Institute of Ecology and Environmental Sciences of Paris

iEES Paris

+

Naturam primum cognoscere rerum

Australian National University

De l'écosystème au graphe dynamique

Comment représenter la nature dans sa complexité

Jacques Gignoux, Ian D. Davies,
Guillaume Chérel, Shayne R. Flint, Eric Lateltin

25 Avril 2024

Ecologie = science des relations entre les êtres vivants et leur environnement

Les trois problèmes de l'écologie

- des objets très variés
- des questions très difficiles
- une grande variété de méthodes

Quelques objets d'étude de l'écologie

Océan
Austral

photo Michel de Saint Blanquat


Australie
centrale
photo Jacques Gignoux


Indonésie
https://www.checkyeti.com/fr/d/1994/15142


Australie
méridionale
photo Jacques Gignoux

Dans les abysses

https://www.science-et-vie.com/questions-reponses/d-ou-viennent-les-fumeurs-noirs-9787

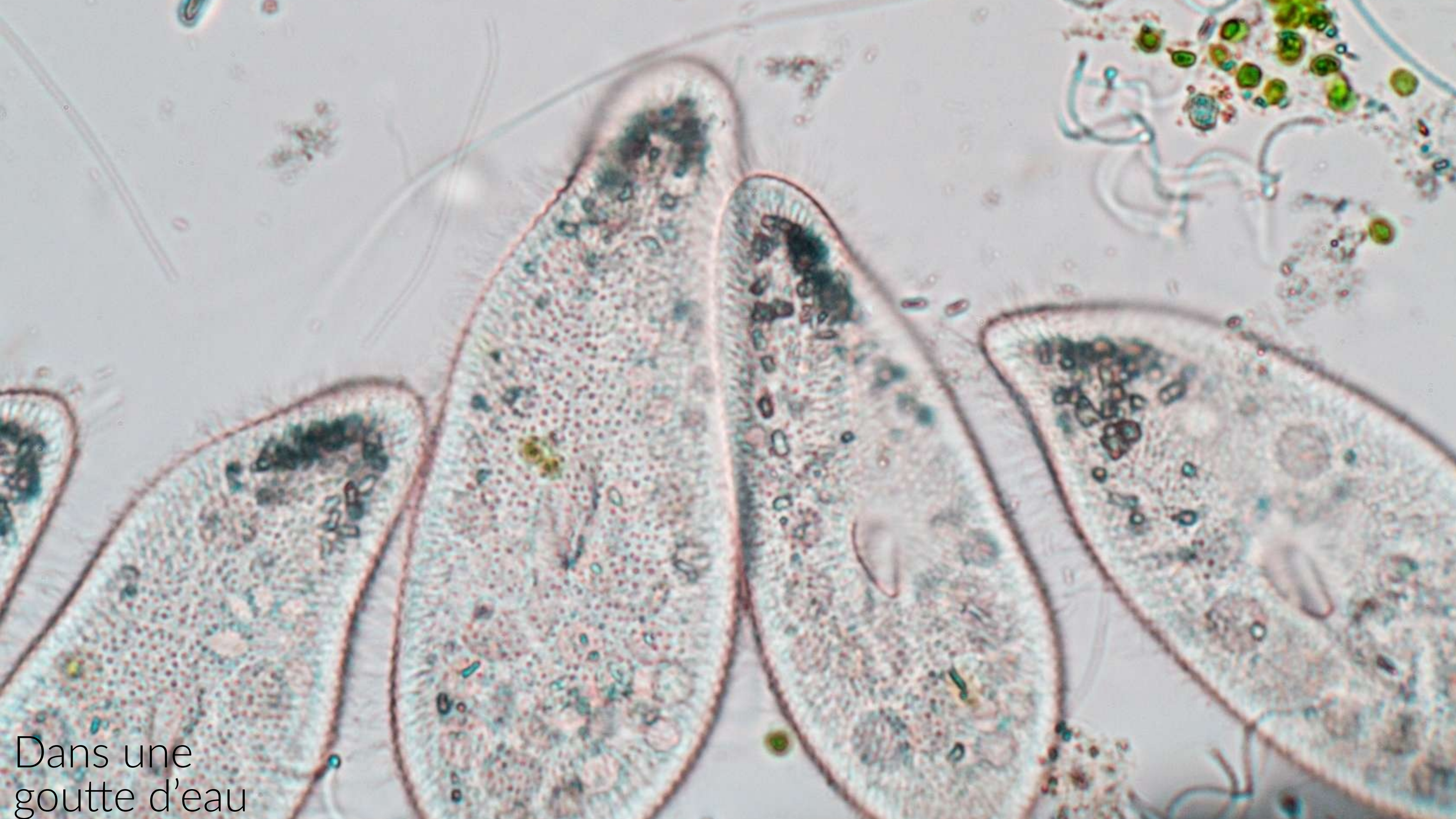

Brésil
https://news.bloomberglaw.com/environment-and-energy/soy-and-the-cerrado-exports-ecology-collide-in-brazils-savanna

Dans une flaque
d'eau en Allemagne

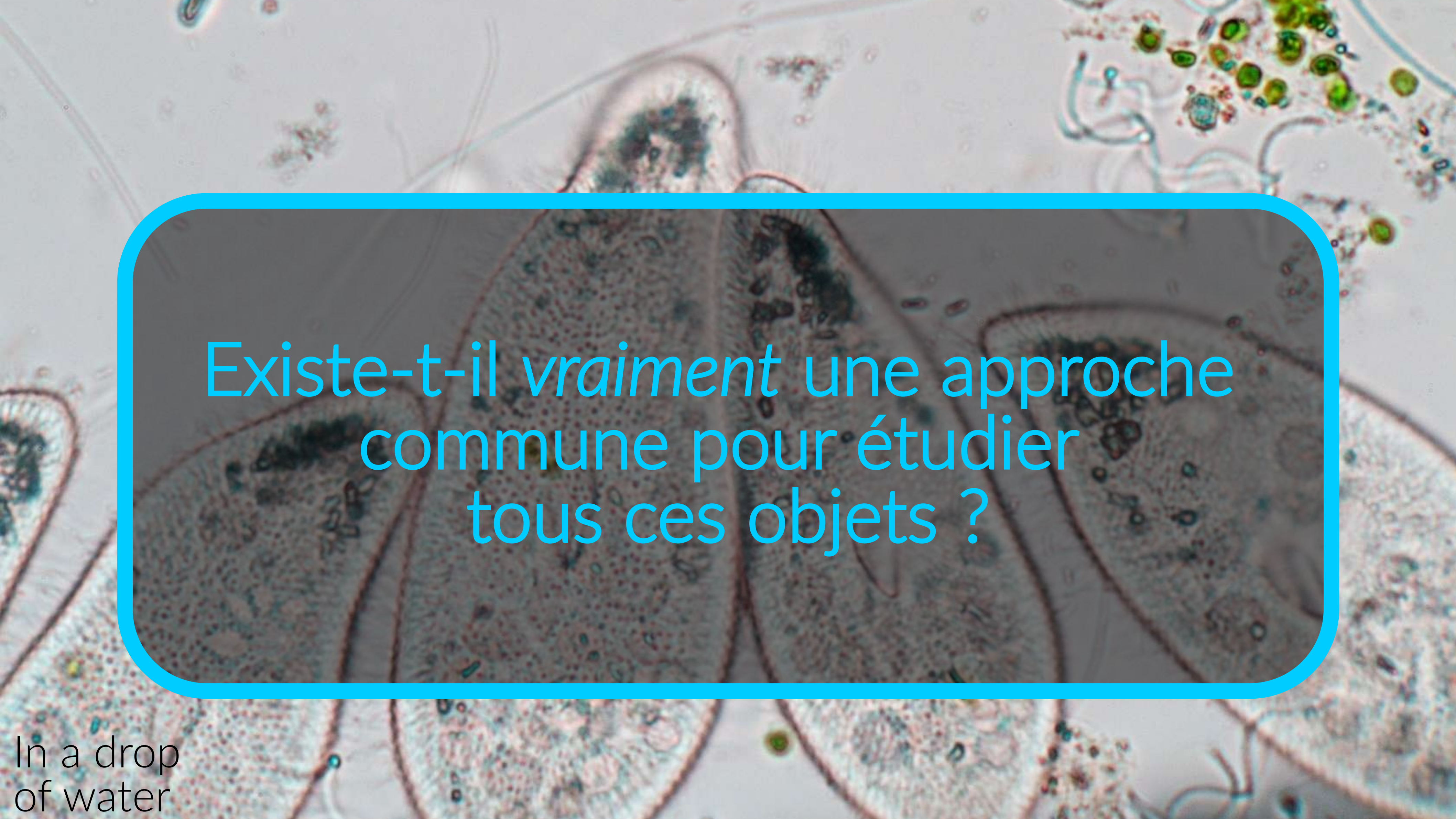
https://atoptics.wordpress.com/tag/bacteria-colours/

Groupe local,
la Galaxie,
bras d'Orion,
système solaire

NASA AS17-148-22727



Dans une
goutte d'eau



Existe-t-il *vraiment* une approche commune pour étudier tous ces objets ?

In a drop of water

Ecology addresses *difficult* questions:

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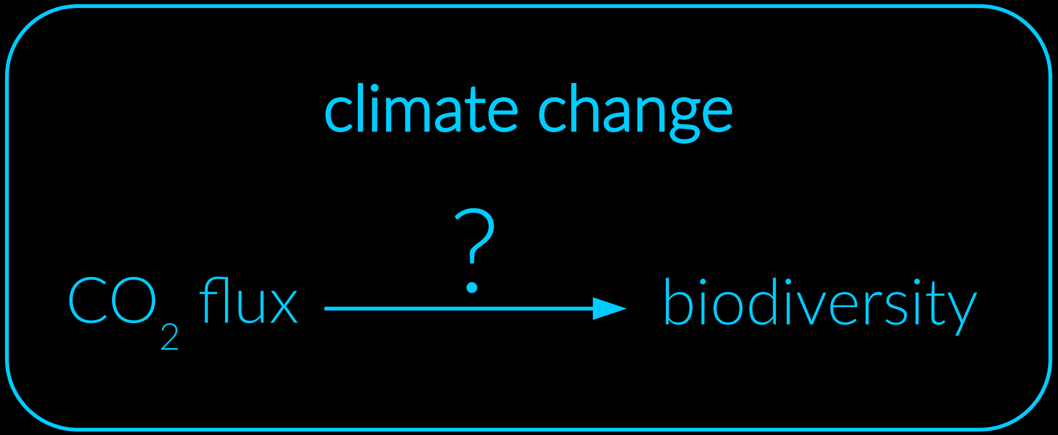
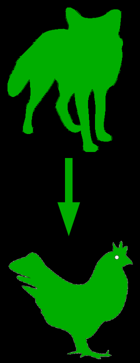


Ecology addresses *difficult* questions:

climate change

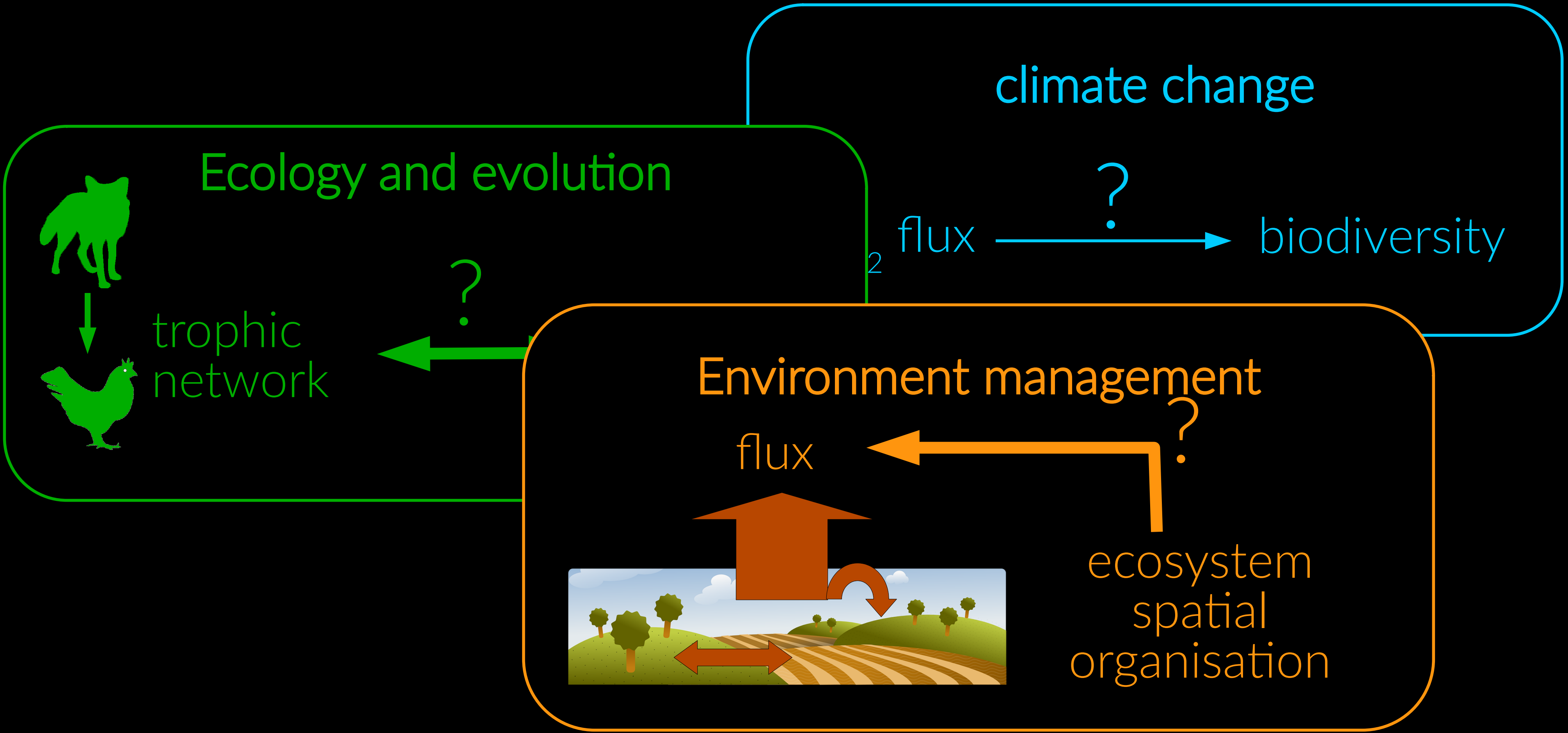
2 flux → ? → biodiversity

Ecology and evolution



trophic network ⟷ ? ⟷ population dynamics

Ecology addresses *difficult* questions:



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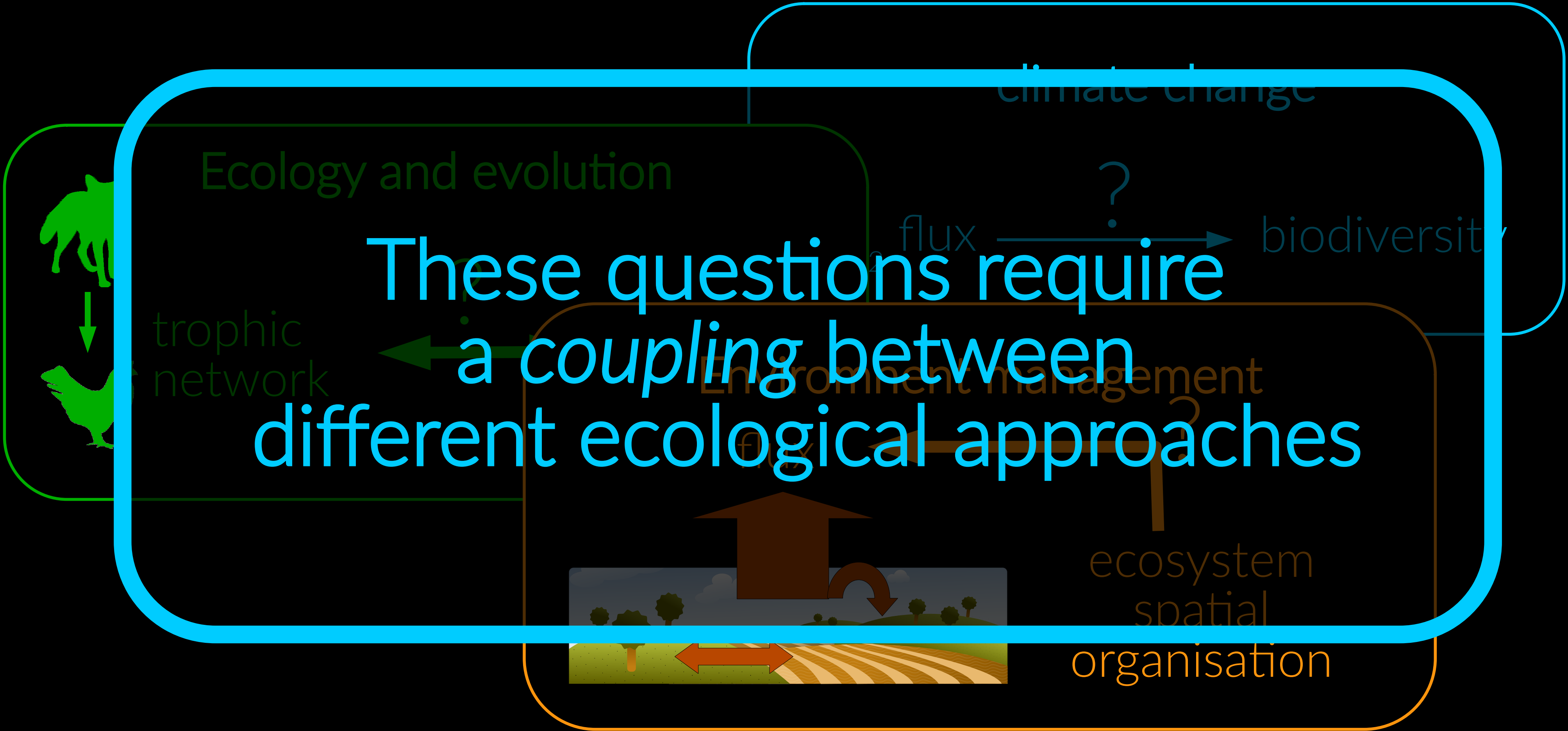


These questions require a *coupling* between different ecological approaches

Ecology is an *integrative* science:

administrativology
etc.
immunology
endocrinology
pedology
histology
etc.
entomology
oceanography
absolutivity
animal behaviour
[bio]geography
systematics
geometry
quantum physics
statistics
geology
genetics
etc.
relativity
etc.
law
gastromony
demography
chinese astrology
hydrology
physiology
relativity
ecology
[bio][geo]chemistry
beerology
evolution
etc.
[micro]meteorology
cell biology
political sciences
game design
climatology
graph theory
programming
plant architecture
thermodynamics
game theory
topography
paleo-whatever-ology
smallestpublishablebitology
system dynamics
etc.
applied epistemology
projectology

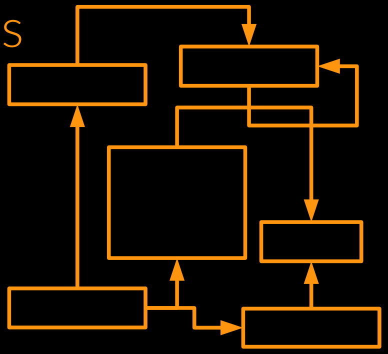
… borrowing methods from other sciences

Ecological sub-fields use poorly compatible representations:

Matter and energy fluxes
Ecophysiology
Ecosystems

↓

Dynamic systems



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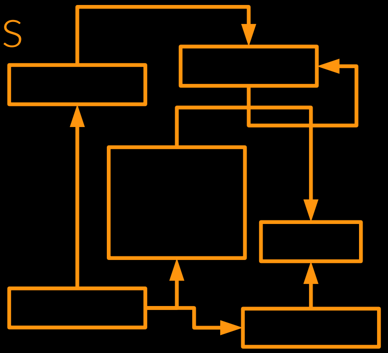

Demography
Genetics
Evolution

↓

Population models
Individual-based models

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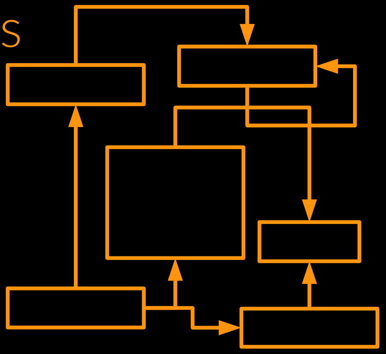

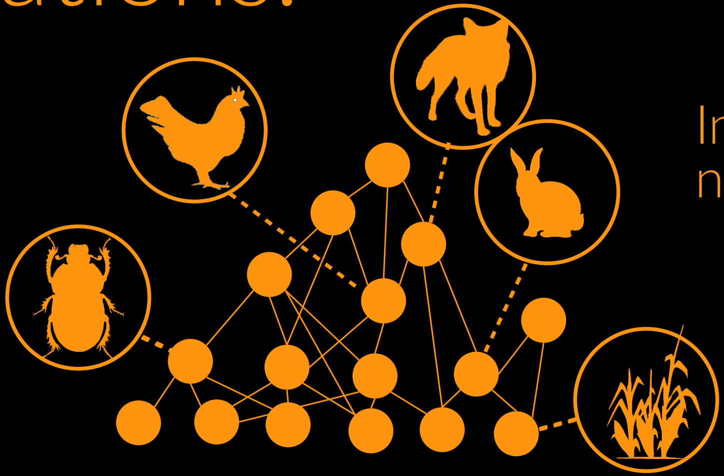

Interaction networks

↓

Graphs

Demography
Genetics
Evolution

↓

Population models
Individual-based models

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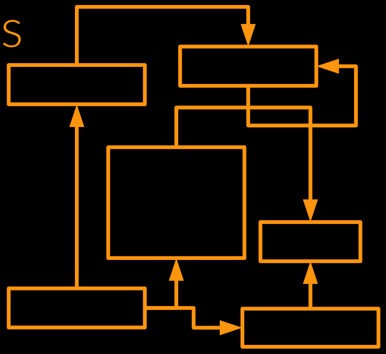

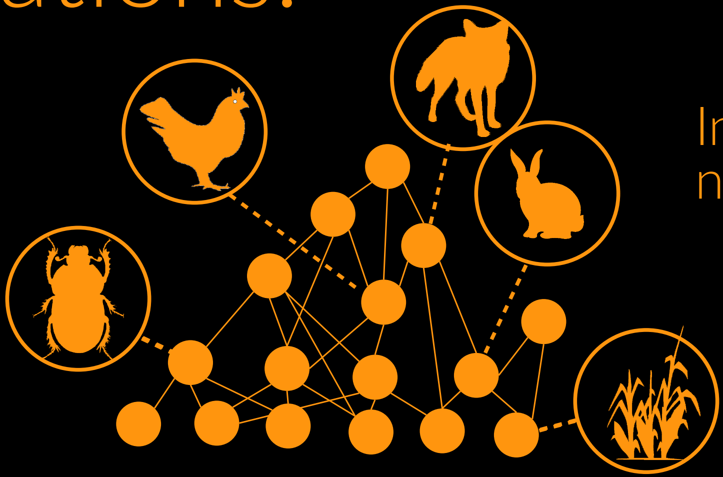

Interaction networks

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Population models
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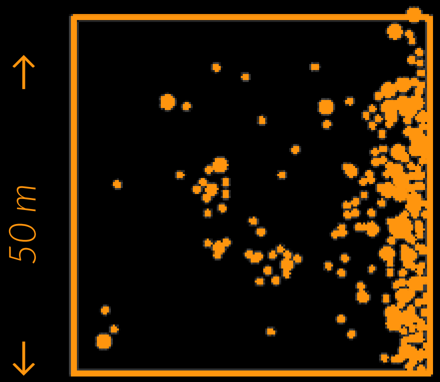


Landscape ecology
Ecosystem structure

↓

Cellular automata

Ecological sub-fields use poorly compatible representations:

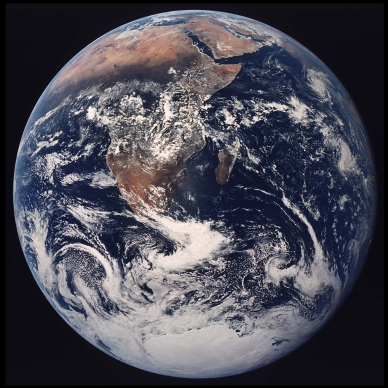
I. The solution to the diversity of objects

The *ecosystem* concept (Tansley, 1935)

'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.'

Ecosystems

- combine physics and biology into a single object
- are scale-independent
- are observer-dependent



Gignoux et al. 2011. Ecosystems 14:1039-1054

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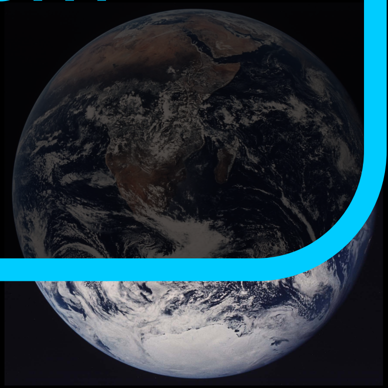
Ecology consists in viewing *everything* as an ecosystem



Gignoux et al. 2011. Ecosystems 14:1039-1054


even this:
somewhere on the internet

or this:

somewhere else on the internet

II. The solution to the difficulty of these questions

Impossible is not French.

We don't care!

It's more fun if questions are not easy!

Plus, practical environmental problems are *always* going to be *difficult*, *complex*, *wicked*, *multi-faceted*, without a unique clear definite solution. **We must get used to this**.

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huh… maybe a method would help

Systems thinking

Churchman, C. W., 1968; Kramer, N., 1977; Checkland, P. & J. Scholes, 1999; Senge, P., 1992.

Shayne Flint

Australian National University

- a set of approaches that can be used to learn about / make decisions on *dynamically complex systems*
- focuses on *the whole* and the *interactions* among the *parts* of a system
- this way we can understand *emergent properties* of an entire system

Flint, S 2008, 'Rethinking Systems Thinking', in David Cook (ed.), Proc. 14th ANZSYS Conference, ECU, Perth.

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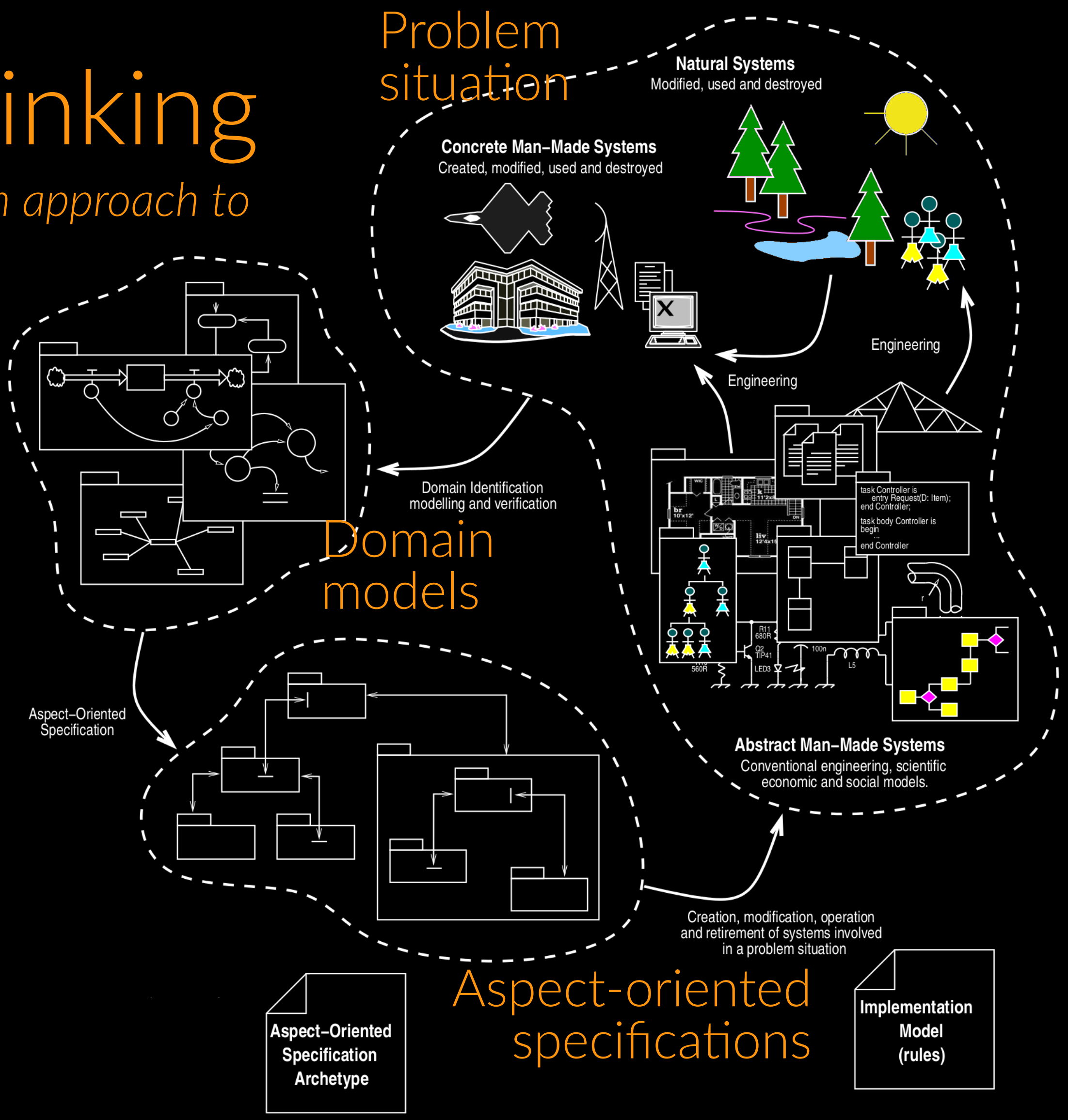
sorry... do you call *this* a method?

Flint, S 2008, 'Rethinking Systems Thinking', in David Cook (ed.), Proc. 14th ANZSYS Conference, ECU, Perth.

Aspect-oriented thinking

Flint SR, 2006. Aspect-Oriented Thinking - An approach to bridging the disciplinary divides. PhD, ANU.

- independently model *aspects* of a *system* describing a problem
  - e.g. any ecosystem complies to *physics* and *biology*
- use rules for combining these aspects into a new system
  - e.g. an *ecophysiology* x *population* model of **my favourite ecosystem**
- that is used to improve the problem situation
  - e.g. test if **my favourite ecosystem** is stable or resilient



1. We will *not* build the ultimate synthesis of all ecological knowledge

rather,

2. We provide *a method to specify an ecological model* addressing any particular problem

Aspect-oriented thinking

Flint SR 2006 Aspect-Oriented Thinking - An approach to bridging the disciplinary divides. PhD. ANU.

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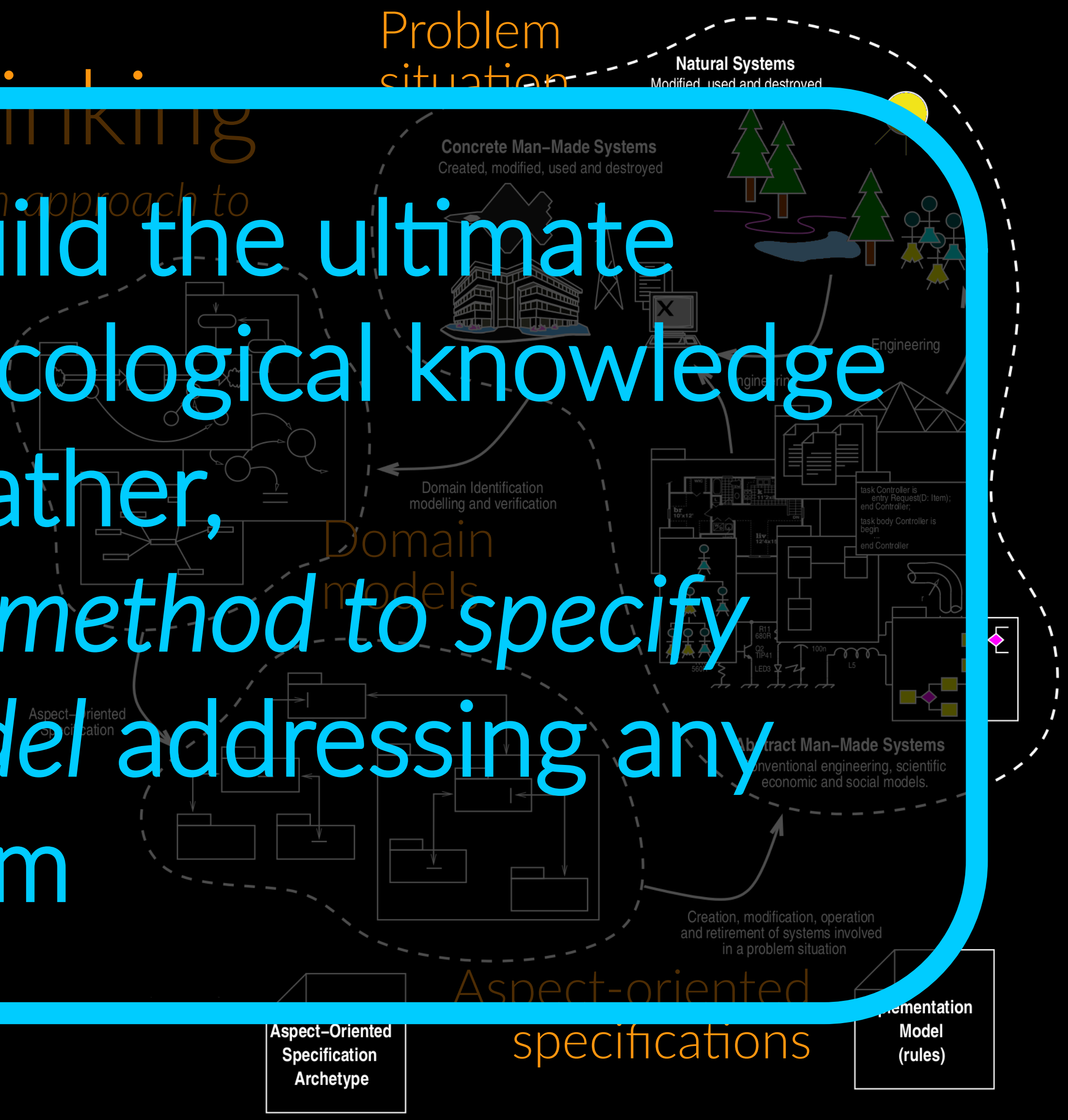


III. The solution to the incompatibility of methods

http://www.lecreusot.com/site/decouvrir/patrimoine/pilon/pilon.php

Make them compatible!

Use good concepts that can be shared

e.g. the system, the ecosystem, etc...

... easy !
(with a steam hammer?)

1. Ecosystems are commonly considered as *complex systems*

1. Ecosystems are commonly considered as *complex systems*

2. Complex systems are assumed to display *emergent properties*

But what is an…

emergent property?

What does that mean?
(does it hurt?)

Not much:

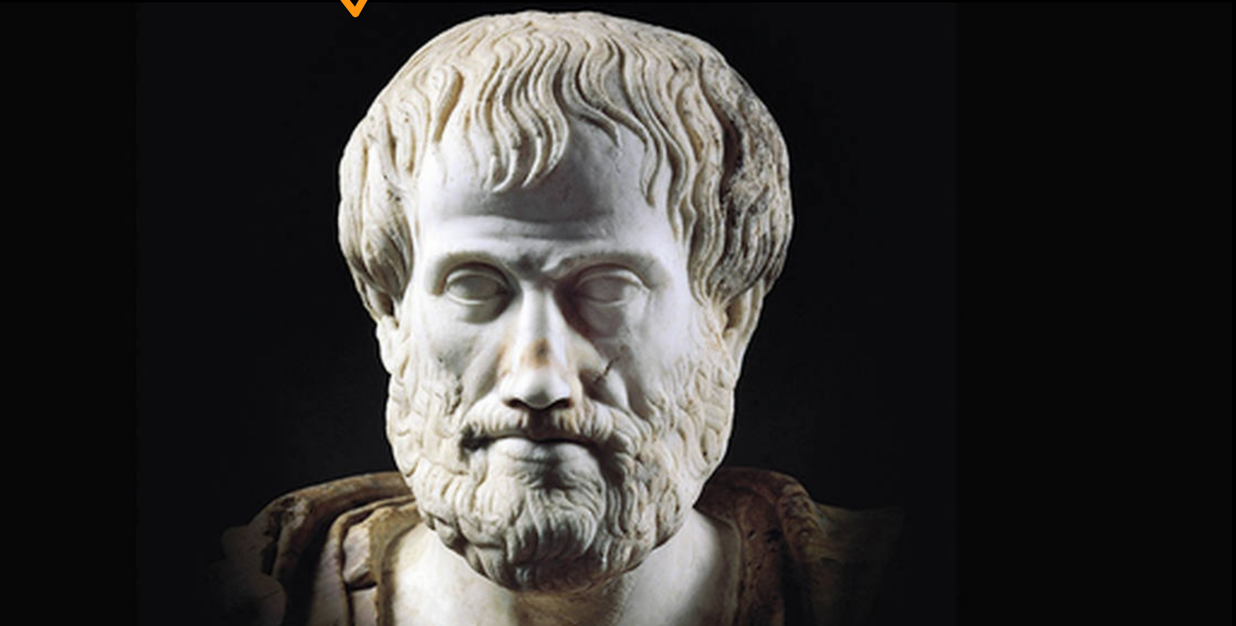
The whole is
more than the
sum of its parts

Αριστοτέλης (-335)

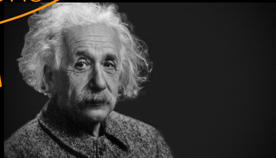
Not much:

The whole is more than the sum of its parts

Αριστοτέλης (-335)



Einstein (1915): 'the mass of an atom is *smaller* than the sum of the masses of its nucleons'



Thank you, old chap, but this is not very helpful.
Modern specialists have much better definitions:

Bedau 1997: Macrostate P of S with microdynamic D is weakly emergent iff P can be derived from D and S 's external conditions but ***only by simulation***.

Ryan 2007: A property is weakly emergent iff it is present in a macrostate but it is not apparent in the microstate, and this macrostate differs from the microstate only in resolution. A weak emergent property is ***a limitation of the observer***, not a property of the system.

Müller 2003: A phenomenon is emergent iff we have (1) a system of entities in interaction whose expression of the states and dynamics is made in an ontology or theory *D* ; (2) the production of a phenomenon [...] which is necessarily ***global*** regarding the system of entities ; (3) the interpretation of this global phenomenon ***by an observer*** [...] in another ontology or theory *D'* ; (4) *D'* is ***irreducible*** to *D*.

Chalmers 2006: We can say that a high-level phenomenon is weakly emergent with respect to a low-level domain when the high-level phenomenon arises from the low-level domain, but truths concerning that phenomenon are ***unexpected*** given the principles governing the low-level domain.

...

[gurgling]

From Guillaume Chérel's PhD (2013)

Définitions de l'émergence

Objectives

Inexplicables à partir des constituants

- Émergence2 (Searle 1992)
- Émergence forte (Bedau 2003)
- Jaegwon Kim (1999)

Explicables sous certaines conditions

- Émergence1 (Searle 1992)
- Émergence faible (Bedau 2003)

Définition basée sur la simulation

Subjectives

- Ronald, Sipper et Capcarrère (1999)
- Forrest (1990)
- Müller (2003)
- Bonabeau et Dessalles (1997)

Apparition d'un langage de description macroscopique

Ook. Ook. Ook. Ook. Ook. Ook. Ook. Ook. Ook. Ook. Ook. Ook. Ook. Ook. Ook. Ook. Ook. Ook. Ook! Ook? Ook! Ook! Ook. Ook? Ook. Ook. Ook. Ook. Ook. Ook.
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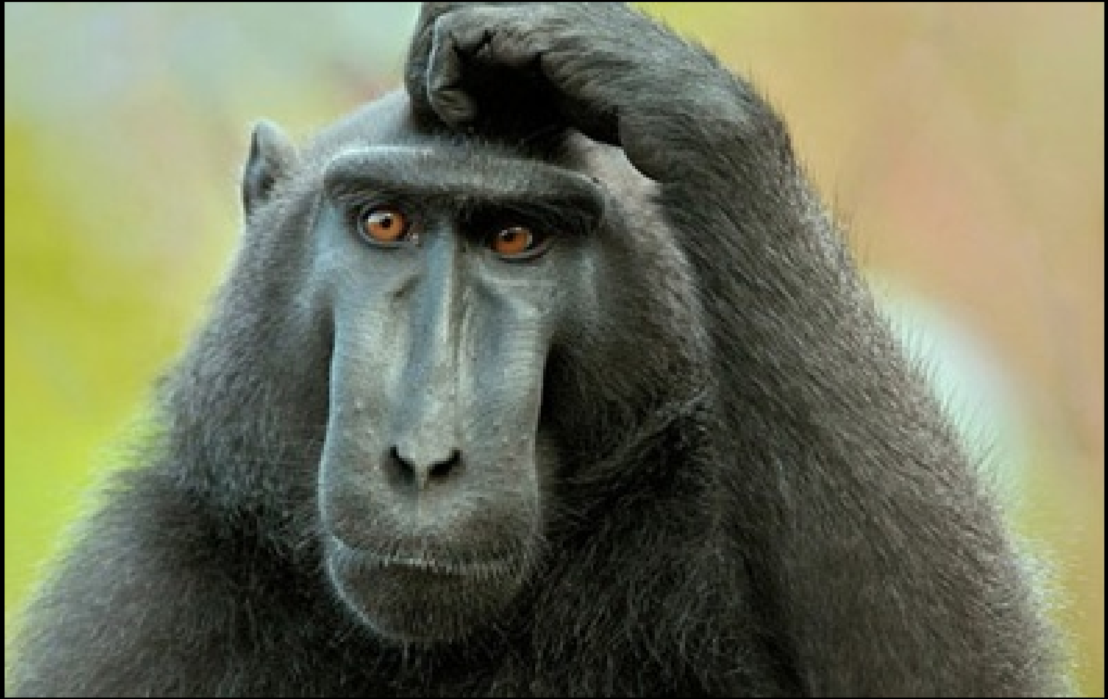

(*) 'So what ?' in the Ook ! Language
(https://www.splitbrain.org/services/ook)

What to do with this mess ?

1) Emergence is of no use to science. Leave it to philosophers and let's go back to our usual ecological concepts

People who agree with this answer may leave the room now

What to do with this mess ?

2) Maybe the mess comes from a poor definition of what emergence is supposed to apply to. Let's try harder.

Ideas :

have a *formal*, *rigorous*, *sound** framework to define the system. which allows to point where emergence could appear

Starting point :

There is only ***one*** common feature between ***all*** emergence definitions :

A ***system*** has a ***microscopic*** and a ***macroscopic*** description

* hopefully

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There is only ***one*** common feature between ***all*** emergence definitions :

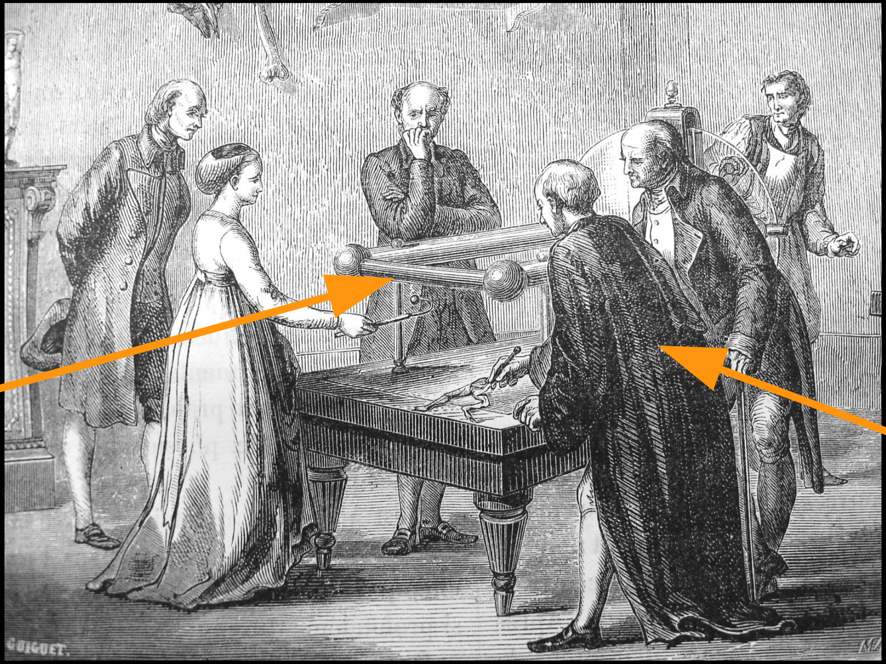
A *system* has a *microscopic*
and
a *macroscopic* description

Let's call such a system
a ***hierarchical*** system

* hopefully

What is a *system* ?

In thermodynamics (Carnot, 1824) :
a system is ***the part of the world under consideration***



system

observer

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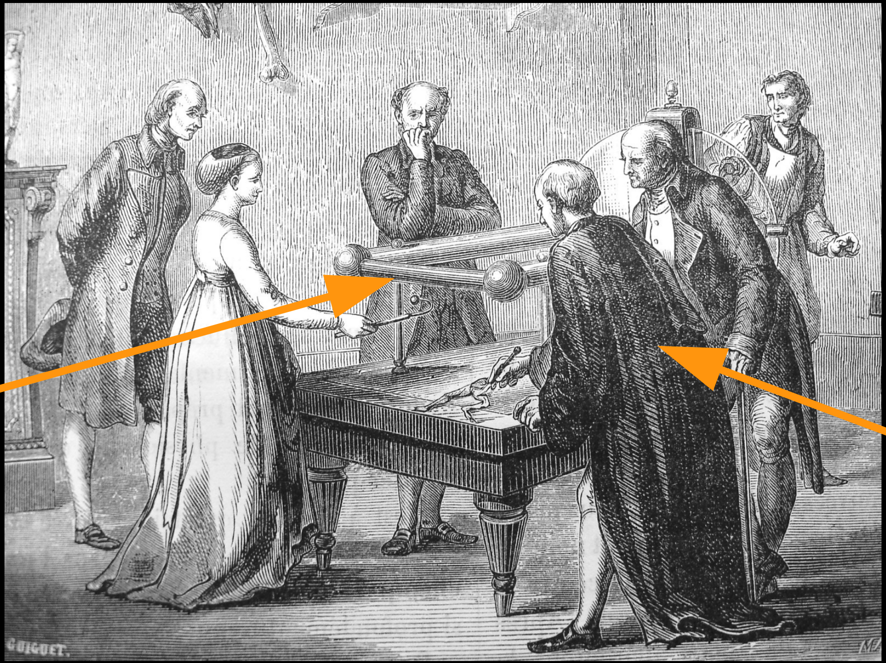
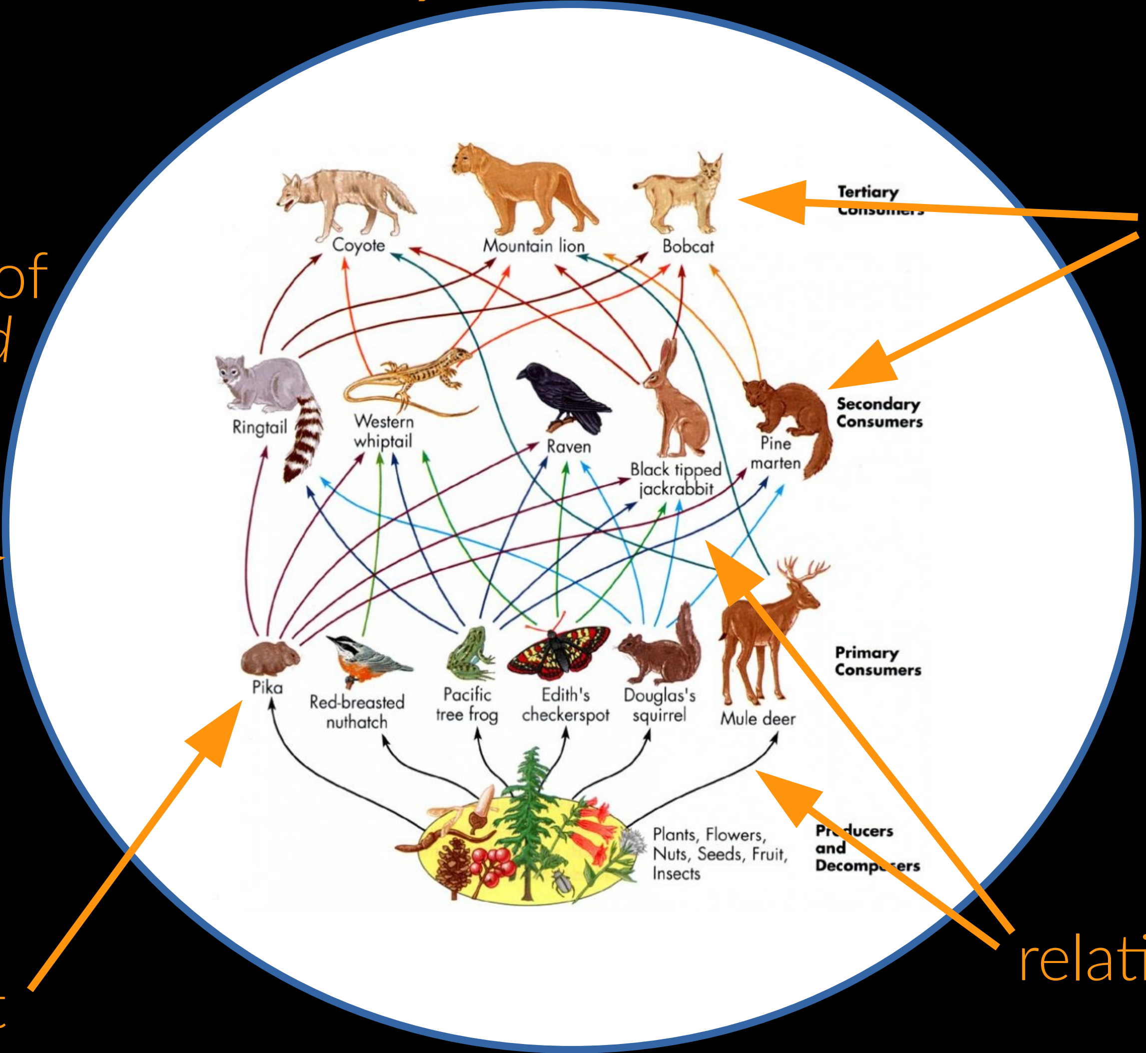


system

observer

What is a *system* ?

In systems thinking (Jordan 1981) :
a system is composed of identifiable entities *and their relationships*



entities

system

relationships

rodent

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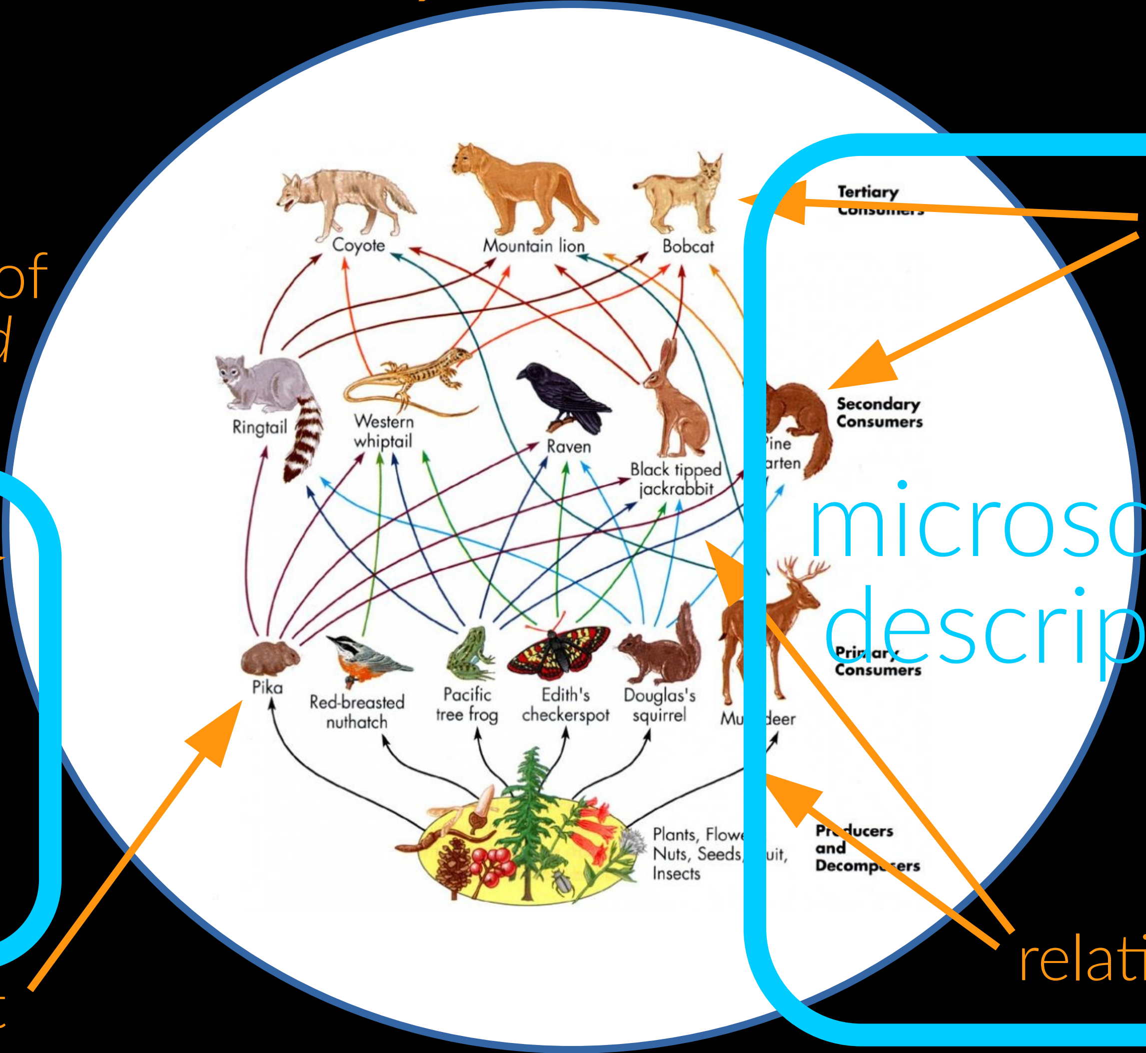


entities

microscopic description

relationships

system

macroscopic description

rodent

Hierarchical system = mathematical graph

A hierarchical system S is defined as the graph:

$$S := (C,\ R,\ \gamma)$$

where C is the set of **components** (nodes) of the system:

$$C := \{c_u\}\ u \leq n_c < \infty\ ,\ c_u \in \mathscr{W}$$

R is the set of **relations** (edges) between components of the system:

$$R := \{r_v\}\ v \leq n_r < \infty\ ,\ r_v \in \mathscr{W}^2$$

and γ is the incidence function, which assigns a relation to a pair of components:

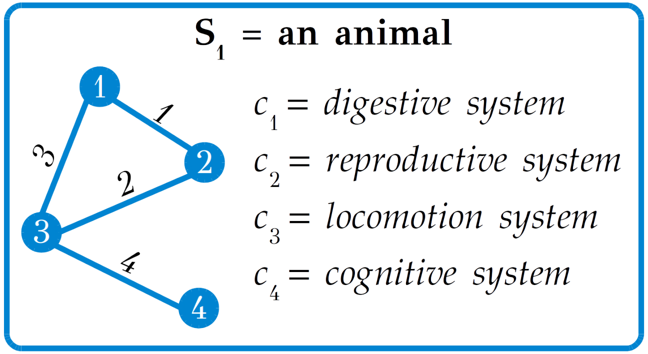
$$\gamma : R \rightarrow C \times C$$
$$r_v \rightarrow (c_i\ , c_j\ )\ i \leq n_c\ , j \leq n_c$$

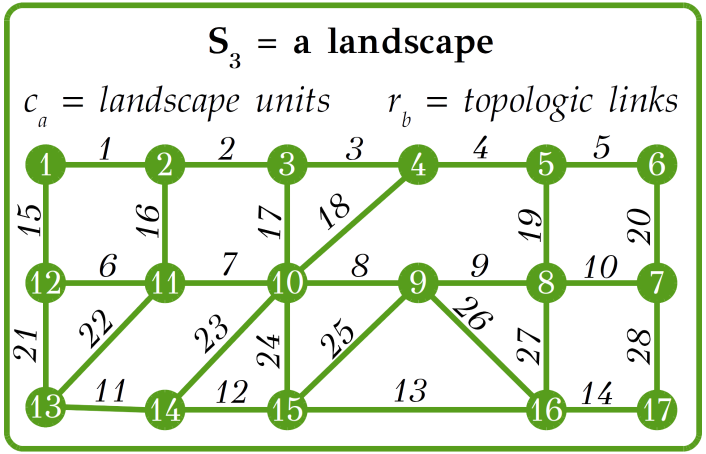
n_c is the number of components and n_r the number of relations of the system; $\mathscr{W}^2$ is the set of applications from $\mathscr{W}$ to $\mathscr{W}$.

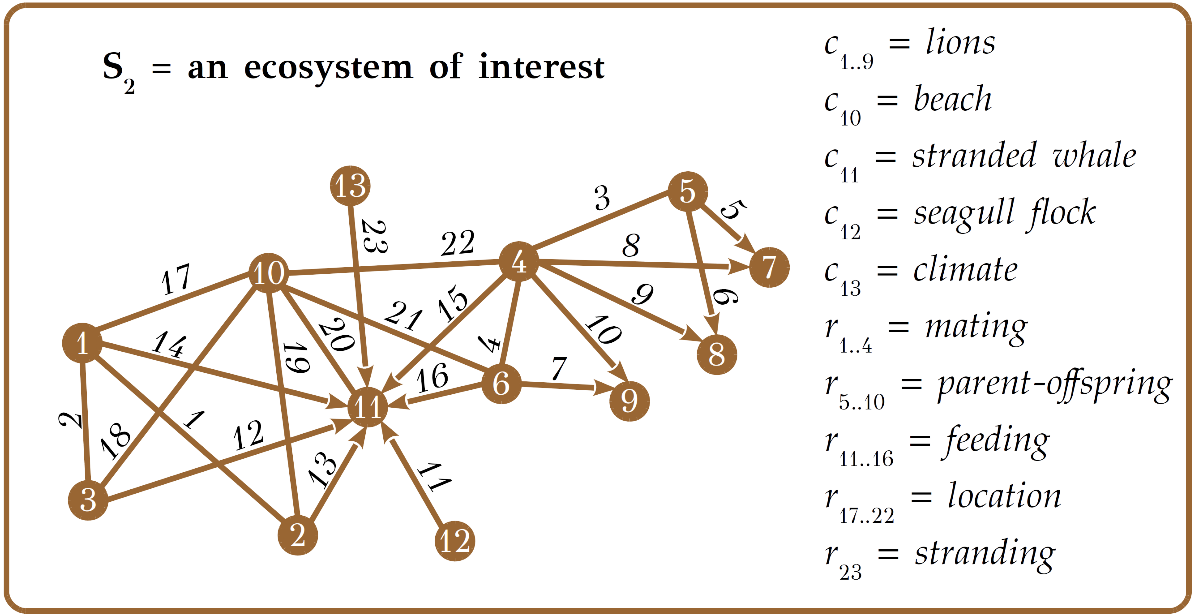
We make no assumption as to the type of graph used to represent S. It can be directed, undirected, a multigraph or any other kind of graph, hence the need for an explicit incidence function.

Gignoux et al. 2017. Ecological Complexity 31:34-49

Examples

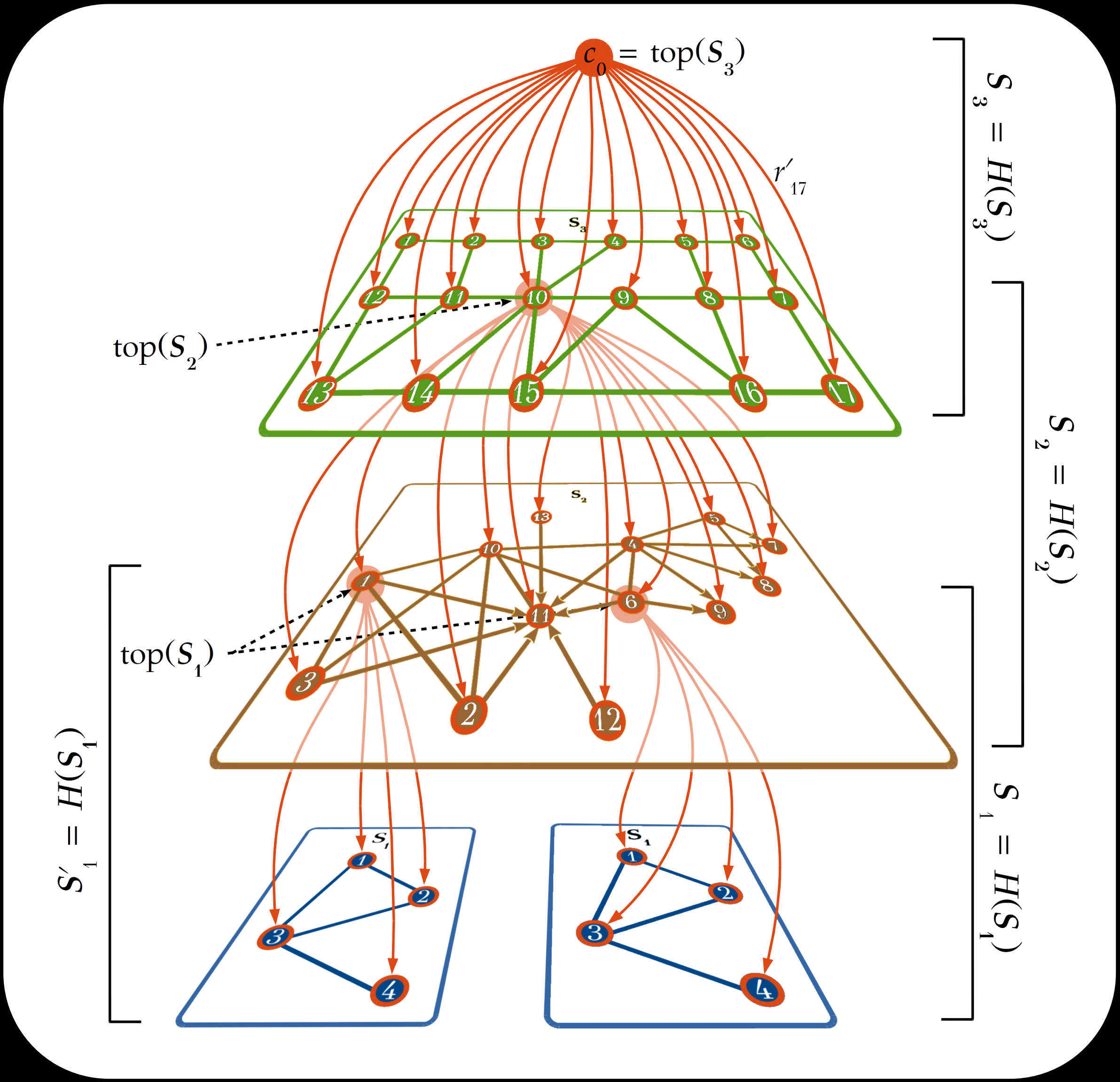






These representations are totally ***observer-dependent***

Where is the hierarchy ?



Observer's point of view:

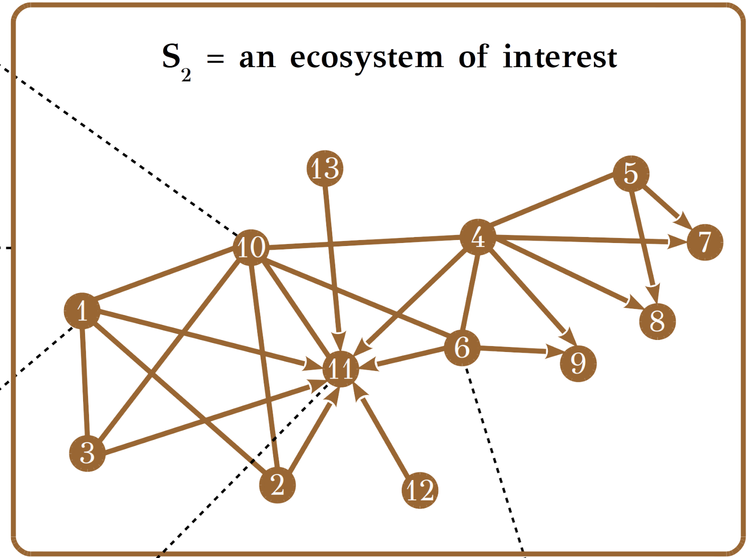
descriptions & descriptors

D_{10}

label	***beach***
surface	$s \in]0;+\infty[$
location	$M_b = (L,l) \in [0;90] \times [-180;180]$

D_S

label	***The Namib desert ecosystem***
location	$M_b = (L,l) \in [0;90] \times [-180;180]$
productivity	$P \in]0;+\infty[$
biomass	$w \in]0;+\infty[$
monthly rainfall	$p = (p_i)_{i \leq 12}, p_i \in \mathbb{R}^+$
photo	



D_1

label	***lion No.1***
biomass	$w \in]0;+\infty[$
sex	$s \in \{m, f\}$
age	$a \in \mathbb{N}$
location	$M = (x,y) \in \mathbb{R}^2$
mating probability	$p \in [0;1]$
photo	

D_{11}

label	***whale***
biomass	$w \in]0;+\infty[$
edible fraction	$\alpha \in [0;1]$
decay rate	$t_d \in \mathbb{R}^+$
location	$M = (x,y) \in \mathbb{R}^2$
photo	

D_6

label	***lion No.6***
biomass	$w \in]0;+\infty[$
sex	$s \in \{m, f\}$
age	$a \in \mathbb{N}$
location	$M = (x,y) \in \mathbb{R}^2$
mating probability	$p \in [0;1]$
photo	

1. Ecosystems are commonly considered as *complex systems*

2. Complex systems are assumed to display *emergent properties*

3. There are dozens of definitions of emergence (Chérel G. 2013, PhD)

4. This because they do not clearly define the system

5. All emergence definitions imply a system with a *microscopic* and a *macroscopic* level of description

6. With a formal definition of the system, we may be able to clearly define emergence.

Gignoux et al. 2017. Ecological Complexity 31:34-49

IV. Emergence in ‘practice’

A first taste of emergence

Surprise of the observer in front of unexpected results :

1. discovery

1. an observer $\mathcal{O}$ of a system S expects the system dynamics to match some predefined pattern, i.e. a particular time series of states $\theta = (\Omega(t),\ \omega_m(t))\ t < \infty$, where m denotes the method chosen by the observer to generate the micro-states, according to some previous knowledge;

2. $\mathcal{O}$ chooses system and element descriptions D_S and $(D_{mw})w{\le}n_e$ assumed to appropriately describe the system in order for its dynamics to display the pattern;

3. using some measurement or computation technique, $\mathcal{O}$ generates a realised dynamic series of system states $\hat{\theta} = (\hat{\Omega}\ (t)\ ,\ \hat{\omega}_m\ (t))t < \infty$

4. $\mathcal{O}$ uses an error function $\varphi(\theta,\ \hat{\theta})$ to compute a distance between the realised system dynamics and the expected pattern;

5. based on some tolerance threshold τ , $\mathcal{O}$ then decides that the realised dynamics does not match the expected pattern when $\varphi(\theta,\ \hat{\theta}) > \tau \geq 0$. We call this event *the observer surprise in front of unexpected results*;

6. Using another set of descriptions $\{D_S{}',\ (D_{mw}{}')\ w{\le}n_e\}$, and repeating steps 3-4, we call discovery of a better description of the system the fact that $\varphi(\theta',\ \hat{\theta}') < \varphi(\theta,\ \hat{\theta})$;

7. Furthermore, when $\varphi(\theta',\ \hat{\theta}') < \varphi(\theta,\ \hat{\theta})$ but $\varphi(\theta',\ \hat{\theta}') > \tau \geq 0$, the discovery is incomplete as there is a possibility to further improve system description beyond the current improvement.

A better description of the system than the expected one is found

How to define macroscopic and microscopic descriptions of the system ?

system component or relation ——— descriptor ——— **state** = values for the descriptor variables

↑

measurement

How do we take the measurements ?

Biomass W : easy
Position (x,y) : easy
Number of neighbours : uh ?
Social rank : ... ?
Population viscosity : ???

How to define macroscopic and microscopic descriptions of the system ?

system component or relation —— descriptor —— **state** = values for the descriptor variables

↑ *measurement*

The ***state*** of a component/relation may depend on neighbour c./r.

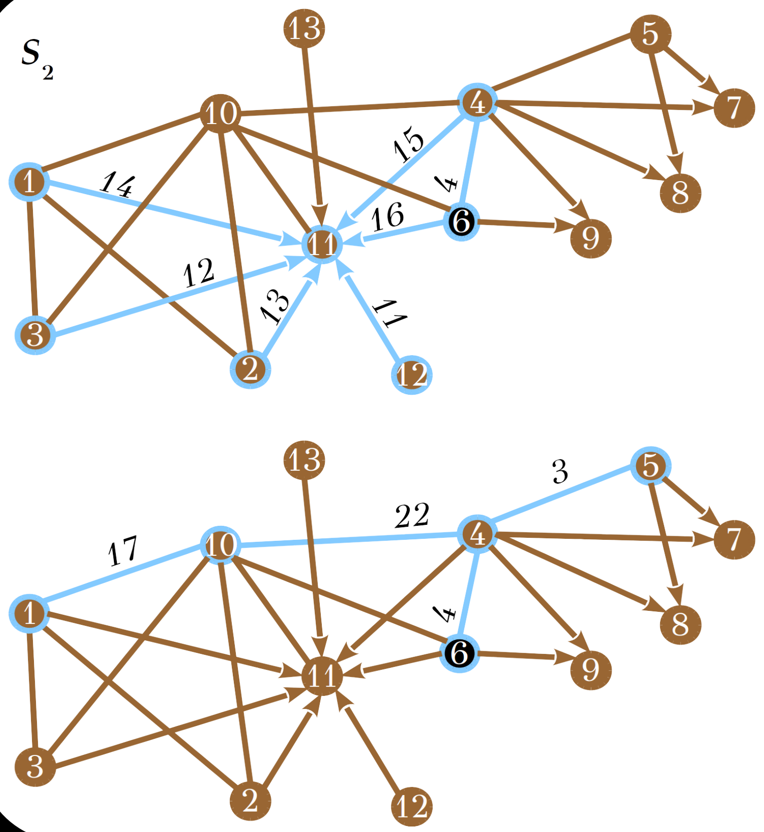
How do we take the measurements ?

Biomass W : easy
Position (x,y) : easy
Number of neighbours : uh ?
Social rank : ... ?
Population viscosity : ???

How to define macroscopic and microscopic descriptions of the system ?

The micro-state:

Measurements are taken on a ***focal element*** relative to a ***local context***, i.e. a subgraph of the system



$l_{2_{1,6}}(c_6) = (C_6 = \{c_6, c_1, c_3, c_2, c_4, c_{12}, c_{11}\},$

$R_6 = \{r_4, r_{11}, r_{12}, r_{13}, r_{14}, r_{15}, r_{16}\},$

$\gamma_6(r_4) = (c_4, c_6)$

$\gamma_6(r_{11}) = (c_{12}, c_{11})$

...)

$l_{6_{1,6}}(c_6) = (C_6 = \{c_6, c_4, c_5, c_{10}, c_1\},$

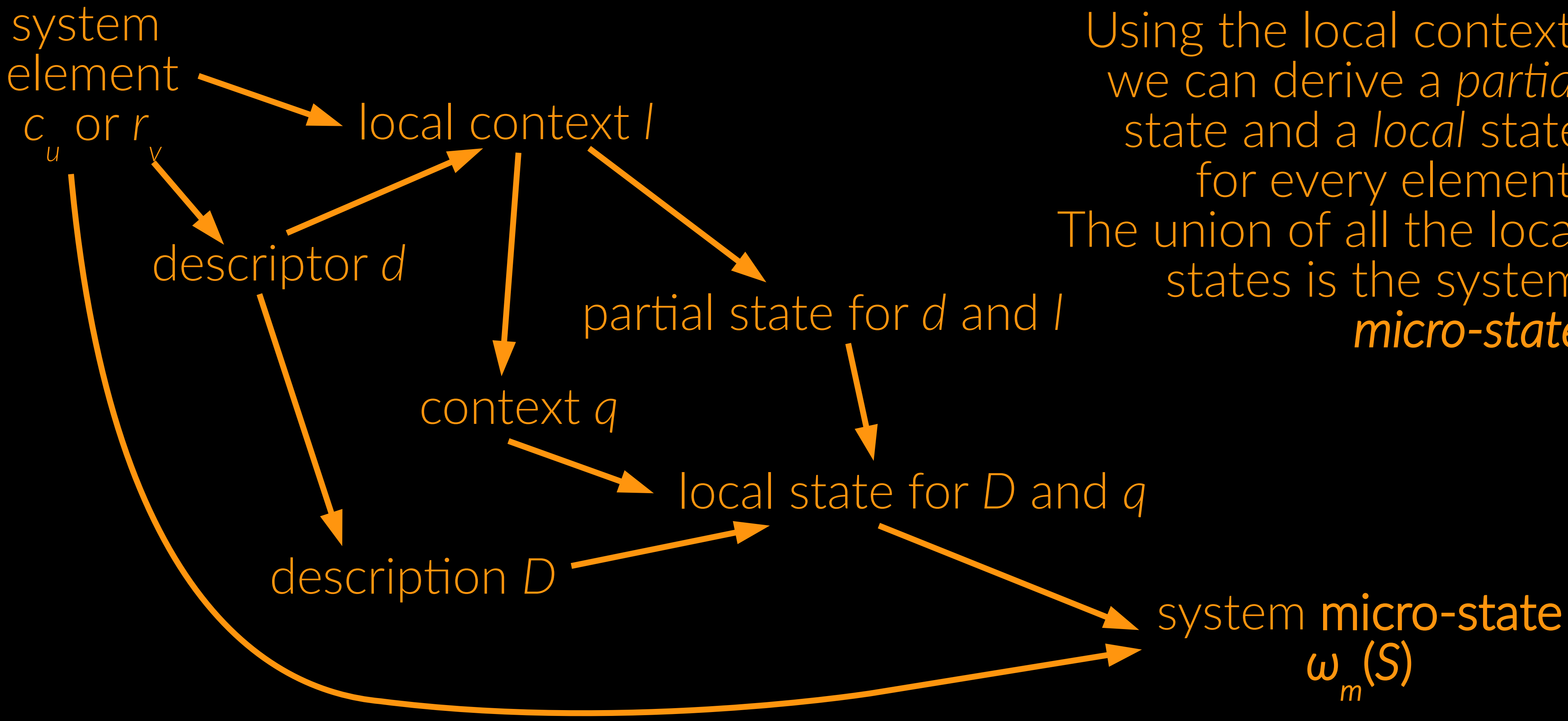
$R_6 = \{r_3, r_4, r_{22}, r_{17}\},$

$\gamma_6(r_3) = (c_4, c_5)$

$\gamma_6(r_4) = (c_4, c_6)$

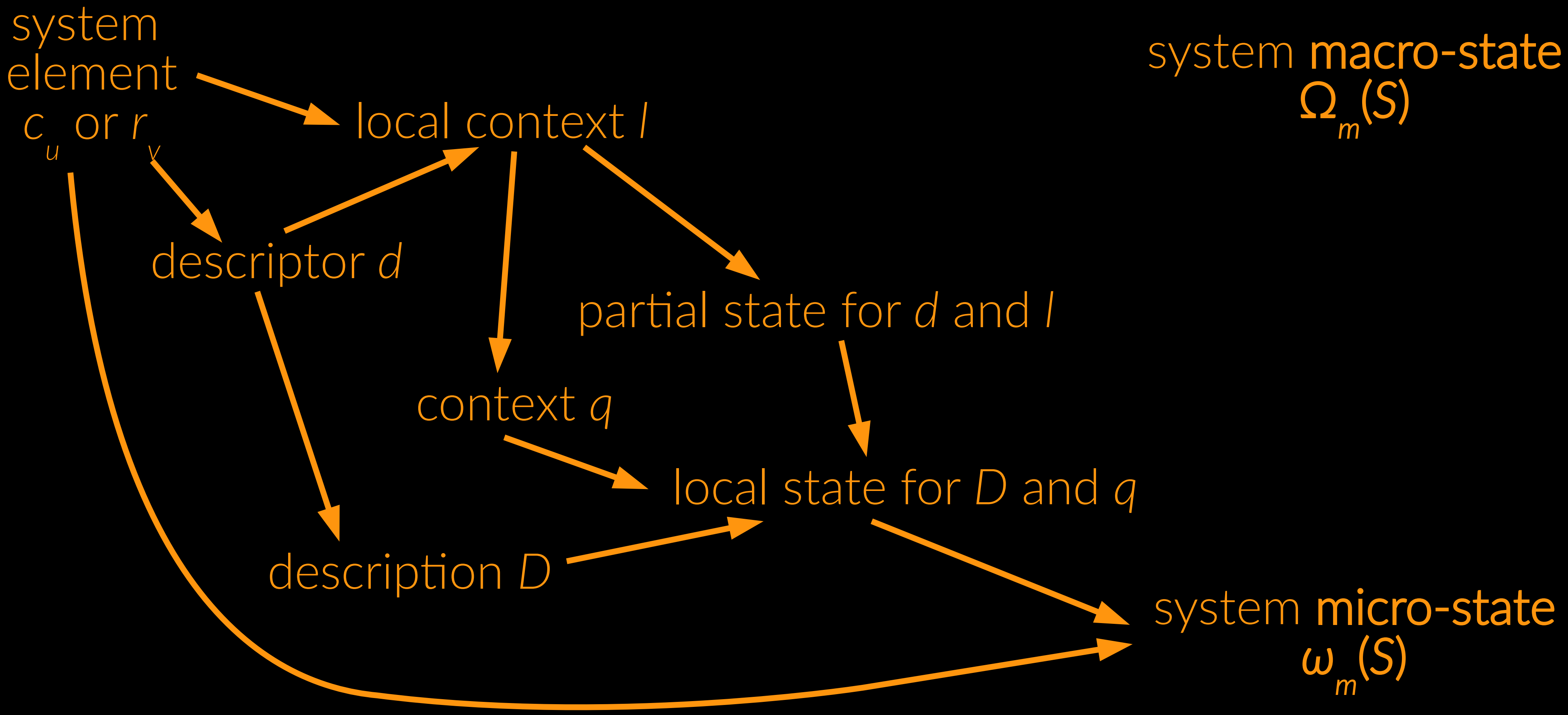
...)

How to define macroscopic and microscopic descriptions of the system ?



Using the local context, we can derive a *partial* state and a *local* state for every element. The union of all the local states is the system ***micro-state***

How to define macroscopic and microscopic descriptions of the system ?



Back to emergence

Emergence due to ignoring relations (no local context):

2. trivial emergence

System *integration* :

$$\mathcal{I}_m(S) = \mathrm{dist}(\ \omega_0(S) - \omega_m(S)\ )$$

$\mathcal{I}_m(S) > 0$ Trivial emergence

system **macro-state**
$\Omega_m(S)$

system **micro-state**
$\omega_0(S)$

Back to emergence

Emergence due to ***computational irreducibility*** (Zwirn & Delahaye 2013) between macro and micro state :

3. weak emergence

only f_s exists and is c.irr.

4. context dependent emergence

f_m exists and is c.irr.

system **macro-state**
$\Omega_m(S)$

upscaling function f_m

system **micro-state**
$\omega_m(S)$

Back to emergence

Emergence due to *comput*
irreducibility (Zwirn & Dela
between macro and micro

3. weak emergence

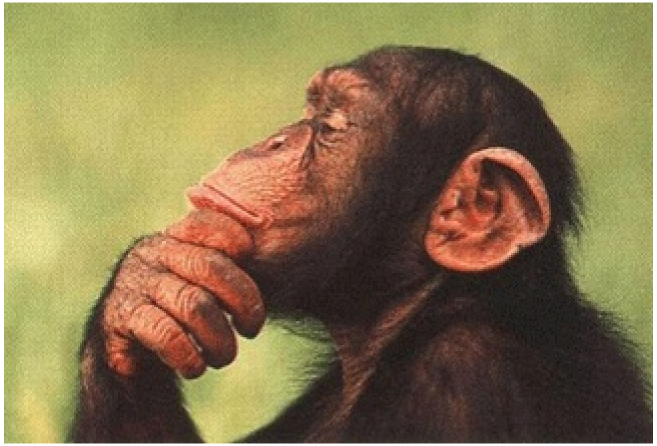
only f_s exists and is

4. context dependent e

f_m exists and is c.ir

Ook. Ook ? Ook ? Ook ! ...

...sorry :
But what happens if
f_m does ***not*** exist ?



macro-state
$\Omega_m(S)$

scaling
nction f_m

micro-state
$\omega_m(S)$

Back to emergence

There is *no way* to compute the macro-state from the micro-state.
This is called ***strong emergence.***
It means there is a god in the system preventing us from understanding it even if we know all its components and relations

Bedau (2003) : Strong emergence starts where scientific explanation ends.

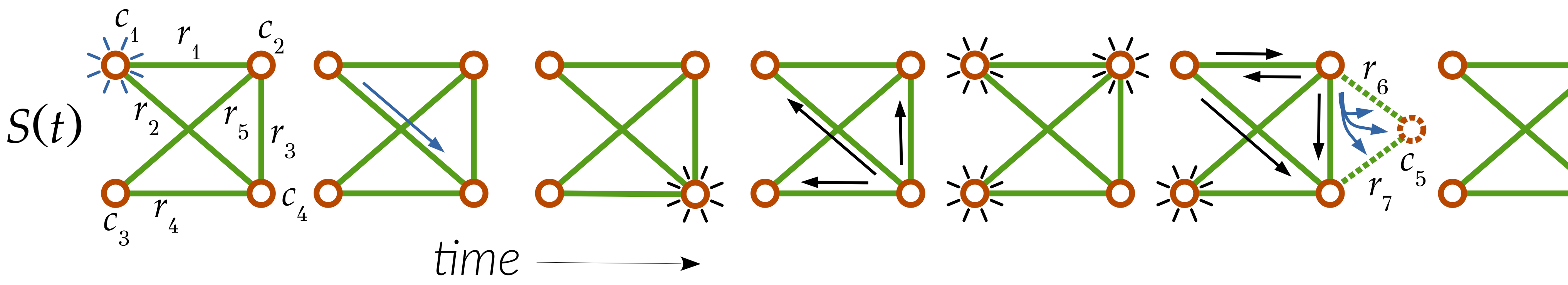
In a scientific world, ***every hierarchical system has an upscaling function***.

Dynamics

OK. Now the graph is going to change with time !

We define

- state changes (in $\omega_m(S)$ and $\Omega_m(S)$)
- structural changes



Dynamics

Two principles :

- *locality of causes* : changes propagate following the network otherwise it's useless to use a graph to represent a system

- *apparent causality* : time grain defines causality otherwise nothing can be said about causality

Causality is at the centre of emergence definitions ('downard and upward causation', 'new causal powers', etc.)

Dynamics

A result (Cybernetics, Ulanowicz, etc.) :

feedback loops disrupt the linear chain of causality by having an effect acting back upon its cause. They can make a system *autonomous* from its environment

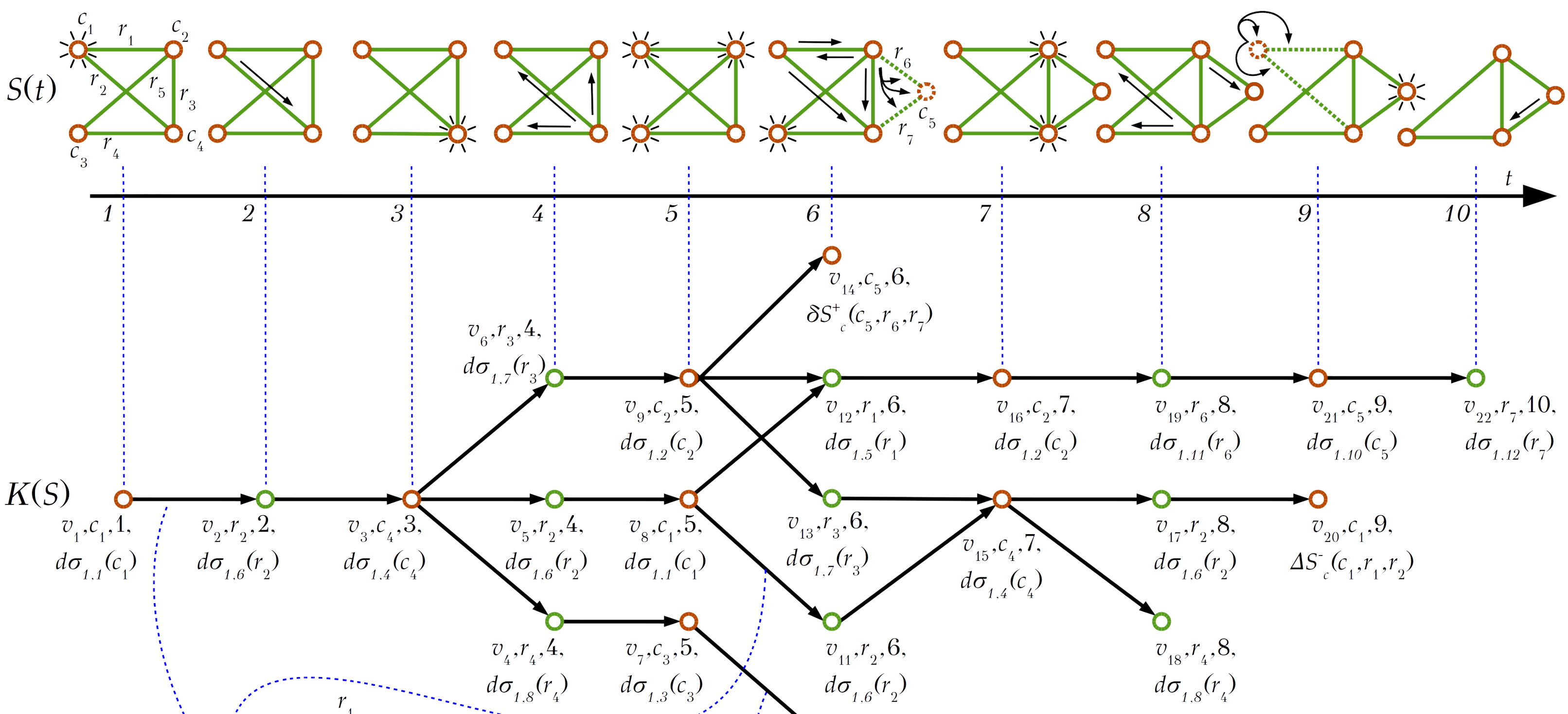
Bedau (1997) : the two hallmarks of emergence

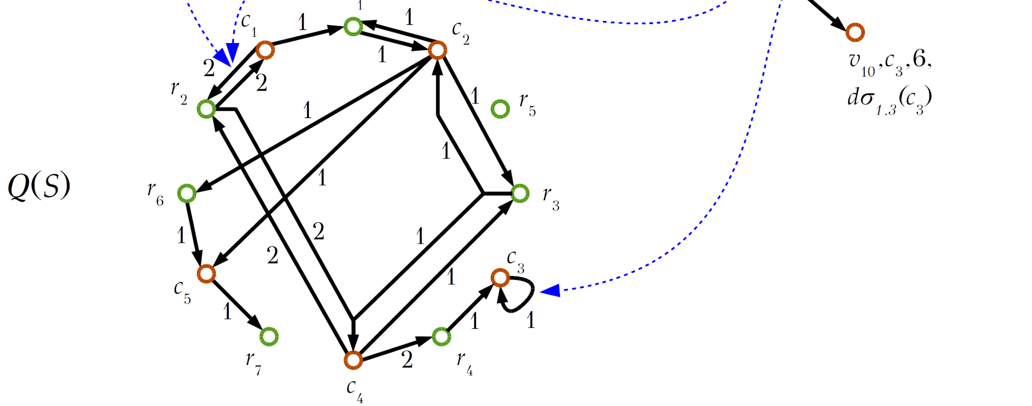
(1) Emergent phenomena are somehow constituted by, and generated from, underlying processes;
(2) Emergent phenomena are somehow autonomous from underlying processes.

Can we track and display causal pathways in a dynamics ?

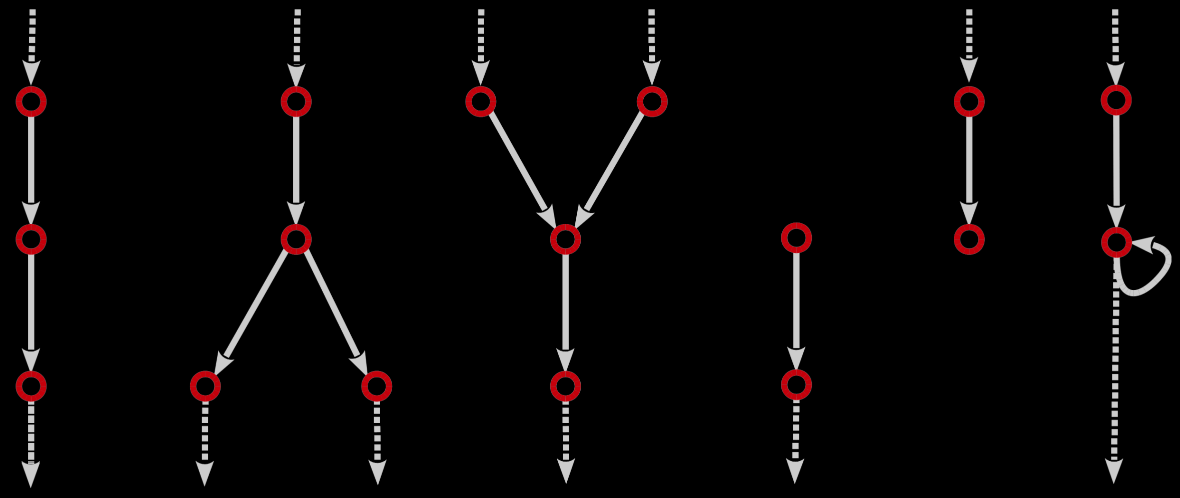
Dynamics

Extracting complex causal trajectories from system dynamics





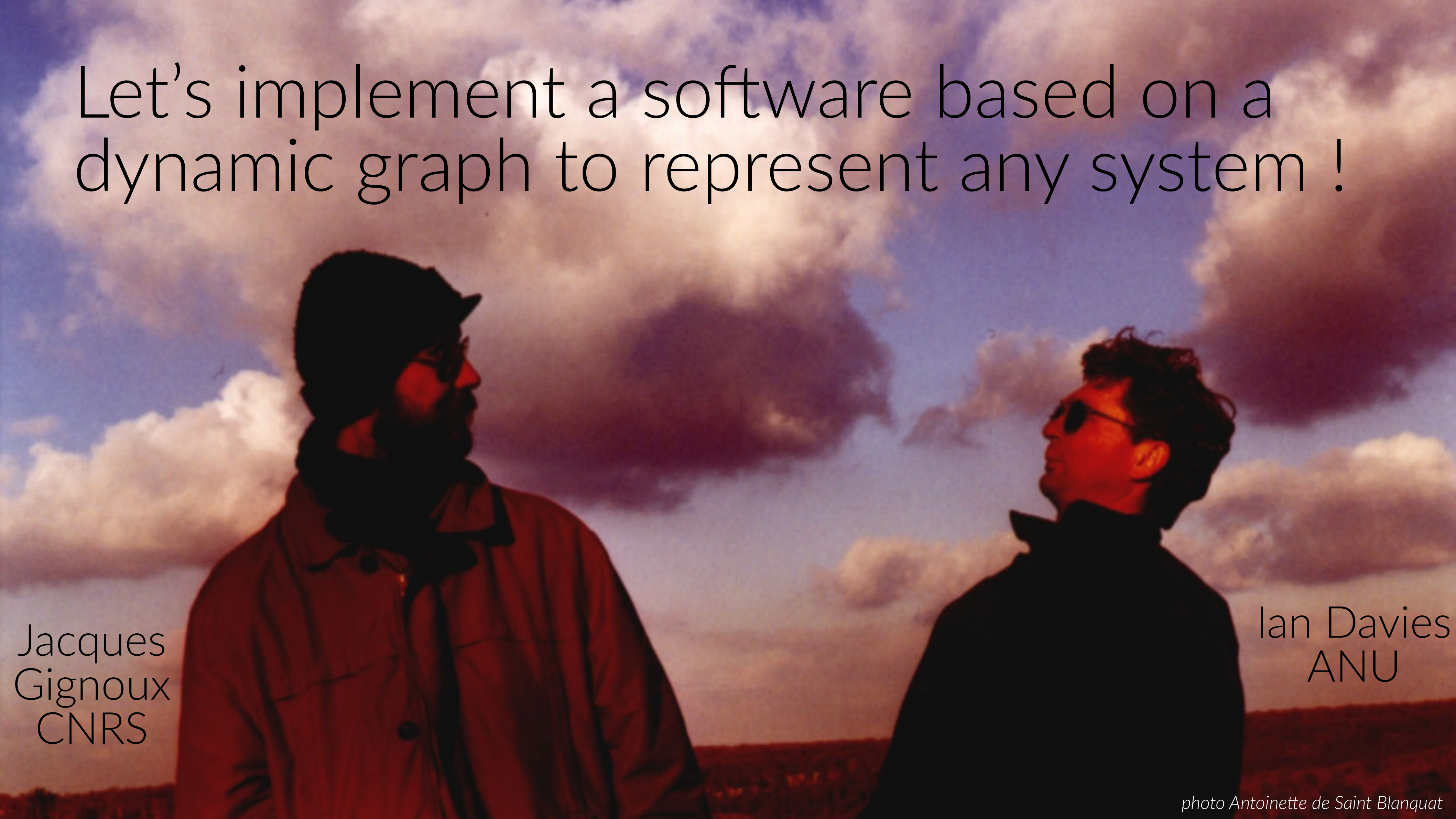
Back to emergence, again



5. Ontological emergence.

1. A hierarchical dynamic system S has ontologically emergent properties when its causal network $Q(S)$ is not a walk, or equivalently, contains loops.

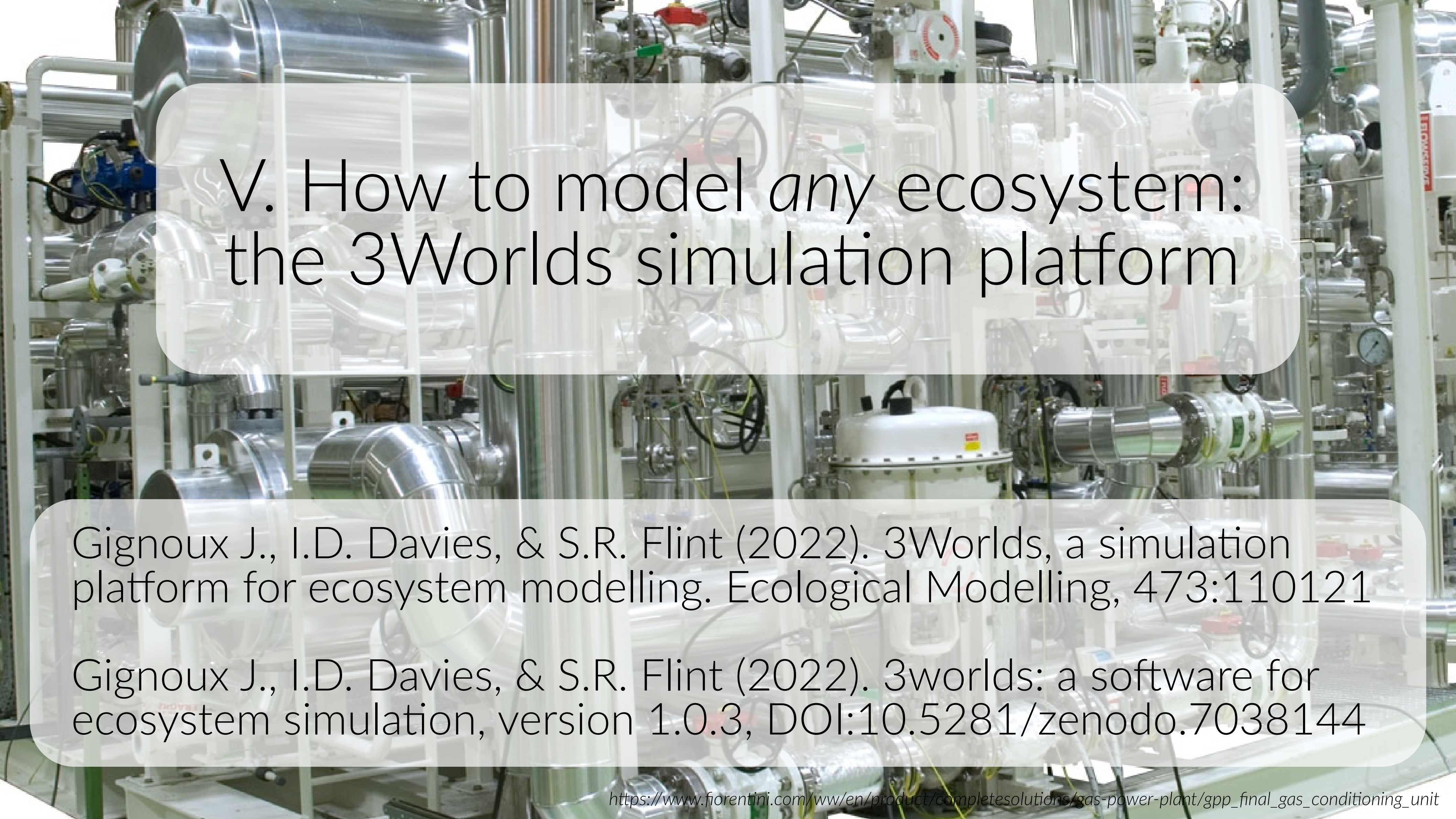
2. The presence of particular causal structures (types 2-6) in the causal network $Q(S)$ of a hierarchical dynamic system S disrupts linear causality.


Let's implement a software based on a dynamic graph to represent any system !
Jacques Gignoux CNRS
Ian Davies ANU
photo Antoinette de Saint Blanquat

V. How to model *any* ecosystem: the 3Worlds simulation platform

Gignoux J., I.D. Davies, & S.R. Flint (2022). 3Worlds, a simulation platform for ecosystem modelling. Ecological Modelling, 473:110121

Gignoux J., I.D. Davies, & S.R. Flint (2022). 3worlds: a software for ecosystem simulation, version 1.0.3, DOI:10.5281/zenodo.7038144



https://www.fiorentini.com/ww/en/product/completesolutions/gas-power-plant/gpp_final_gas_conditioning_unit

Thank you for your attention

Ook.