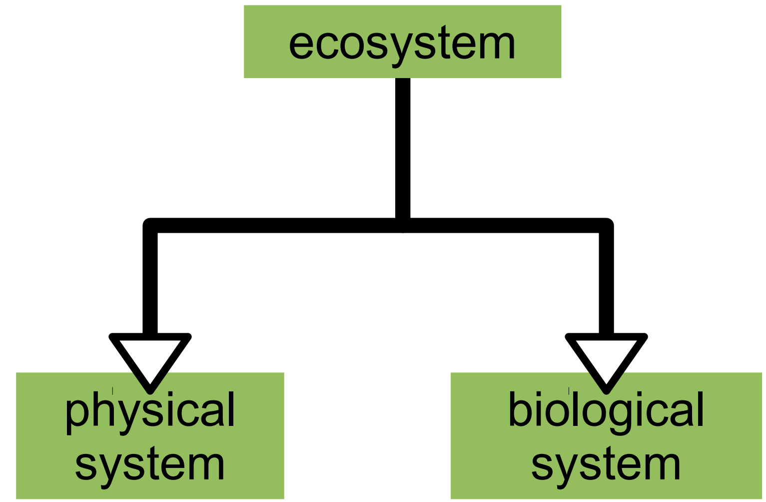
Biological or physical system: a creative ambiguity



the ecosystem *has* a physical and a biological part

*'the whole system (in the sense of physics), including not only the **organism-complex**, but also **the whole complex of physical factors**'*

ecosystem = a mixture of organisms and 'physical factors'

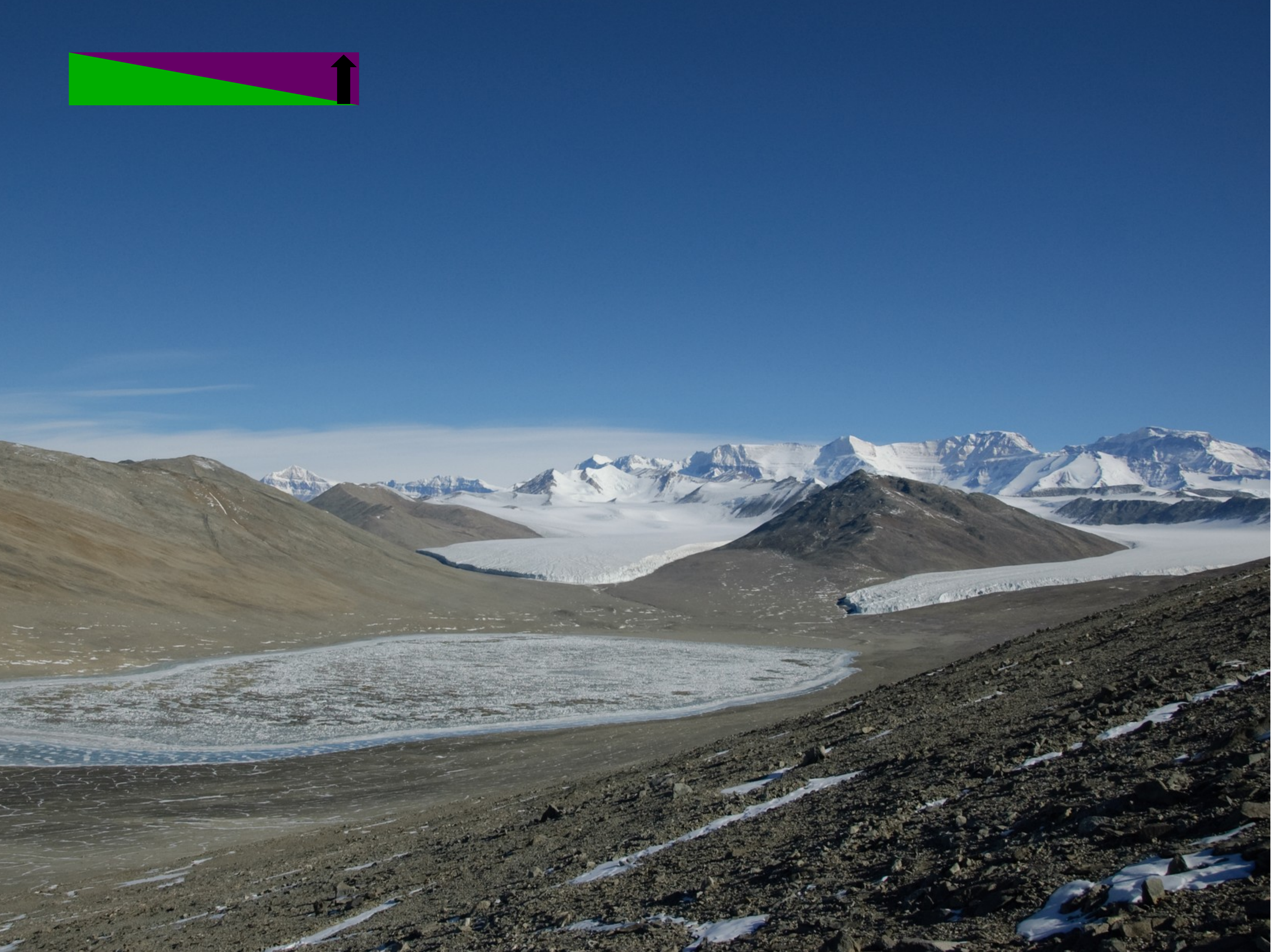


the ecosystem *is* a physical and a biological system

*'when we are trying to think fundamentally we cannot separate them from their special environment, with which they form **one physical system**.'*

ecosystem = a system studied with the methods of physics and biology

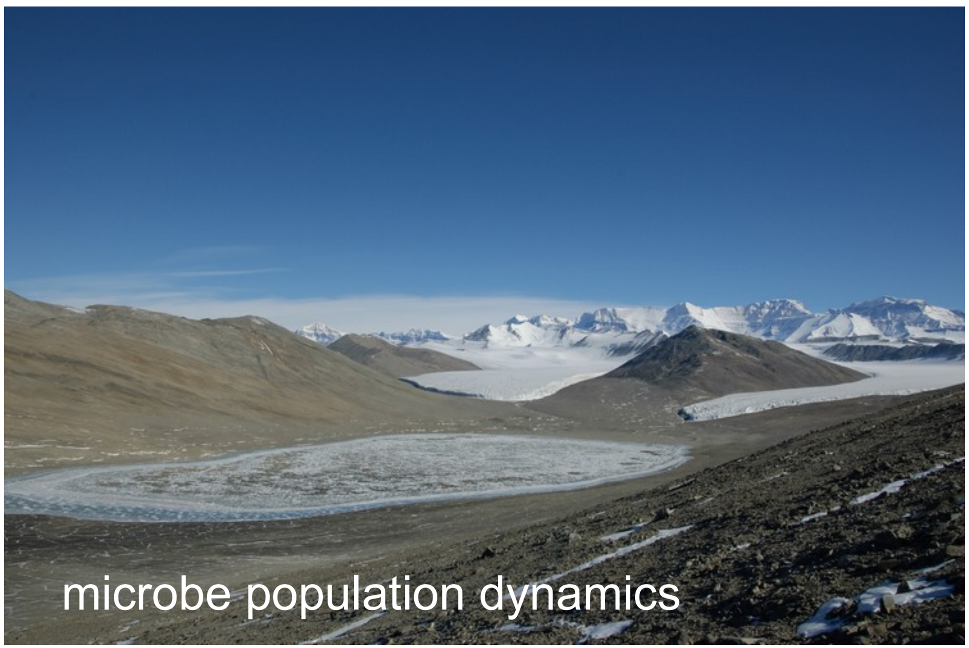

physics-dominated
ecosystem
organism-dominated
ecosystem



The dual nature of ecosystems

Ecosystems as biological systems :
birth, death, reproduction, demography, discrete states, decision, stochasticity

Ecosystems as physical systems :
matter and energy fluxes, thermodynamics, continuous states, determinism, conservation laws



1 system, 2 ***representations***

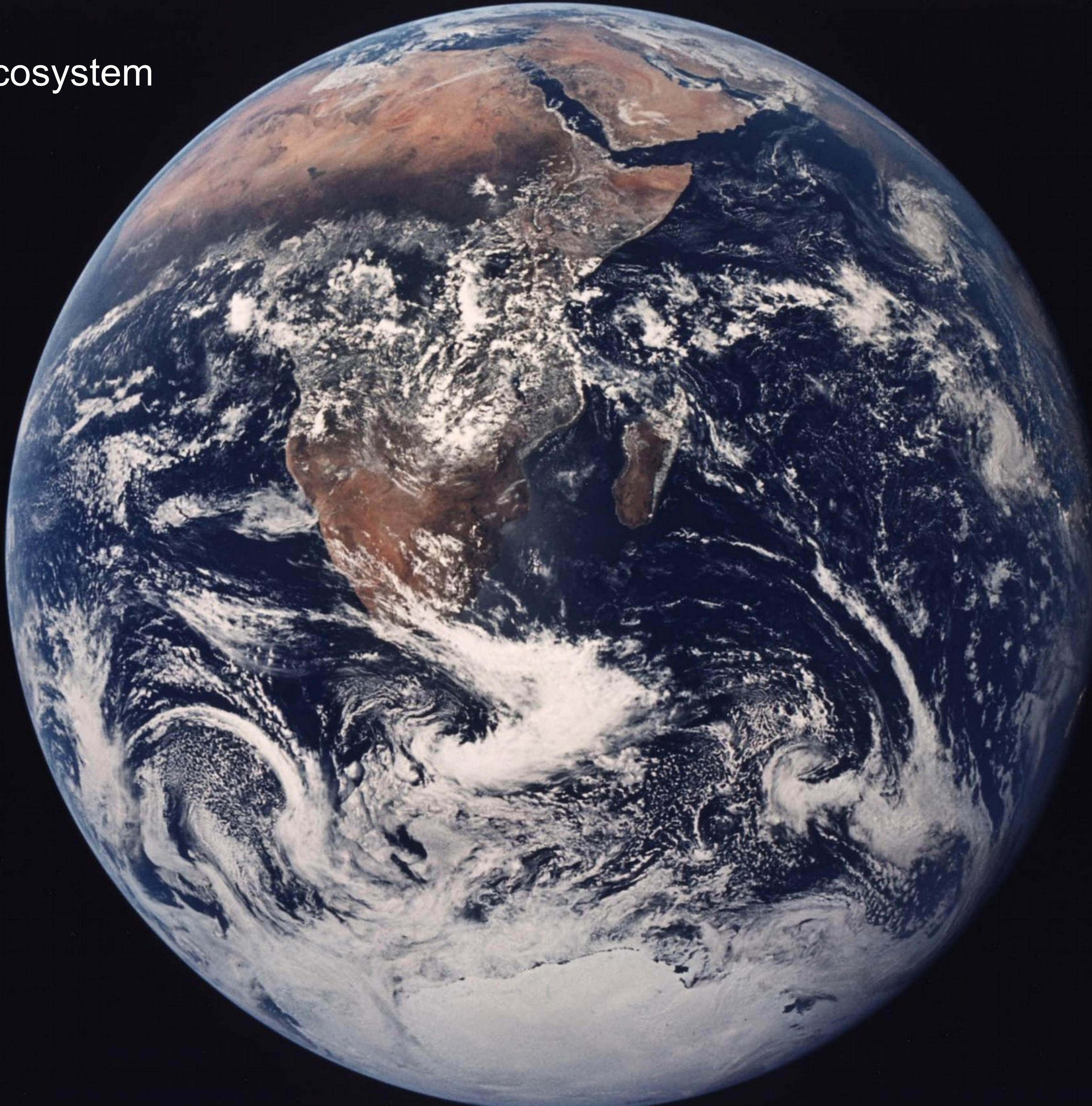
representation = description of a system using a particular method

[...]
But the more fundamental conception is, at is seems to me, the whole *system* (in the sense of physics), including not only the organism-complex, but also the whole complex of physical factors forming what we call the environment of the biome – the habitat factors in the widest sense. Though the organisms may claim our primary interest, when we are trying to think fundamentally we cannot separate them from their special environment, with which they form one physical system.

There is no idea of space, time, or scale in Tansley's definition

2. The ecosystem is a scale-independent concept

a large ecosystem



a small ecosystem

Further down in Tansley's paper:

'... a system we isolate for the purpose of the study'.
'The isolation is partly artificial, but is the only possible way in which we can proceed'
'The mental isolates we make are by no means all coincident with physical systems, though many of them are, and the ecosystem among them.'

3. The ecosystem is an *arbitray construct*, a *representation* of the real world

cf. Carnot (1824) : system = the part of the world *under consideration*

The *holocoen* [(Friederichs 1927) = 'a naturally delimited part of the biosphere'] never achieved the success of the ecosystem concept.

Jax 2006: criteria for a good definition: clarity, consistency, *applicability*

Good news:

Everything is an ecosystem !

1. ecosystem = physical + biological system
2. scale independent
3. arbitrary construct

→ **(almost) anything can be studied as an ecosystem**

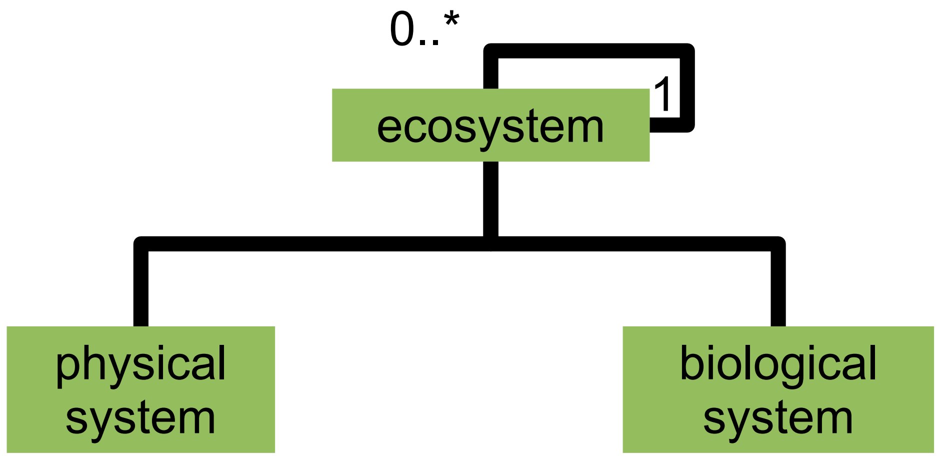
The ecosystem is the basic building block of ecology. **Ecology consists in viewing everything as ecosystems.**


OREGON

The ecosystem as a ***self-similar*** object

If anything can be treated as an ecosystem, any part of an ecosystem is still an ecosystem:

Ecosystems can be nested



2 problems

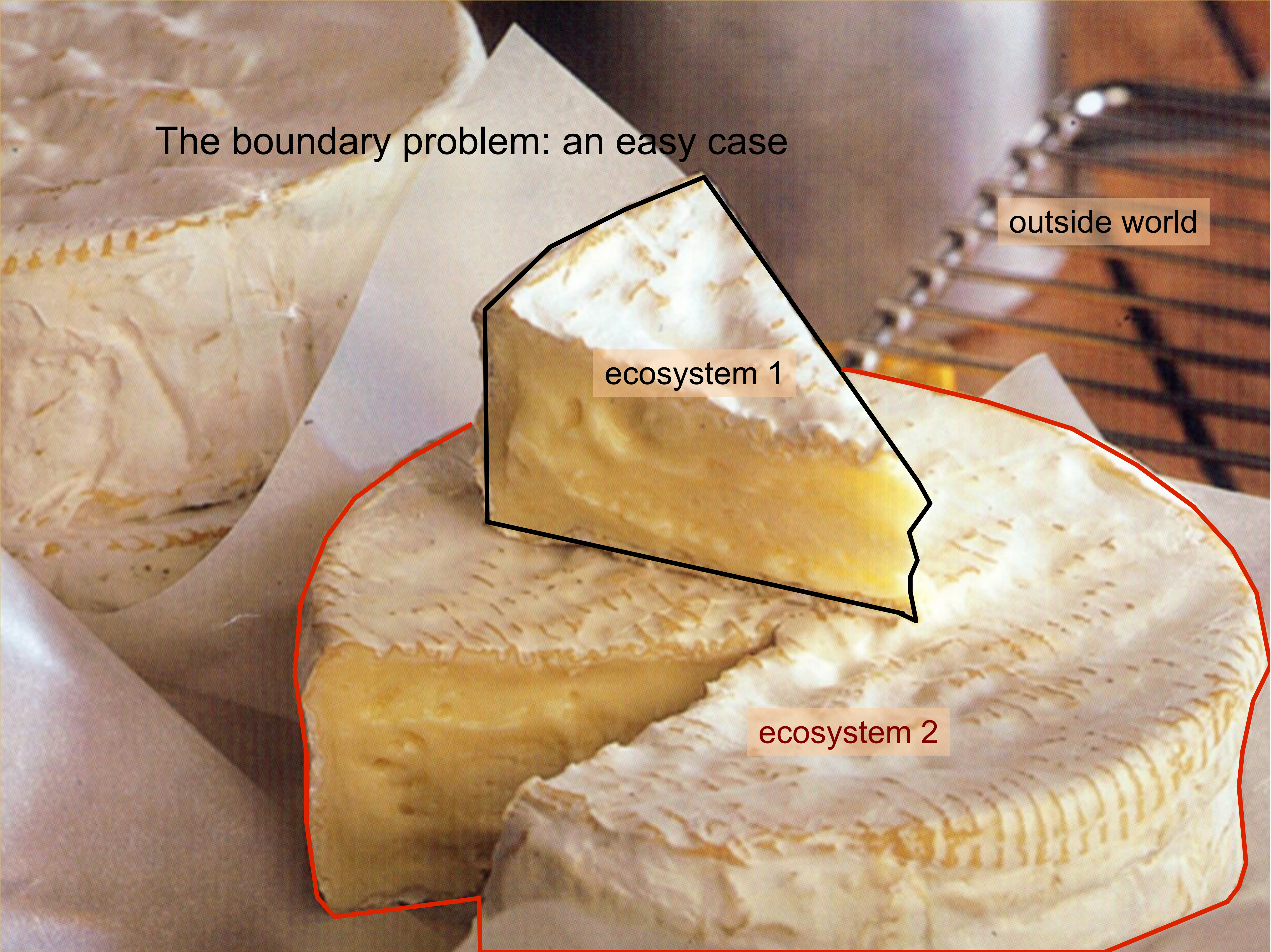
The boundary problem:

In practice, how do we delineate ecosystems in the field?
If I want to work on « the forest », where do I sample and take measurements ?

The abstraction problem:

Can the sub-systems of an ecosystem be represented at the same abstraction level ?
Is the ecosystem a consistent representation of the real world ?

The boundary problem: an easy case




A not so easy case
Should the lake be isolated from its water catchment ?

The decision to consider the lake or the lake within its catchment is a **choice**.

It is usually motivated by 'the purpose of the study', although scientific tradition also interfers.

What is the link with 'the purpose of the study' ?

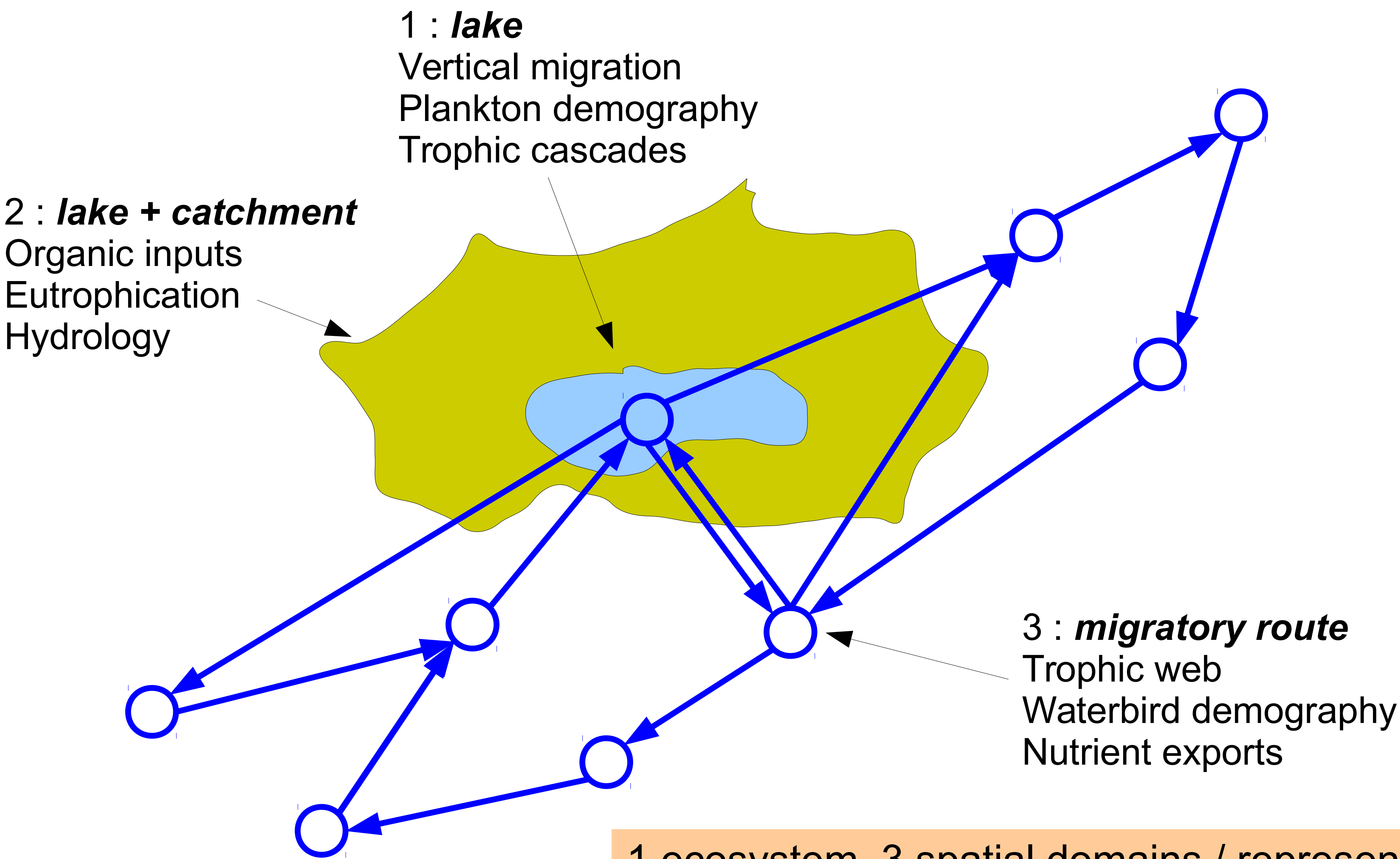
Examples:

- considering the water catchment around the lake means we are dealing with water runoff (a particular **ecological process**).

- if we were interested by the full trophic network of the lake, we might consider migratory birds as top predators. We would then extend the spatial domain differently (eg where is the lake on a migration route). That's another **ecological process.**

The spatial domain we consider depends on the **ecological processes** we want to consider in the study (which depend on the purpose of the study).

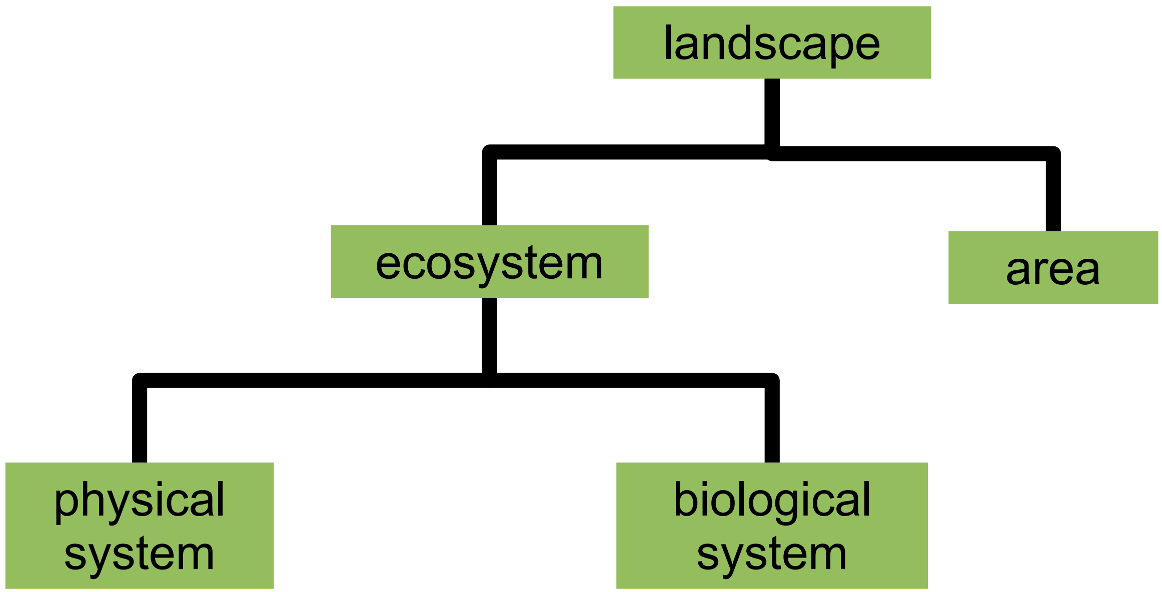
Consequence: since spatial domain of interest depends on ecological processes, there may be *as many different spatial domains* as processes considered in the ecosystem.



1 ecosystem, 3 spatial domains / representations

The ecosystem and the landscape

A landscape is an 'ecosystem' within an area (Lepczyk et al. 2008)



space is central to the definition of the landscape, while it is *absent* from that of the ecosystem

Lepczyk C.A., C.J. Lortie & L.J. Anderson, 2008. An ontology for landscapes. *Ecological Complexity*, 5:272-279

The ecosystem *concept* and the ecosystem *object*

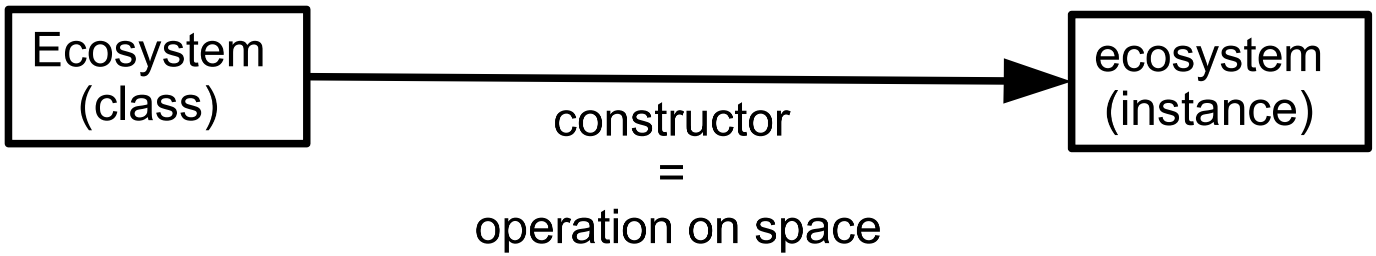
The practical problem of the field ecologist :

There is no obligate need to refer to space or scale when thinking or modelling the ecosystem – the ecosystem used in this case is just a *concept*

There is a need to locate a place where to sample when experimenting on an ecosystem in the field – the ecosystem in this case is an *object* representative of the ecosystem *concept.*

This is known as the *class-instance* relation in object progamming.

Here, to get an *instance* '**`my_ecosystem_for_experimentation`**' of the *class* '**`Ecosystem`**', we need an operation on space. But once we have the instance, we might not need to refer to space anymore.

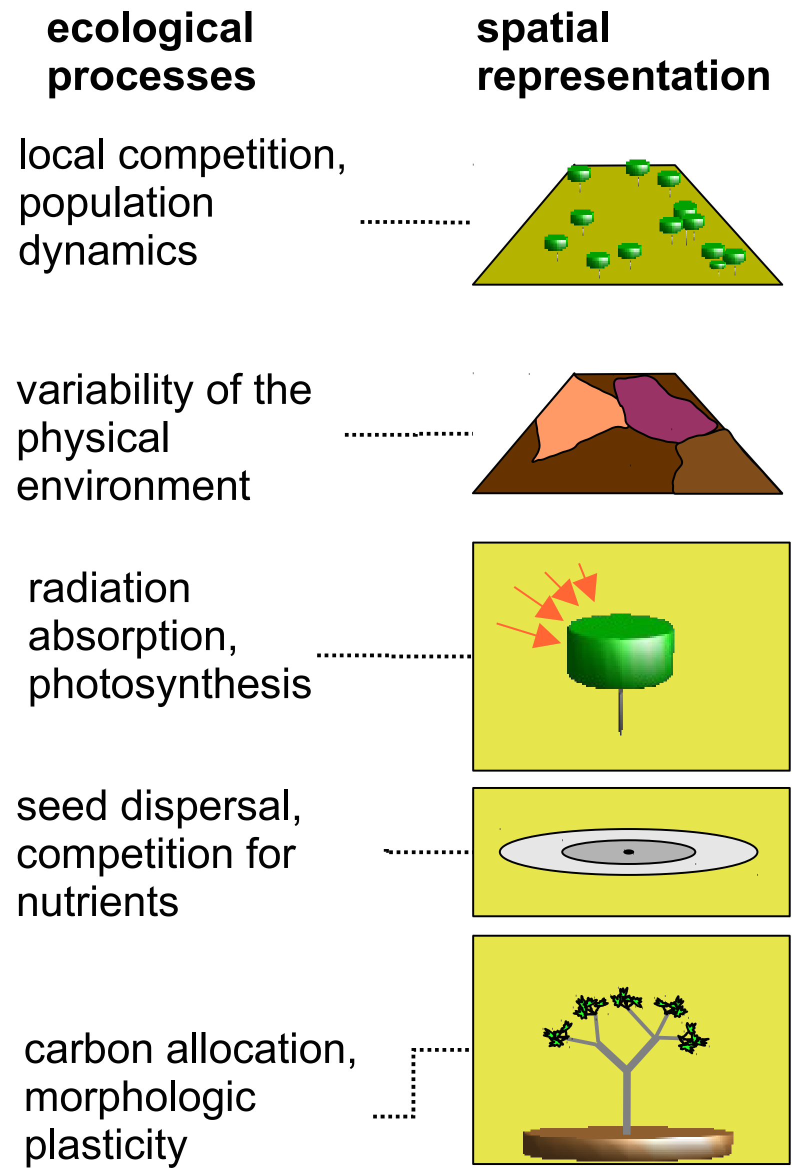


Application for modelling

1 associate processes to spatial representations of an ecological object (based on computation optimisation)

2 manage interaction between processes through spatial overlaying of spatial representation of an ecological object

ANR Project : the 3Worlds modelling platform for ecosystem simulation



The abstraction problem

'*Abstraction is used to reduce and factor out details so that one can focus on a few concepts at a time*' [wikipedia]

Do we need to know every organism in an ecosystem?
What is the correct level of detail for an ecosystem ?
- parsimony principle.

Can we describe an ecosystem to the same level of, e.g., biological organization (e.g. population or individual)?

What is the consequence of inconsistency in the level of abstraction of ecosystem components?

At first sight, it makes sense to decribe an ecosystem at the same level of abstraction for all its components (as a complex system)

But this seems **impossible**: whatever ecosystem is studied, some of its parts will *always* be more detailed than others.

Examples:

- population level: too many & unknown species !

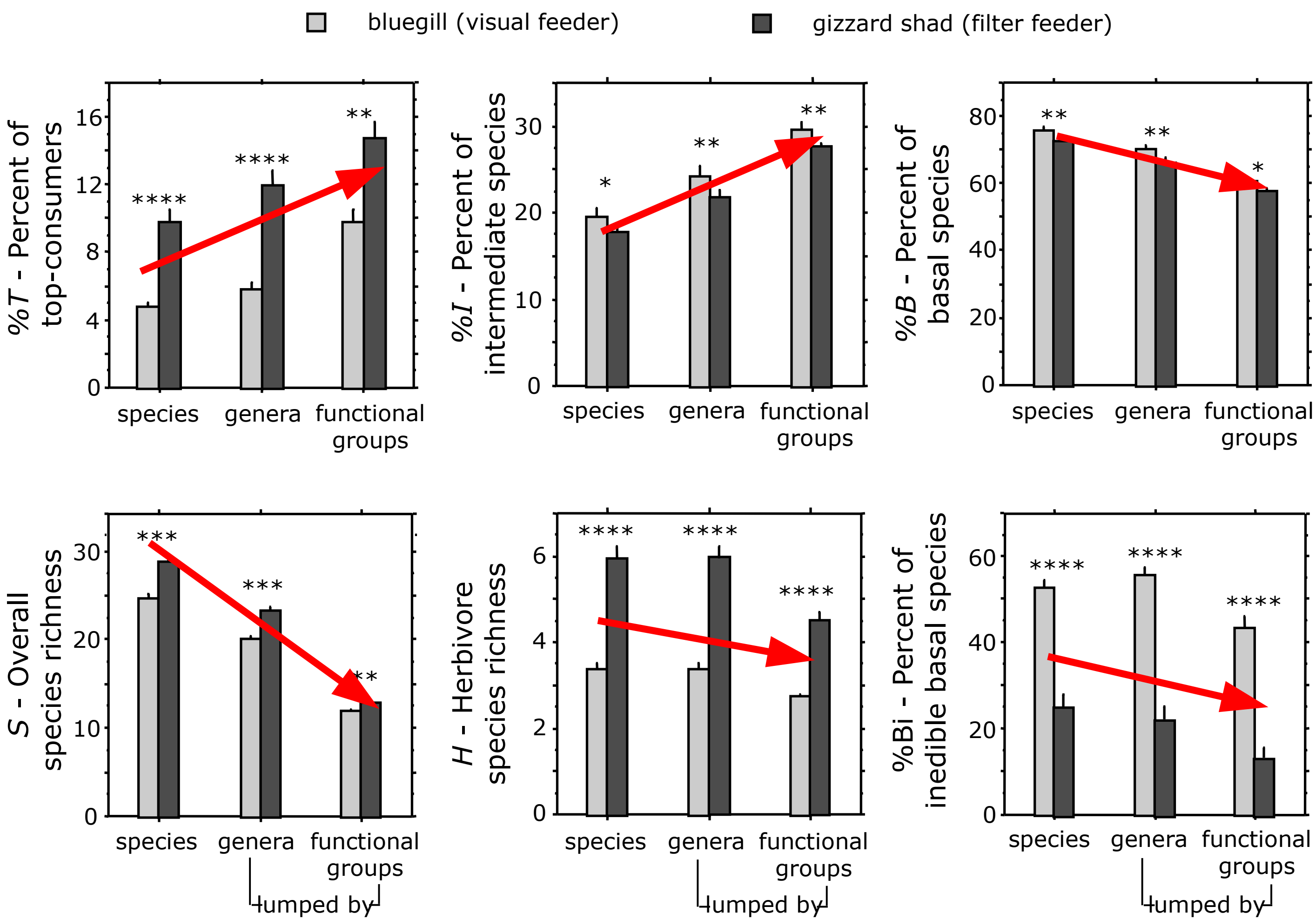
- individual level: sizes of individual organisms span 7-8 orders of magnitude.

The common practice is to focus on dominant species, features, traits. Which may affect resilience and other traits, eg response to climate change

This is a BIG issue !

Importance of the level of abstraction: an example from trophic networks

Hulot et al. 2000; Lazzaro et al. 2009



Properties of trophic network as a function of the lumping of trophic species (=abstraction level of the network)

System-level (emergent) properties depend on the level of abstraction

The abstraction problem: solutions ?

1 There is no fully consistent representation of an ecosystem

2 The level of abstraction impacts the system-level properties

Possible fixes:

- simulation platforms that allow to play with the level of abstraction (using eg the self-similarity of ecosystems)

- base the high-level representation of emergent properties on simulated emergence at lower levels

e.g. Boulain N, Simioni G, and Gignoux J. (2007). Changing scale in ecological modelling: a bottom up approach with an individual based vegetation model. Ecological Modelling, 203:257-269.

Is the ecosystem a complex system ?

A complex system is a system made of interacting parts, which displays *emergence* due to interaction between parts.

Problem: *many* definitions of emergence, with no agreement among them
Emergence as novelty or limit to knowledge (Chérel 2013)

Chérel, G. 2013. Détection et abstraction de l'émergence dans des simulations de systèmes complexes : application aux écosystèmes de savane. Thèse de doctorat, UPMC/ UNA.

Dessalles, J.-L., J.-P. Müller, and D. Phan (2007)

Assad, A. and N. H. Packard (1992)

Forrest, S. (1990)

Ronald, E., M. Sipper, and M. Capcarrère (1999)

Bedau, M. A. (2003)

Bonabeau, E. and J.-L. Dessalles (1997)

Kim, J. (1999)

Müller, J.-P. (2003)

Bedau, M. A. (2008)

Searle, J. (1992)

Zwirn, H, and Delahaye, JP (2013)

The 'hallmarks of emergence' (Bedau 1997) :

(1) Emergent phenomena are somehow *constituted by, and generated from*, underlying processes;

(2) Emergent phenomena are somehow *autonomous from* underlying processes.

Bedau, M.A., 1997. Weak emergence. In: Malden, M.A., ed., *Philosophical perspectives: Mind, causation, and world*, pp. 375-399. Wiley-Blackwell

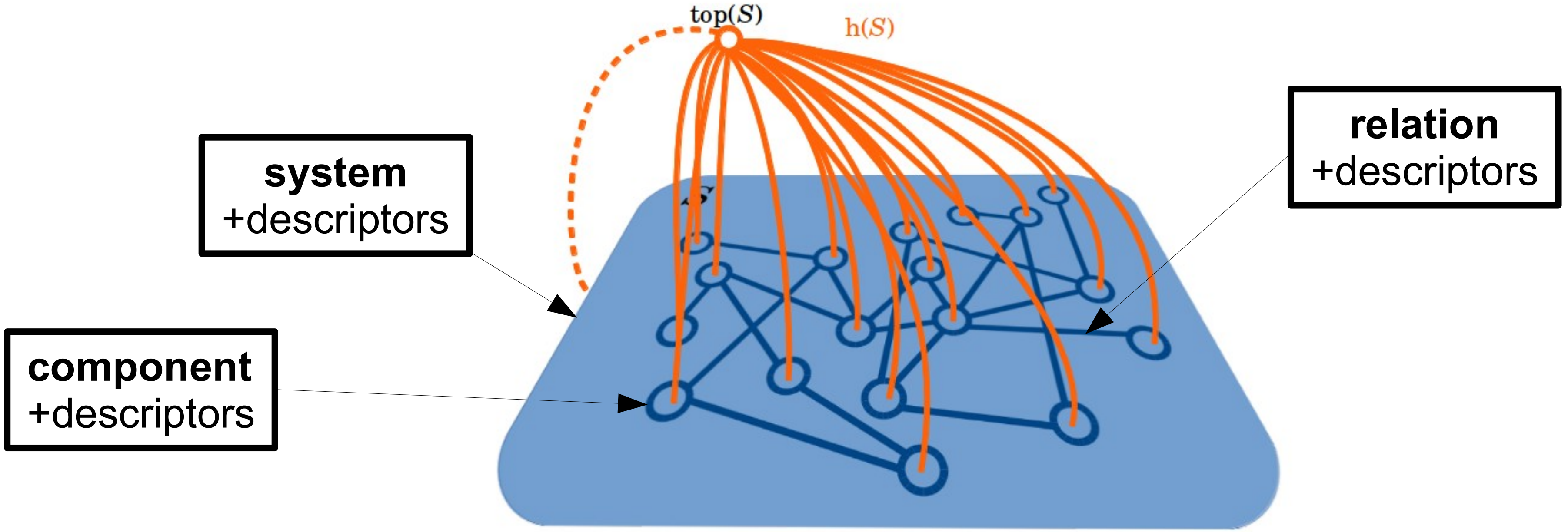
Is anything useful derivable from this mess ?

Only *one* common point : emergence arises in systems with a « *microscopic* » description and a « *macroscopic* » description.

This defines a *hierarchical system*.

What is the best representation of a hierarchical system ?

a **dynamic graph :**



The ecosystem as a hierarchical system

The ecosystem is self-similar = hierarchical

Components = objects relevant to the purpose of the study ; must include biological components and an environment (possibly the whole graph)

Relations = rules for interactions between components

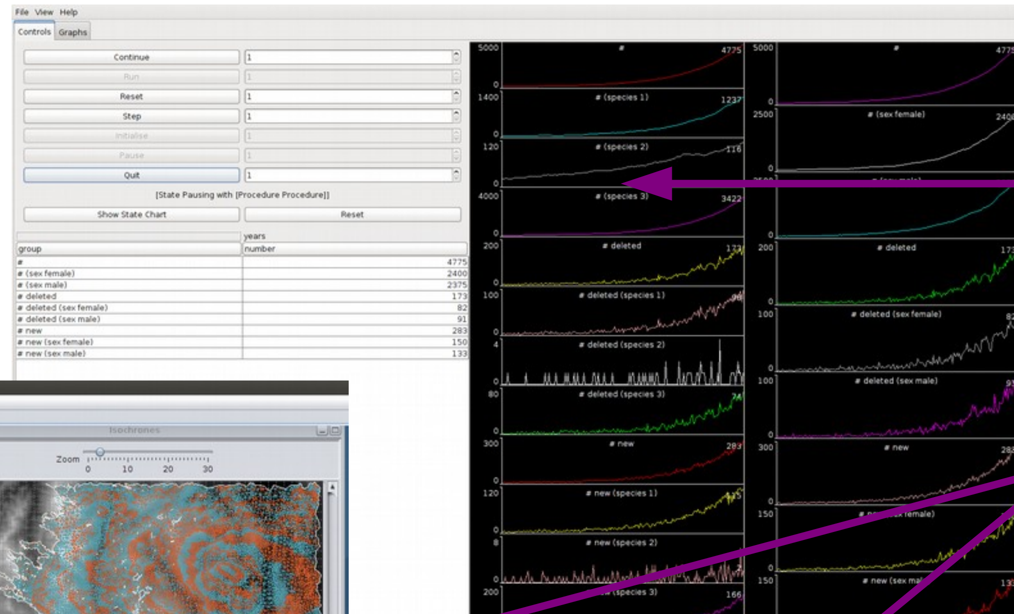
4 types of « emergence » in a hierarchical system:

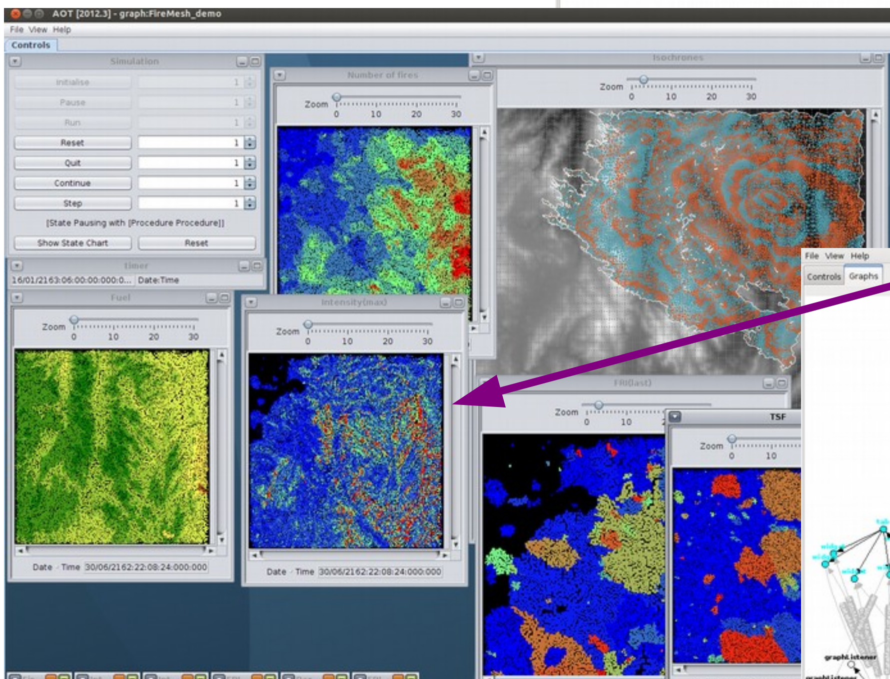
- 'naive' : arises from neglecting/ignoring interactions
- 'discovery' : arises from missing descriptors
- 'weak' : due to computational irreducibility between micro- and macro-state
- '?': due to *causal loops* (feedbacks) within the system

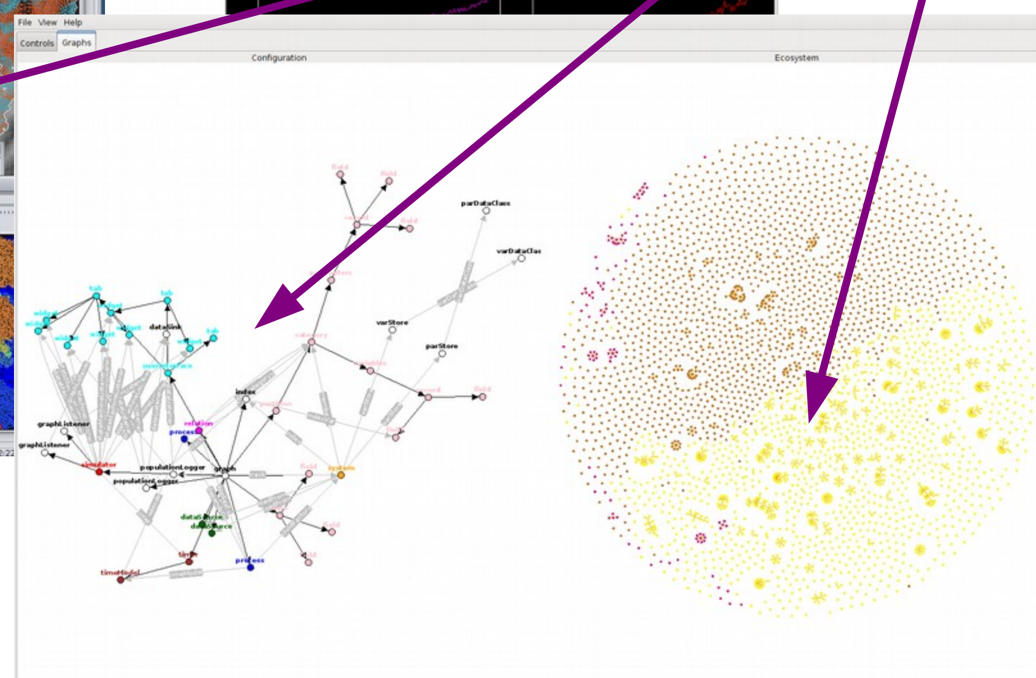
... conceptual work in progress

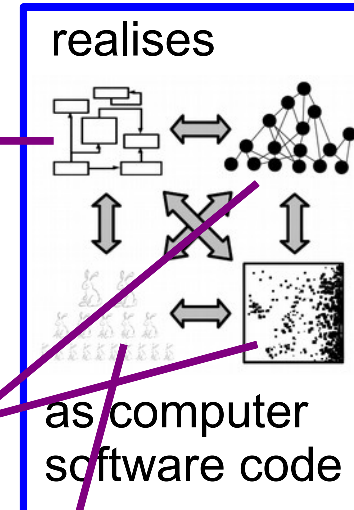
Simulation as an integration tool

the 3Worlds platform
ANR-CIS 2008-2011
+ in collaboration with ANU









- *multifactorial* and *multi-scale*
- *versatile abstraction level*

Conclusion

Broad applicability only comes from general concepts – but we need *good* concepts to do so

The ecosystem definition is rich enough to constrain a simulation platform

Emergence is linked to hierarchical systems, which are easy represented as graphs

... which are easy to implement as simulation tools (3Worlds)