INSTITUTE OF ECOLOGY AND ENVIRONMENTAL SCIENCES OF PARIS

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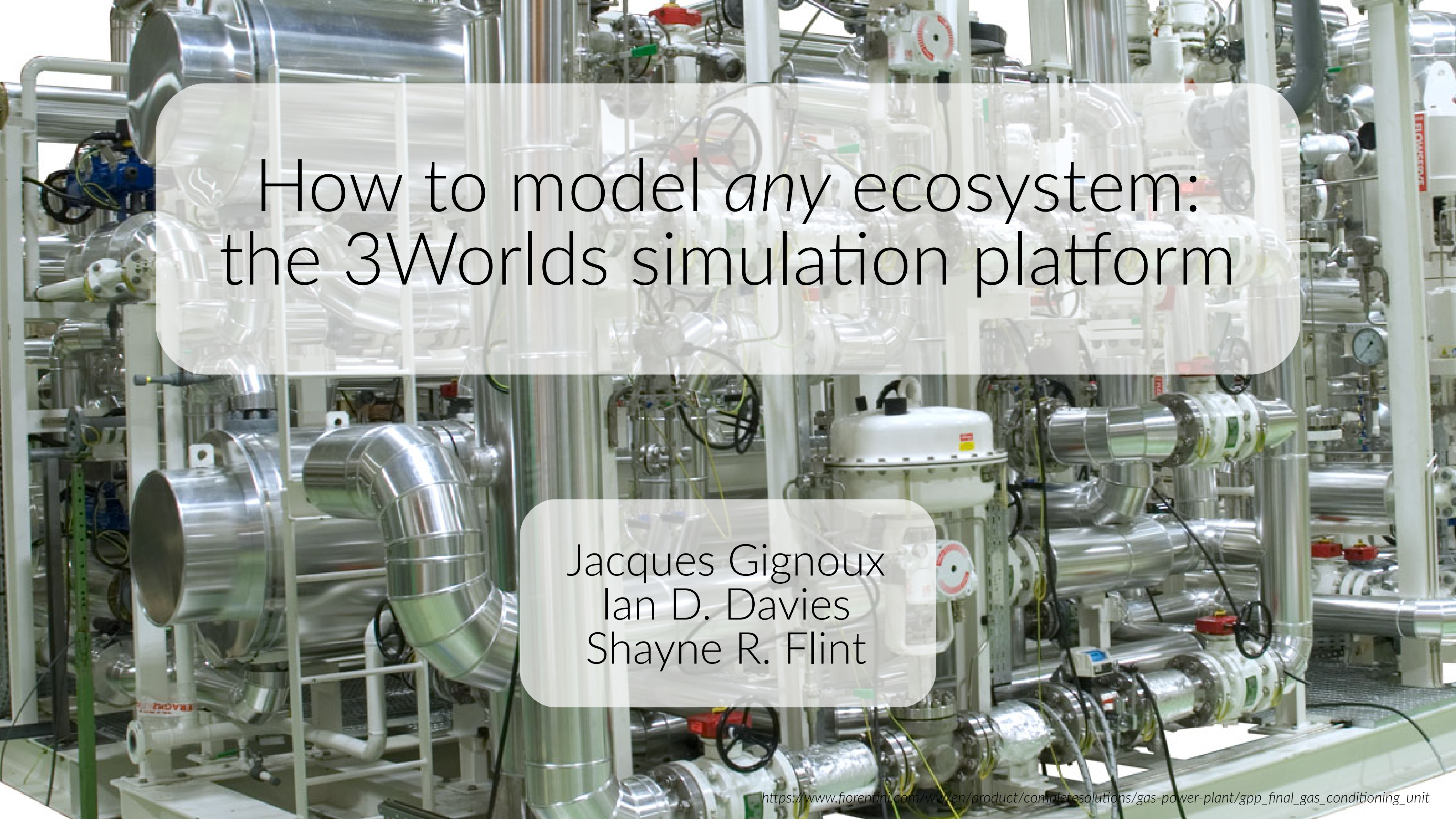
+

NATURAM PRIMUM COGNOSCERE RERUM

Australian National University



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

Jacques Gignoux
Ian D. Davies
Shayne R. Flint

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

Three difficulties of Ecology

Ecology:

- studies very different objects
- addresses very difficult questions
- uses many different methods

Ecology looks at incredibly different objects

...and pretends to have a method

photo Michel de Saint Blanquat


photo Jacques Gignoux


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

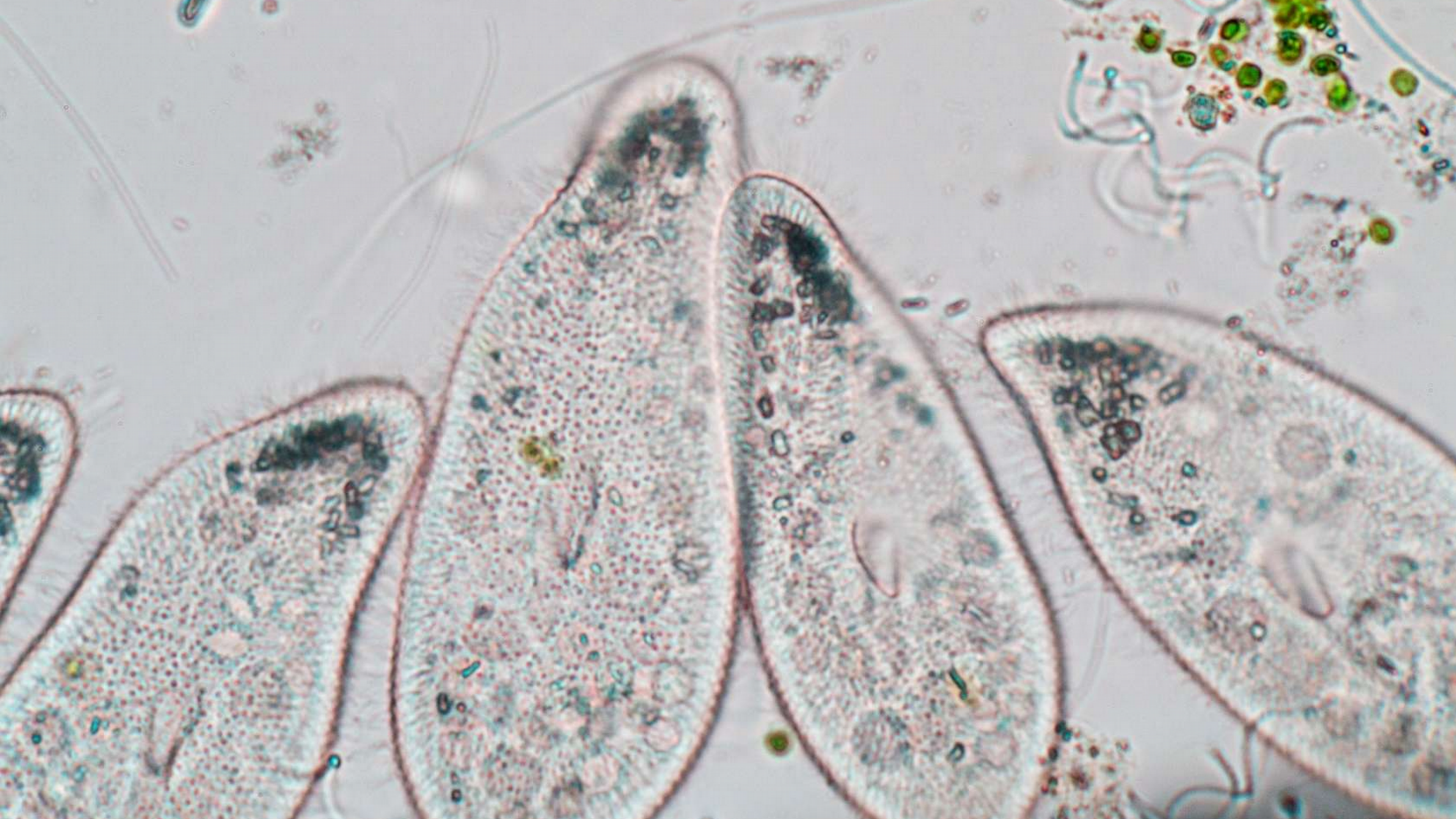
photo Jacques Gignoux

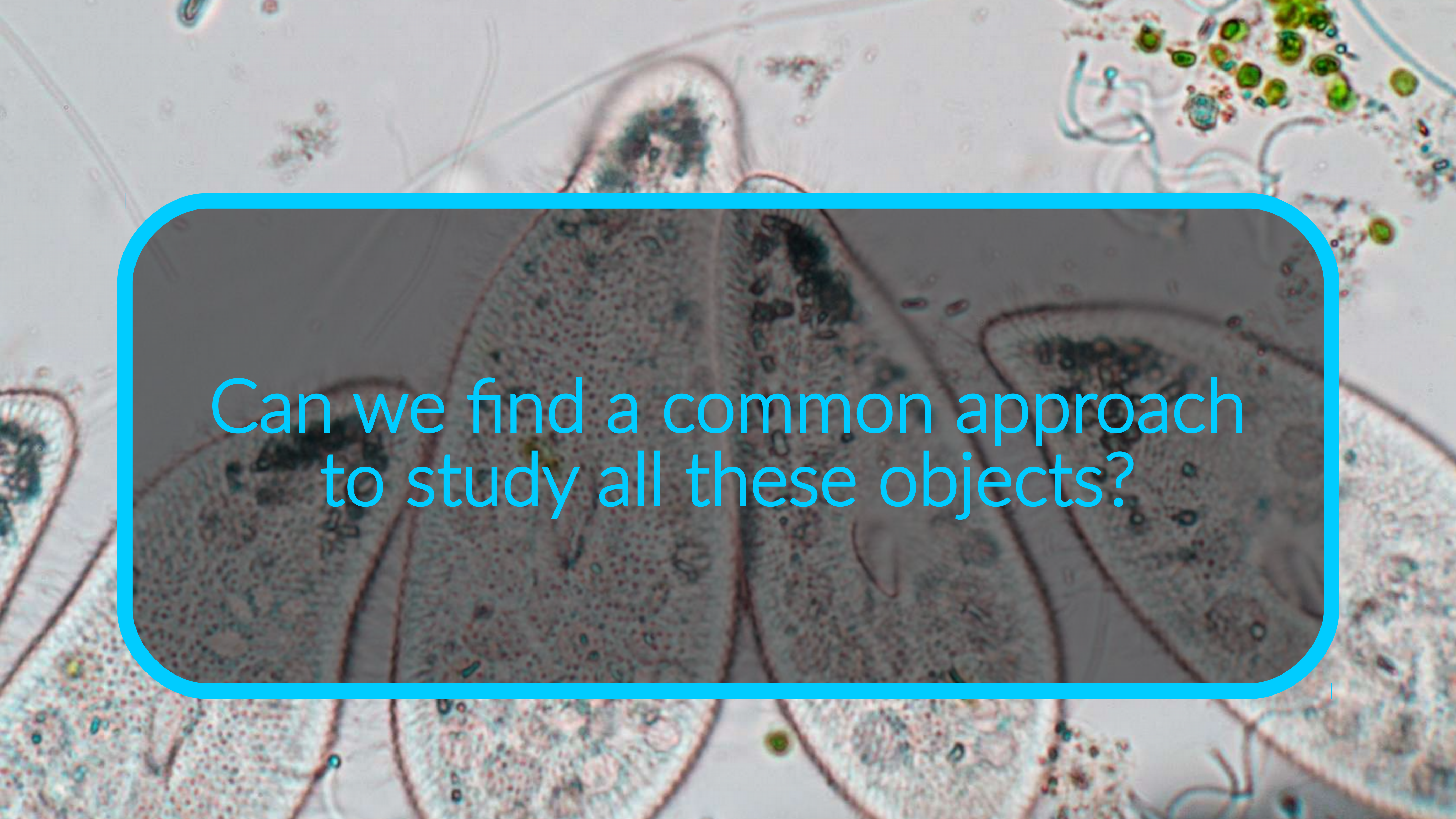
https://www.science-et-vie.com/questions-reponses/d-ou-viennent-les-fumeurs-noirs-9787

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

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

NASA AS17-148-22727




Can we find a common approach
to study all these objects?

Ecology addresses *difficult* questions:

Ecology addresses *difficult* questions:

climate change

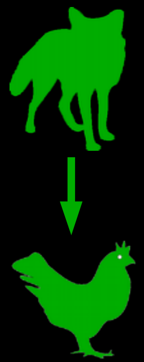
CO_2 flux $\xrightarrow{?}$ biodiversity

Ecology addresses *difficult* questions:

climate change

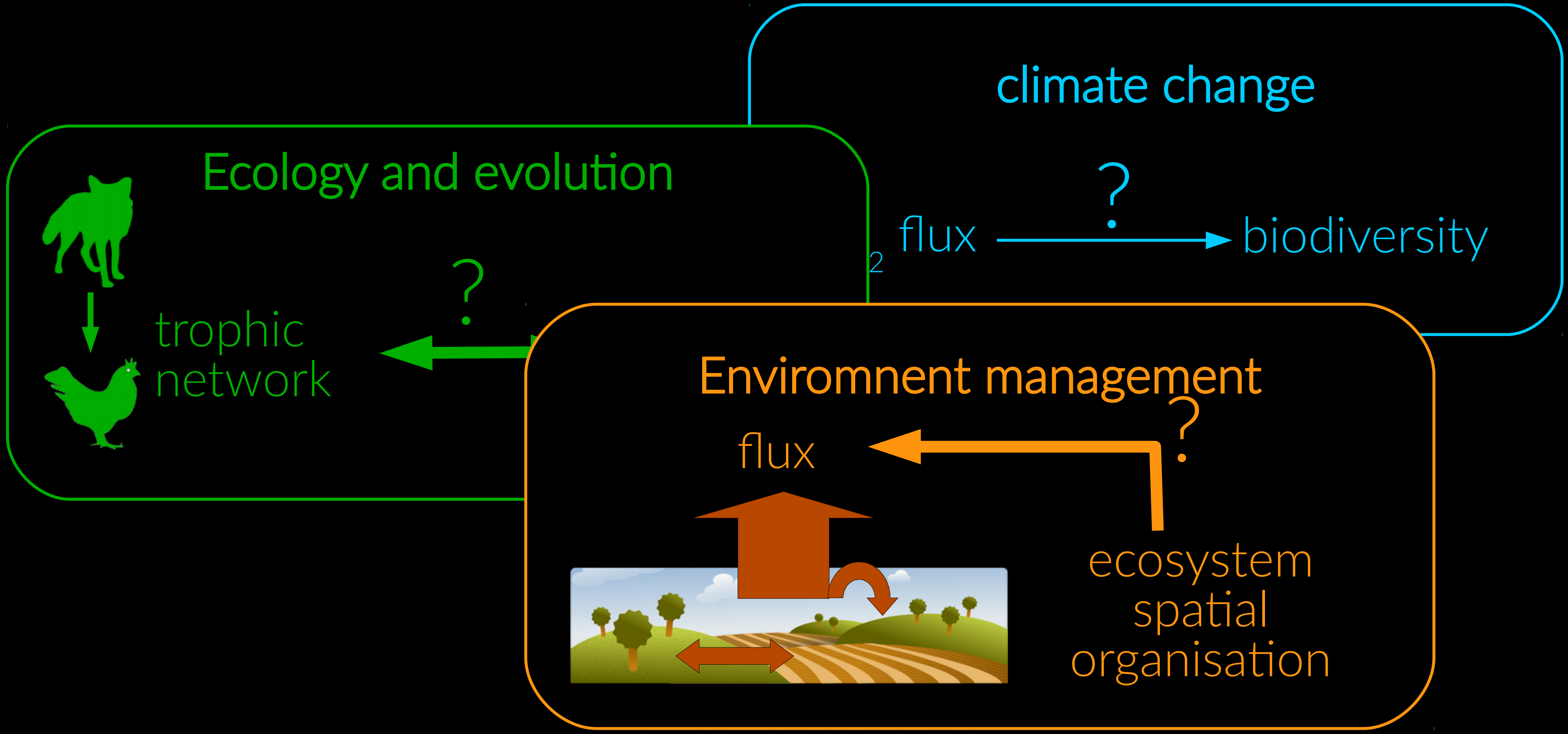
$_2$ flux → ? → biodiversity

Ecology and evolution

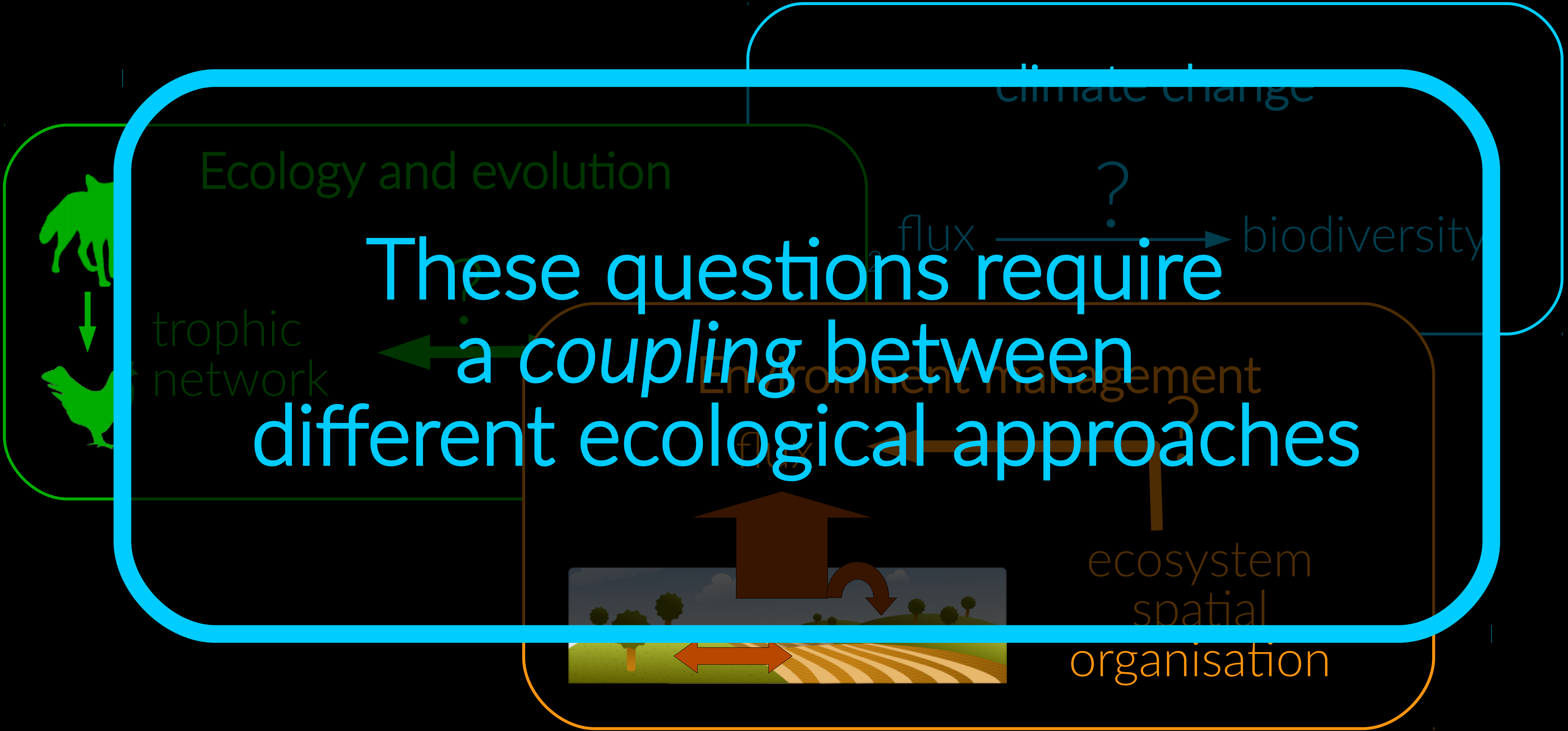


trophic network ⟷ ? ⟷ population dynamics

Ecology addresses *difficult* questions:



Ecology addresses *difficult* questions:



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
chinese astrology
demography
hydrology
physiology
relativity
ecology
[bio][geo]chemistry
evolution
beerology
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

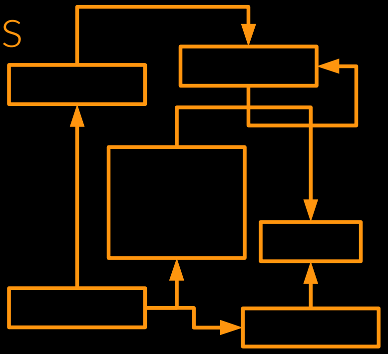
… borrowing methods from other sciences

Ecological sub-fields use poorly compatible representations:

Matter and energy fluxes
Ecophysiology
Ecosystems

↓

Dynamic systems



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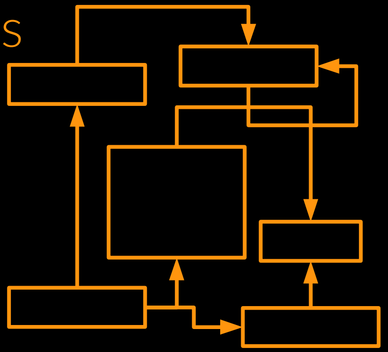

Dynamic systems

Demography
Genetics
Evolution

Population models
Individual-based models

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Matter and energy fluxes
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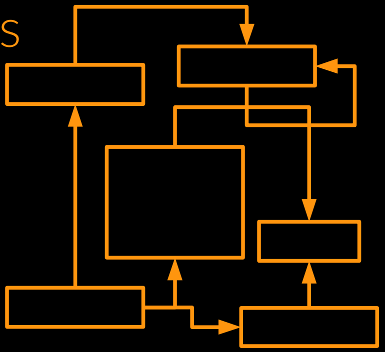
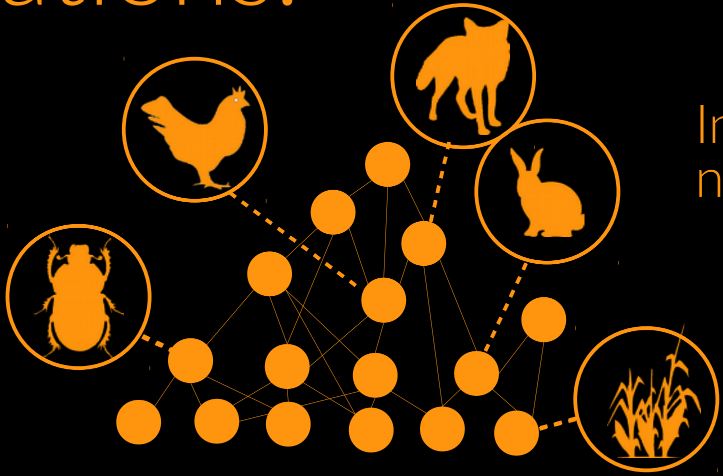
Ecosystems

Dynamic systems





Interaction networks

Graphs

Demography
Genetics
Evolution

Population models
Individual-based models

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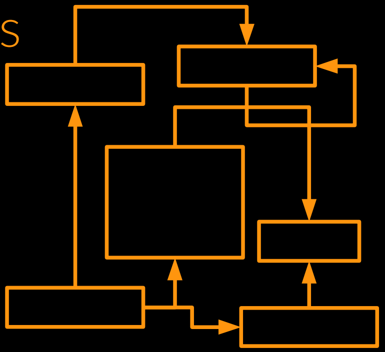
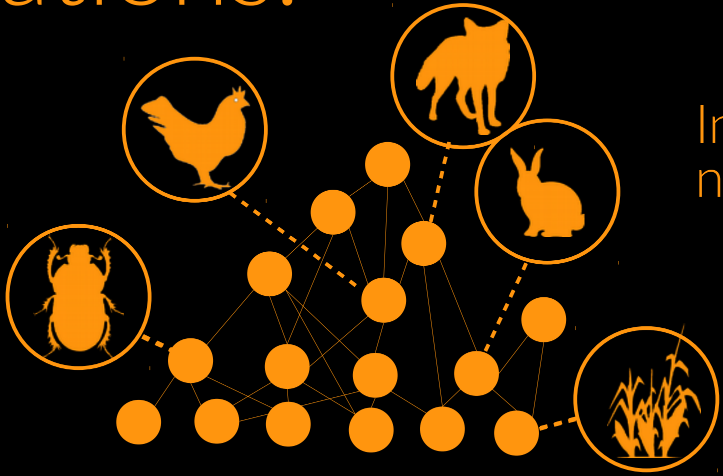
↓

Dynamic systems





Interaction networks

↓

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Demography
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↓

Population models
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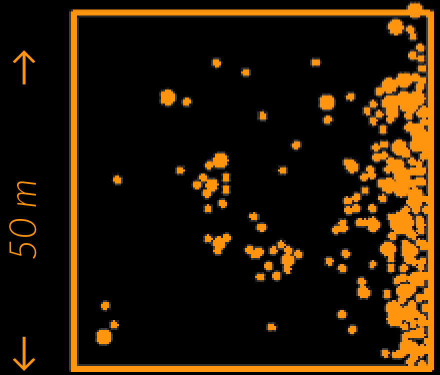

Landscape ecology
Ecosystem structure

↓

Cellular automata

Ecological sub-fields use poorly compatible representations:

How can we make these work together?

I. The solution to the diversity of objects

The *ecosystem* concept (Tansley, 1935)

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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Ecosystems

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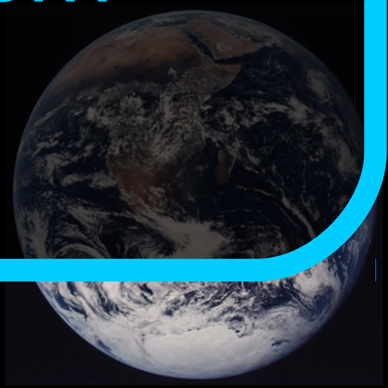
- are scale-independent
- are observer-dependent

Ecology consists in viewing *everything* as an ecosystem



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

somewhere on the internet


or this:
somewhere else on the internet

II. The solution to the difficulty of questions

We don’t care!

That’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.**

Systems thinking

Shayne Flint

Australian National University

https://thesystemsthinker.com/systems-thinking-what-why-when-where-and-how/

Problems that are ideal for a systems thinking intervention have the following characteristics:

- The issue is important.
- The problem is chronic, not a one-time event.
- The problem is familiar and has a known history.
- People have unsuccessfully tried to solve the problem before.

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

III. The solution to the incompatibility of methods

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

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:

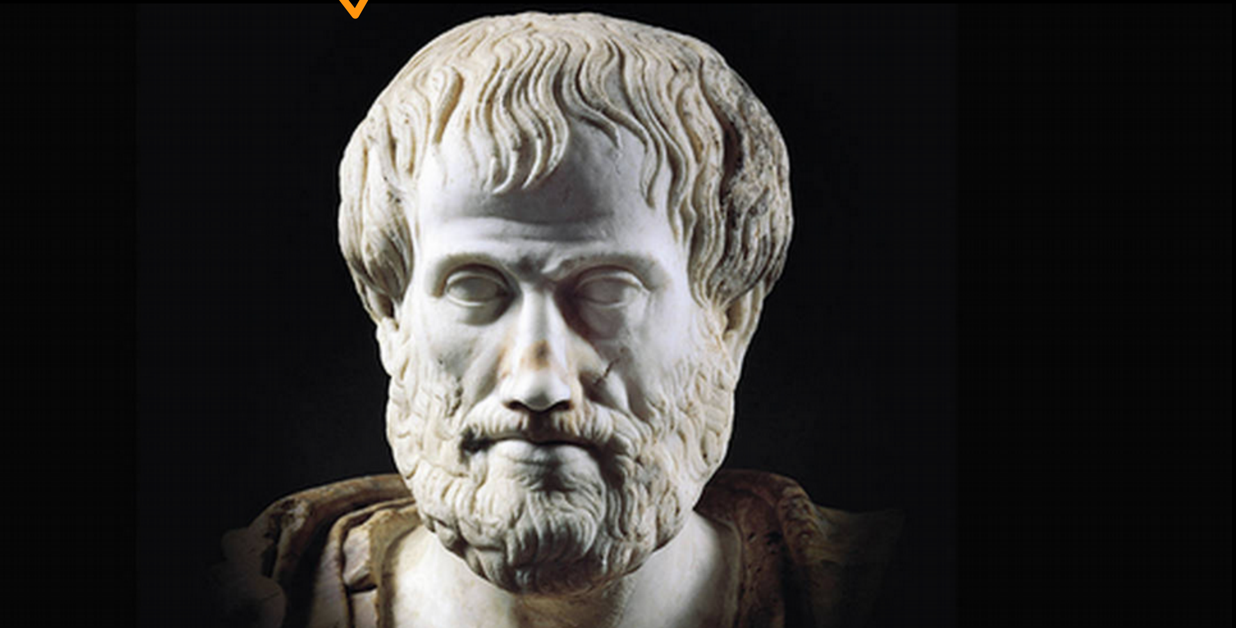
The whole is more than the sum of its parts

Αριστοτέλης (-335)

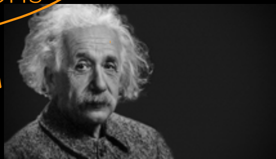
Not much:

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]

1. Ecosystems are commonly considered as *complex systems*

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

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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

The hierarchical system

A **system** is
- a part of the world under consideration (Carnot 1824)
- composed of identifiable entities *and their relationships* (Jordan 1981)

All emergence definitions imply that a system has a *microscopic* and a *macroscopic* description

Let's call **Hierarchical System** a system ('macro'-scale) made of inter-related parts ('micro'-scale)

'Hand with reflecting sphere'
lithograph by M.C. Escher

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

A hierarchical system is best represented by a mathematical graph

A hierarchical system S is defined as the graph:

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

where $\boldsymbol{C}$ is the set of components (nodes) of the system:

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

$\boldsymbol{R}$ is the set of relations (edges) between components of the system:

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

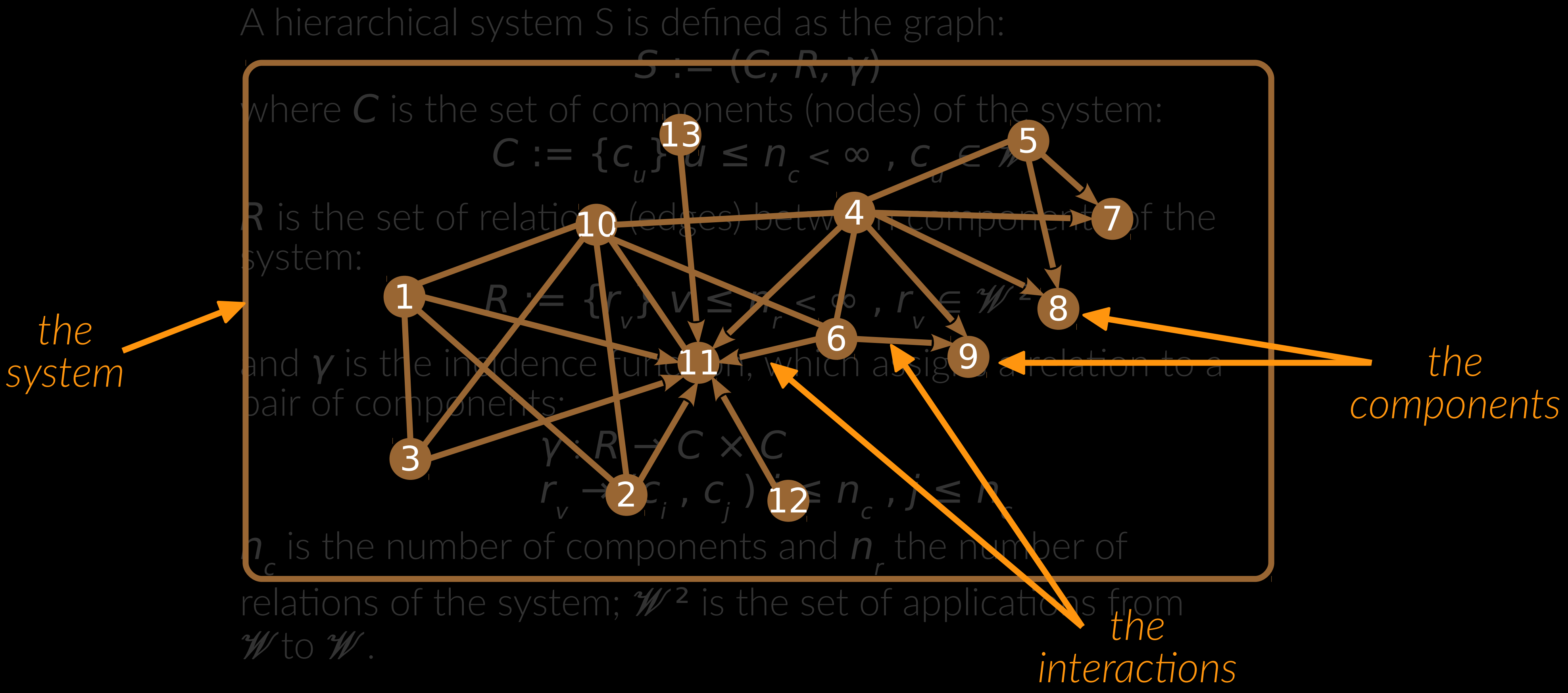
and $\boldsymbol{\gamma}$ is the incidence function, which assigns a relation to a pair of components:

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

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

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

A hierarchical system is best represented by a mathematical graph



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

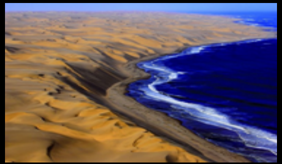
A hierarchical system is best represented by a mathematical graph

state = descriptors

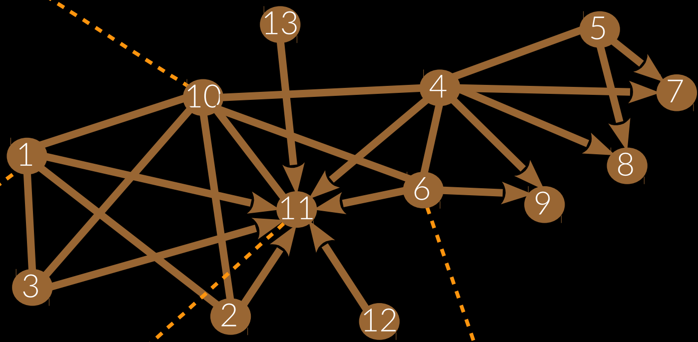
structure = graph

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



S_2 = an ecosystem of interest



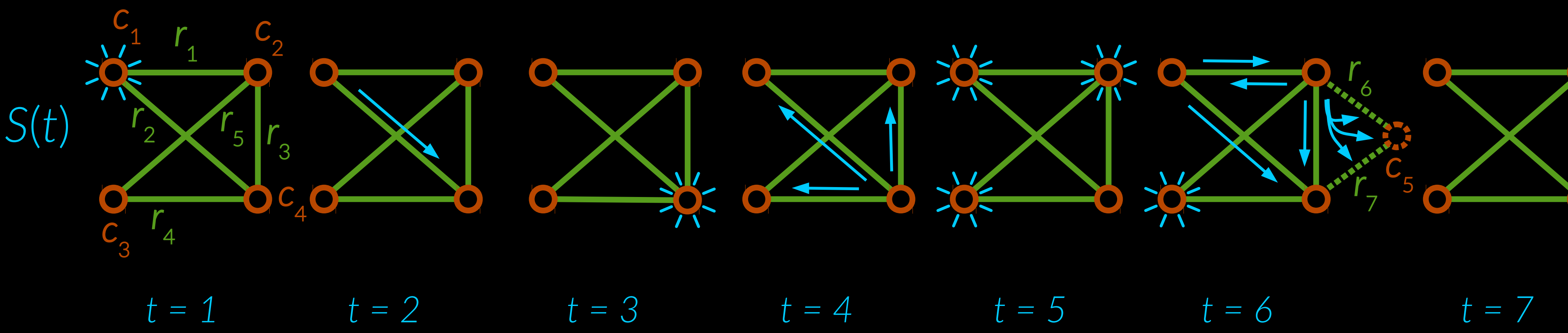
D_1
- label: *lion No.1*
- biomass: $w \in]0;+\infty[$
- sex: $s \in \{m,f\}$
- age: $a \in \mathbb{N}$
- location: $M = (x,y) \in \mathbb{R}^2$
- mating probability: $p \in [0;1]$
- photo

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

A dynamic graph

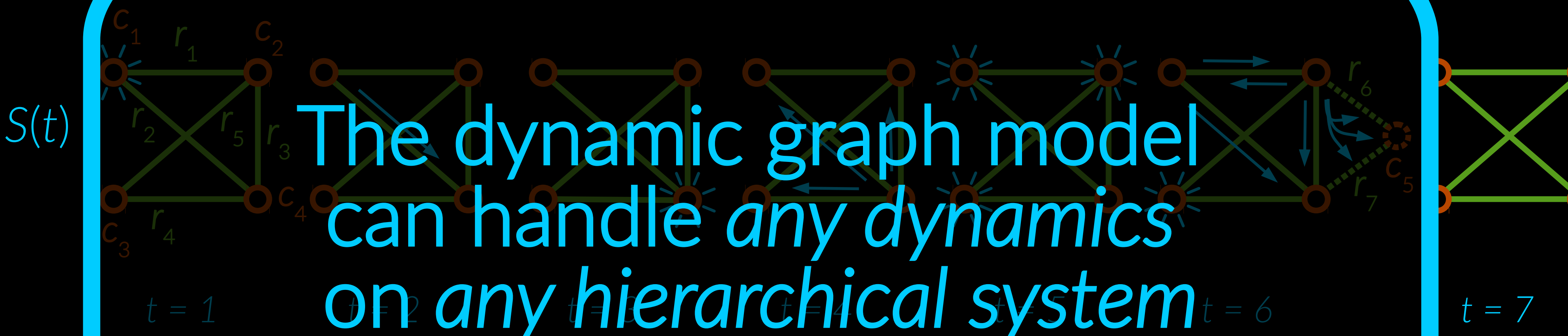
Harary & Gupta 1997. Dynamic graph models, Math. Comp. Model. 7:79-87



Changes propagate locally
State changes may be continuous
Structural changes are always discrete
Causality may be analysed

A dynamic graph

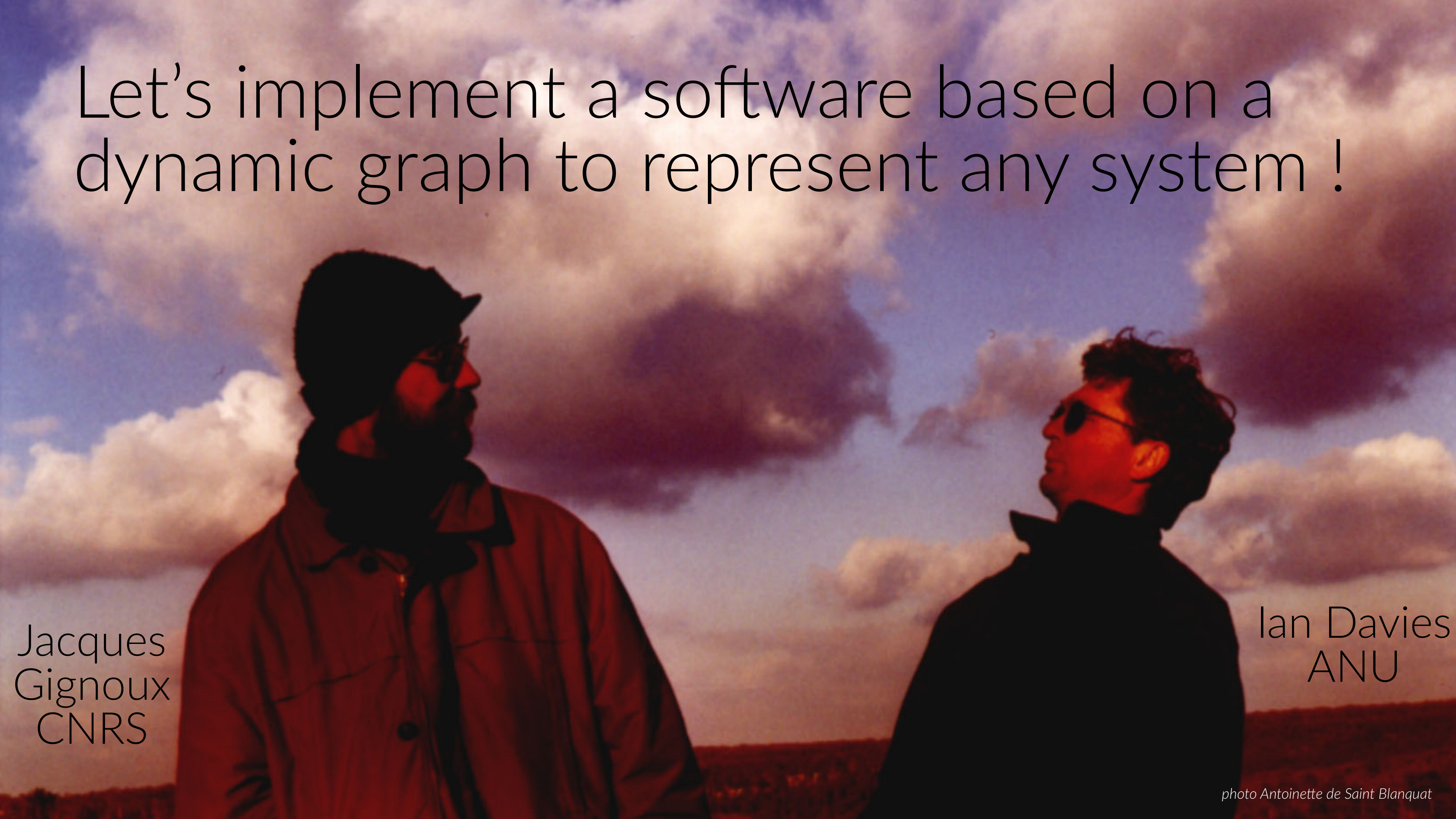
Harary & Gupta 1997. Dynamic graph models, Math. Comp. Model. 7:79-87



The dynamic graph model can handle *any dynamics* on *any hierarchical system*

Changes propagate locally
State changes may be continuous
Structural changes are always discrete
Causality may be analysed

Let's implement a software based on a dynamic graph to represent any system !



Let’s implement a software based on a dynamic graph to represent any system !

[TODO : scan cartoon]
Alors là, mon cher, vous êtes en pleine science-fiction
Ecosystem simulators are among the most complex
existing programs (Coquillard & Hill 1997)

IV. The 3Worlds simulation platform

'Three worlds' lithograph by M.C. Escher

Aims of 3Worlds

To provide ecological modellers with a simulation tool able to :

1. Deal equally well with physics and biology
2. Handle multiple spatial and temporal scales
3. Play with the level of detail in system description
4. Enable to model any ecological problem one can think of
5. Provide quick feedback while building a model
6. Smoothly scale up to large scale simulation experiments
7. Facilitate model intercomparison

...all this without reinventing the wheel too many times, if possible

Key design concepts

The modelled system is a *dynamic graph*
= { *components*, *relations* }

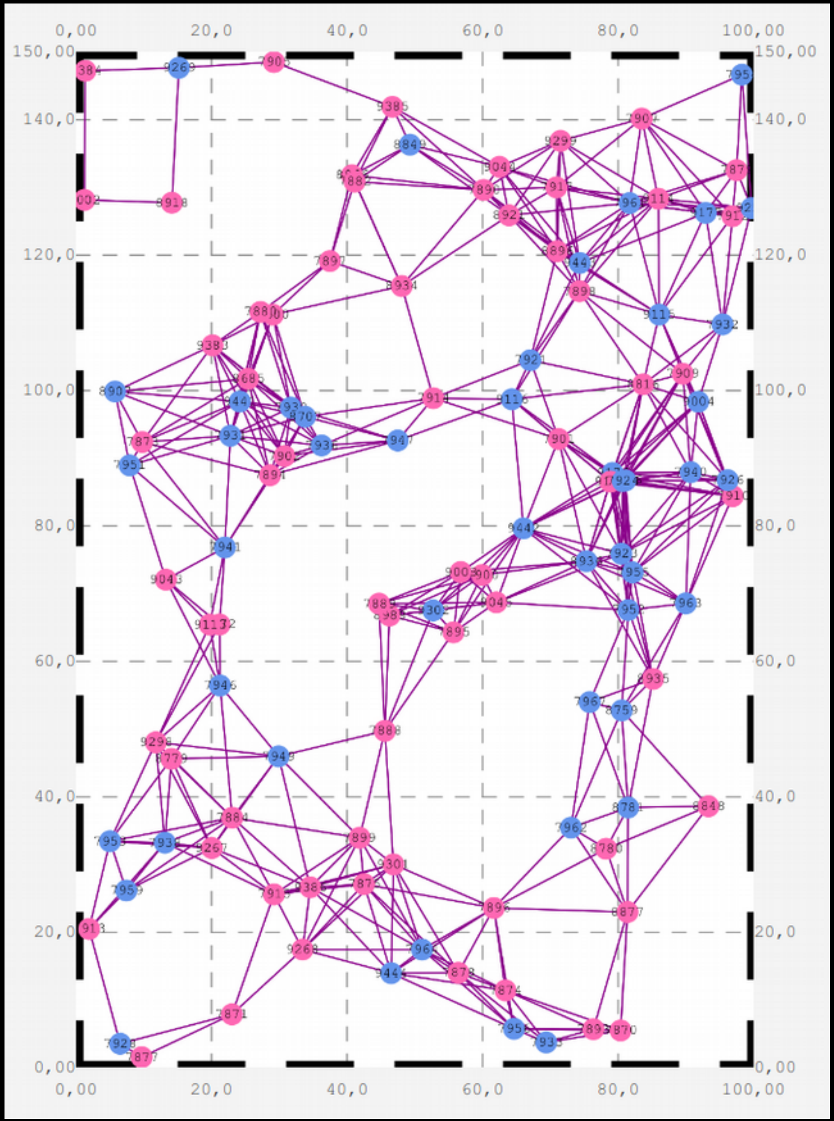
a generalisation for

individual-based models (IBMs)

Grimm V, Railsback S (2005) Individual-based modelling and ecology. Princeton U.P.

multi-agent systems (MASs)

Bousquet F, Le Page C (2004) Multi-agent simulations and ecosystem management: a review. Ecol. Model. 176:313–332.



Key design concepts

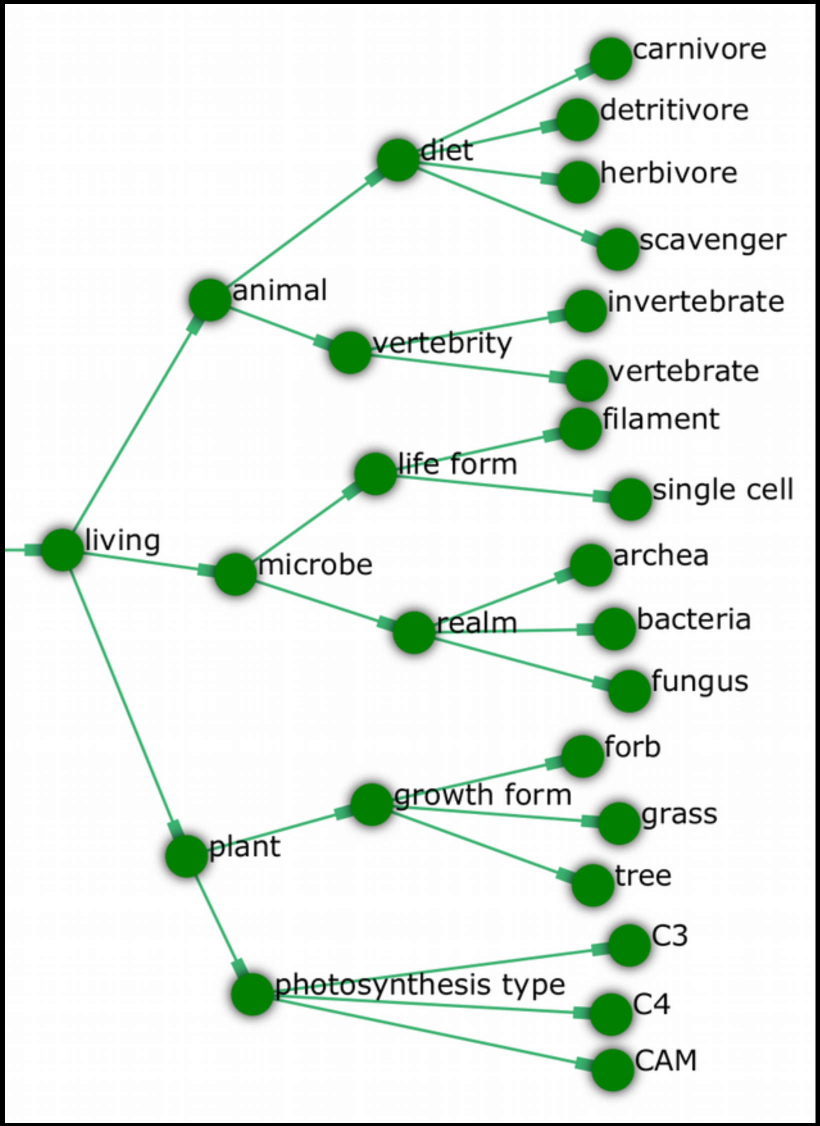
Categories to group components ‘that look like each other’

Members of a category:

- have the same descriptors
- are affected by the same processes

cf. the *class* concept in UML and OOP

http://uml.org/what-is-uml.htm
https://en.wikipedia.org/wiki/Object-oriented_programming



Key design concepts

Multiple *time models*

Simultaneous events as the rule (contrary to MASs)

MONO_UNIT
single time unit, calendar-compatible (default value)

GREGORIAN
real calendar time

YEAR_365D
365-days years, no weeks, no months

YEAR_13M
28-days months, 13-months/52-weeks years

WMY
28-days months, 12-months/48-weeks years

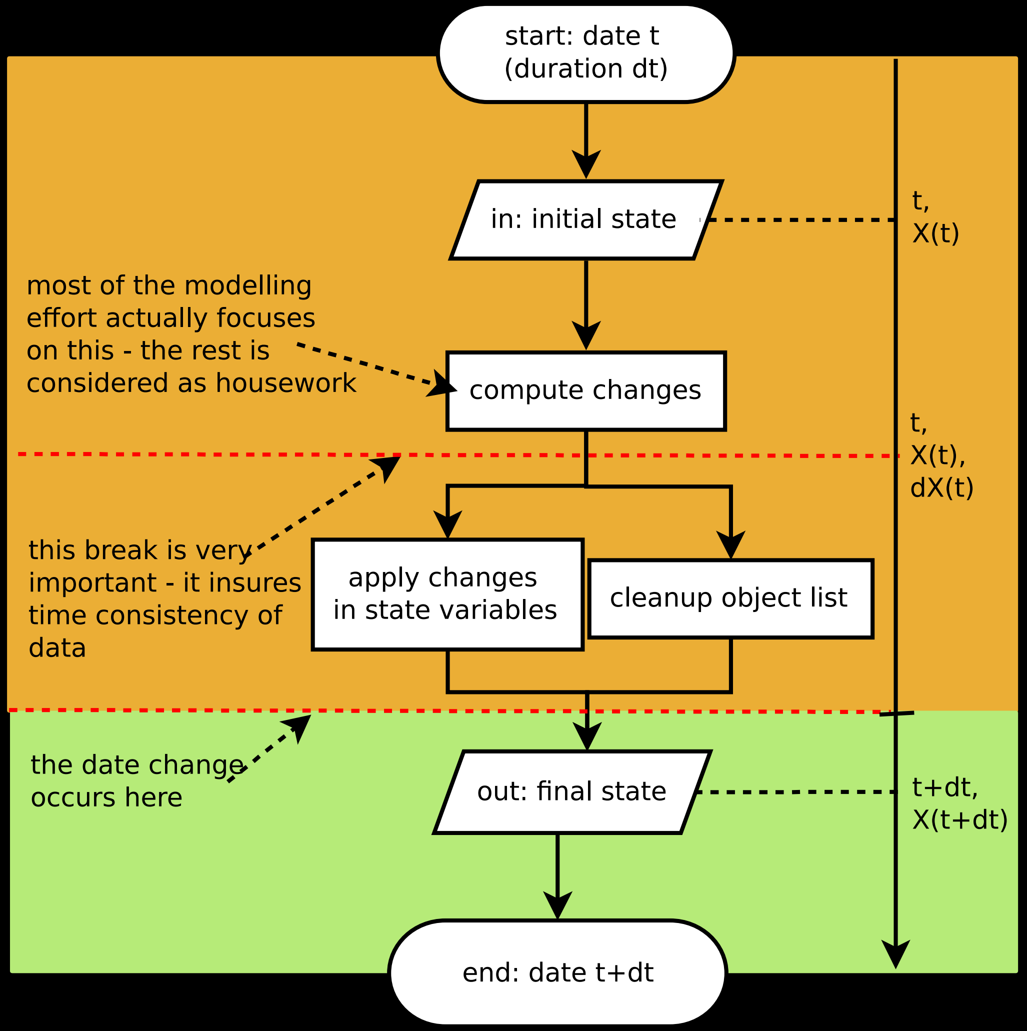
MONTH_30D
30-days months, weeks replaced by 15-days fortnights

YEAR_366D
366-days year, months replaced by 61-days bi-months

LONG_TIMES
long time units only (month or longer), calendar-compatible

SHORT_TIMES
short time units only (week or shorter), calendar-compatible

ARBITRARY
arbitrary time units with no predefined name

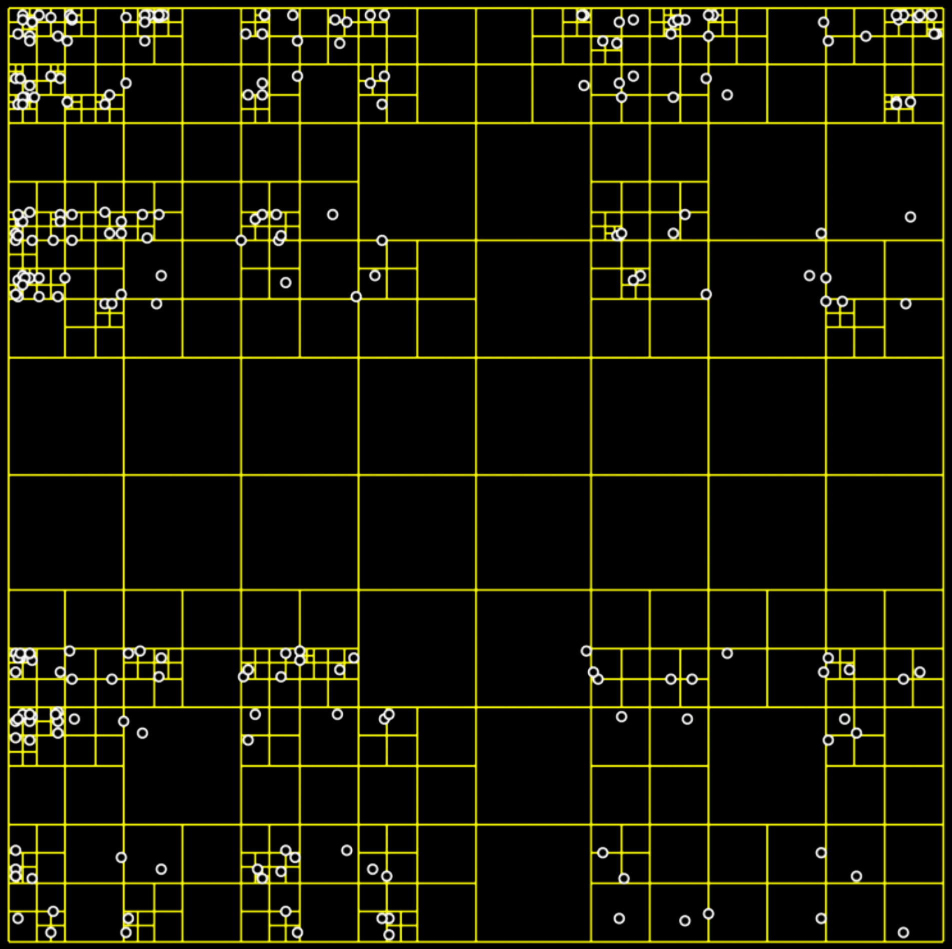


Key design concepts

Space *optional*

Uses *Kd-trees* to optimize searches for establishing relations

Samet H (1984) The Quadtree and Related Hierarchical Data Structures. Computing Surveys 16:187–260



6 different types of edge-effect correction

2 different types of space

[many more to come!]

https://fr.wikipedia.org/wiki/Quadtree

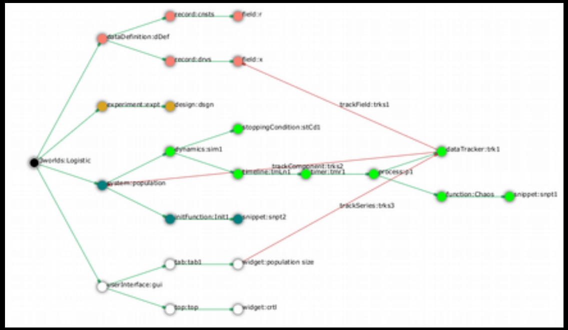
Key design concepts

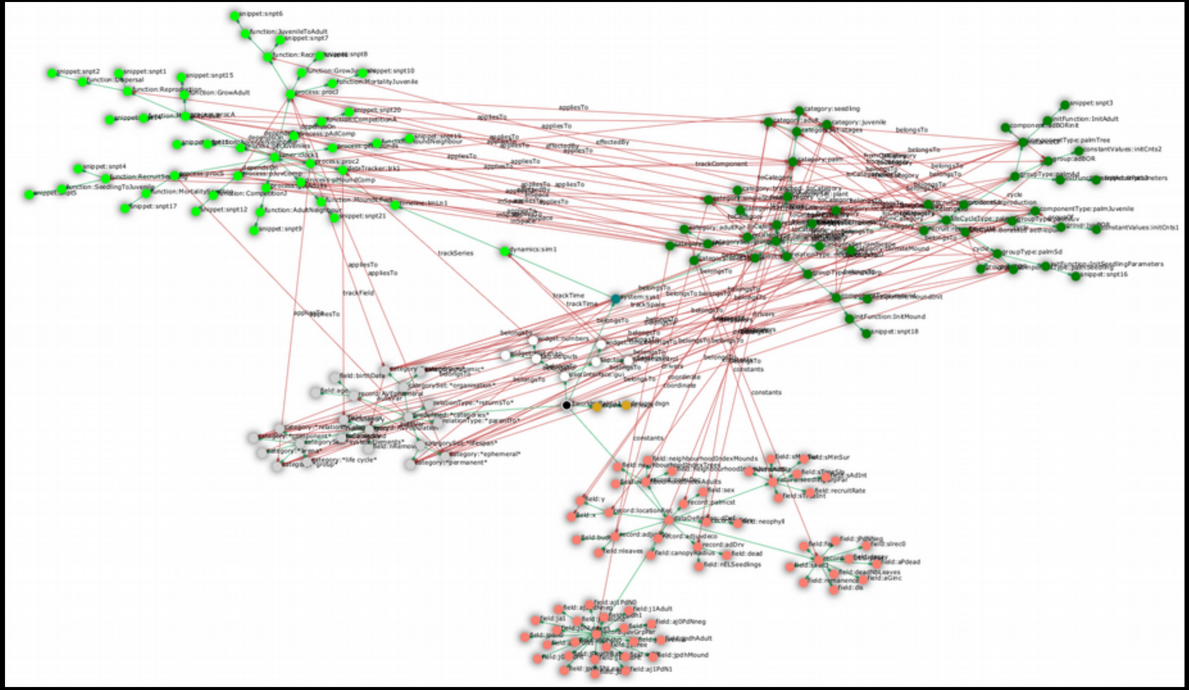
Configuration

- is a *graph* (static but editable)
- is checked against an archetype

Flint SR (2006) Aspect-Oriented Thinking - An approach to bridging the disciplinary divides. PhD, Australian National University

- 's can be **compared**





The importance of model intercomparison

Example 1 (*Lim & Roderick, 2009. An atlas of the global water cycle, 293pp.*):
Question: Will it rain more in Australia because of climate change?
Method: comparison of the predictions of 20 global climate models.

The main points to emerge were:

(a) Of the 39 model runs examined, the Australian average precipitation for 1970-1999 varied from 190.6 to 1059.1 mm per yr. The observed annual precipitation for Australia over the 20th century falls in range of ~ 400 to 500 mm per yr. Hence **there were large differences between model simulated precipitation and observations.**

(b) When compared to observations, some models show little year-to-year variation in simulated Australian precipitation while other models showed markedly more year-to-year variation than present in the observations. **Those differences presumably relate to differences in model formulations.**

The importance of model intercomparison

Example 2 *(VEMAP members, 1995. GBC 9:407-437)*:
Question: Are vegetation predictions of 6 models consistent for the USA?
Method: runs of 6 models on the same datasets.

Conclusions:

(a) The VEMAP results indicate that **uncertainty also exists** in our ability to simulate ecological responses to elevated CO_2 and global warming

(b) Various combinations of vegetation redistribution and altered biogeochemical cycles could produce scenarios ranging from **increases in forest area** [...] to **losses of forest area** [...]

(c) The areas of arid regions of the United States **could remain similar to today, or expand** considerably.

(d) Between forest and arid regions lie grasslands and shrub-steppe regions, **which exhibit complex responses**.

The importance of model intercomparison

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(d) Between forest and arid regions lie grasslands and shrub-steppe regions, **which exhibit complex responses**.

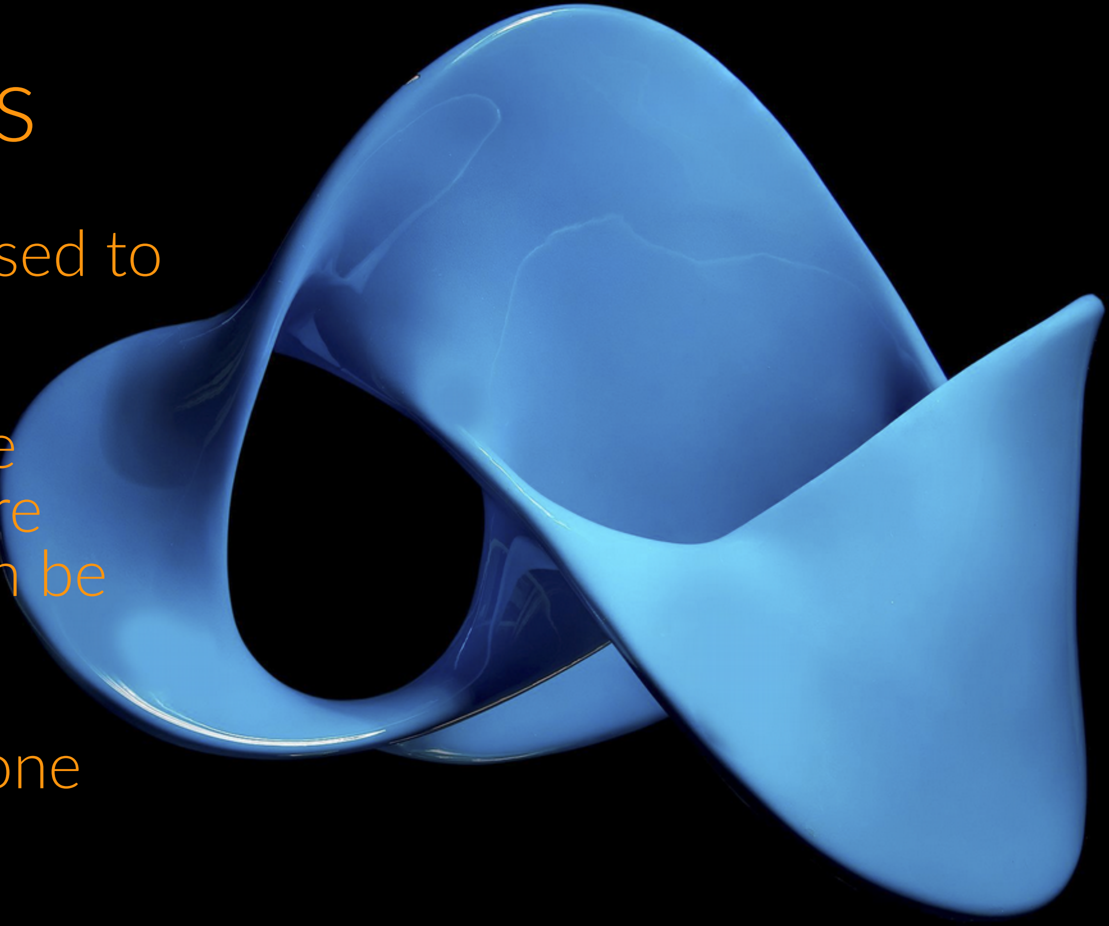
We should do better because comparing graphs is easier

Key design concepts

Flexibility: any function can be used to represent an ecological process

For each 3Worlds model, a single 'user-code' file is generated where code for ecological processes can be edited

A complex IBM can be setup in one week of work.



this magnificent illustration of a 'figure eight knot' symbolizes the perfection and elegance of the 3Worlds software solutions.
Of course it has nothing to do here

https://en.wikipedia.org/wiki/Figure-eight_knot_(mathematics)#/media/File:Superf%C3%ADcie_-_bordo_n%C3%B3_figura-oito.jpg

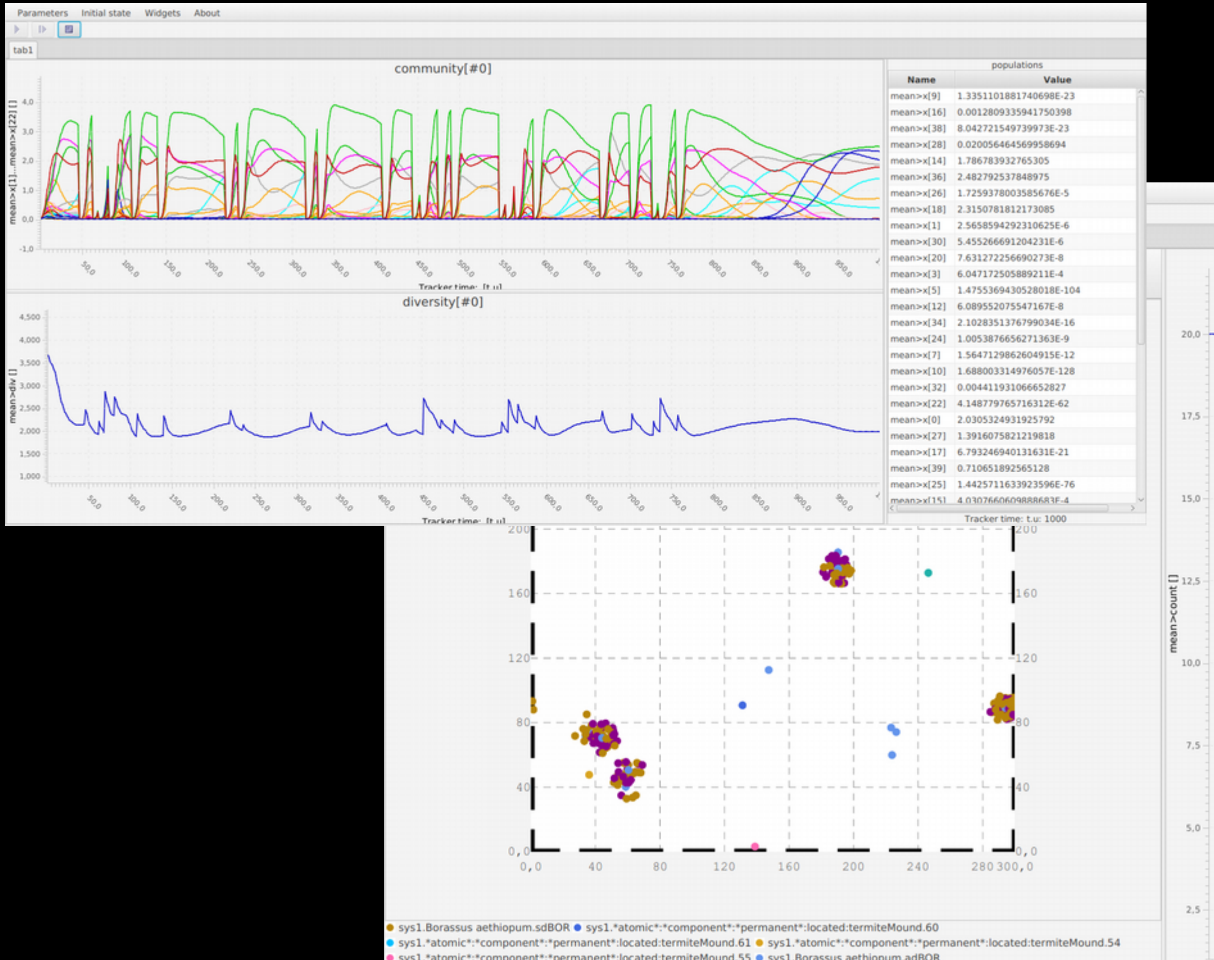
Key design concepts

Use case 1 :
developing model
quick feedback on outputs

Use case 2 :
simulation experiment
parallel computing

[coming soon :
OpenMole integration
https://openmole.org/]

OpenMOLE
the model exploration software



Key design concepts

Provenance made easy:

2 files fully describe a model (possibly more if input data): the configuration graph and the user java code

ODD (Overview, Design, Details): a standard for model description

Grimm et al. (2006) Ecol. Model. 198:115–126.

Grimm et al. (2010) Ecol. Model. 221:2760–2768.

3Worlds automatically generates an ODD skeletton for any model as an OpenOffice file

...it doesnt yet write the article, though.

In practice

java language for portability

~125,000 lines of code (GCMs 50-750,000)

2 applications:
ModelMaker to edit configurations
ModelRunner to launch a simulation experiment

runs on Linux, Mac, Windows

curently 13+ models [many more to come]

[optimisation to come]

In practice

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ModelMaker to edit configurations
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currently 13+ models [many more to come]

[optimisation to come]

This is no science-fiction
but more tests are needed

V. Some applications

The starling (*Sturnus vulgaris*).

- Flies.
- Loves being in a (huge) group.
- Is very noisy and shits while perching.

A flock of starlings

https://www.leprogres.fr/multimedia/2017/12/01/les-cliches-insolites-du-mois-de-decembre-a-travers-le-monde

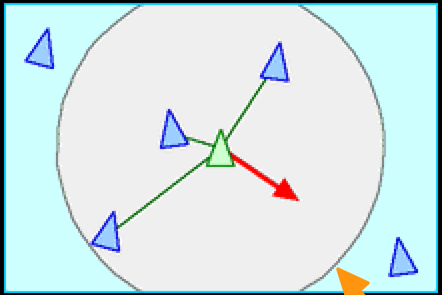
Fish also do it

(so one need not be very clever)

http://www.plongee-libre.fr/slideshow/banc-de-poissons-en-indonesie/

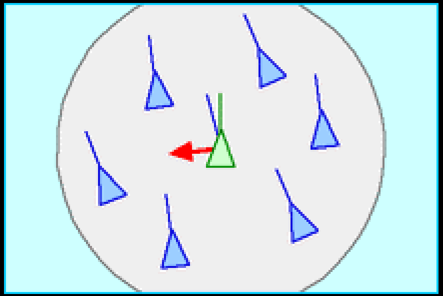
And it’s very easy to model with only 3 rules:

1 **separation**: avoid flockmates (close neighbours)

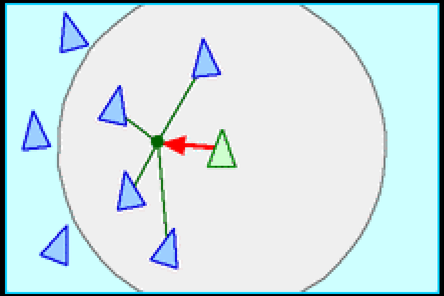


visual field

2 **alignment**: follow average heading of flockmates



3 cohesion: move towards barycentre of local flockmate group



Reynolds, 1987. Computer Graphics 21:25-34

figures from https://en.wikipedia.org/wiki/Boids

Configuration:

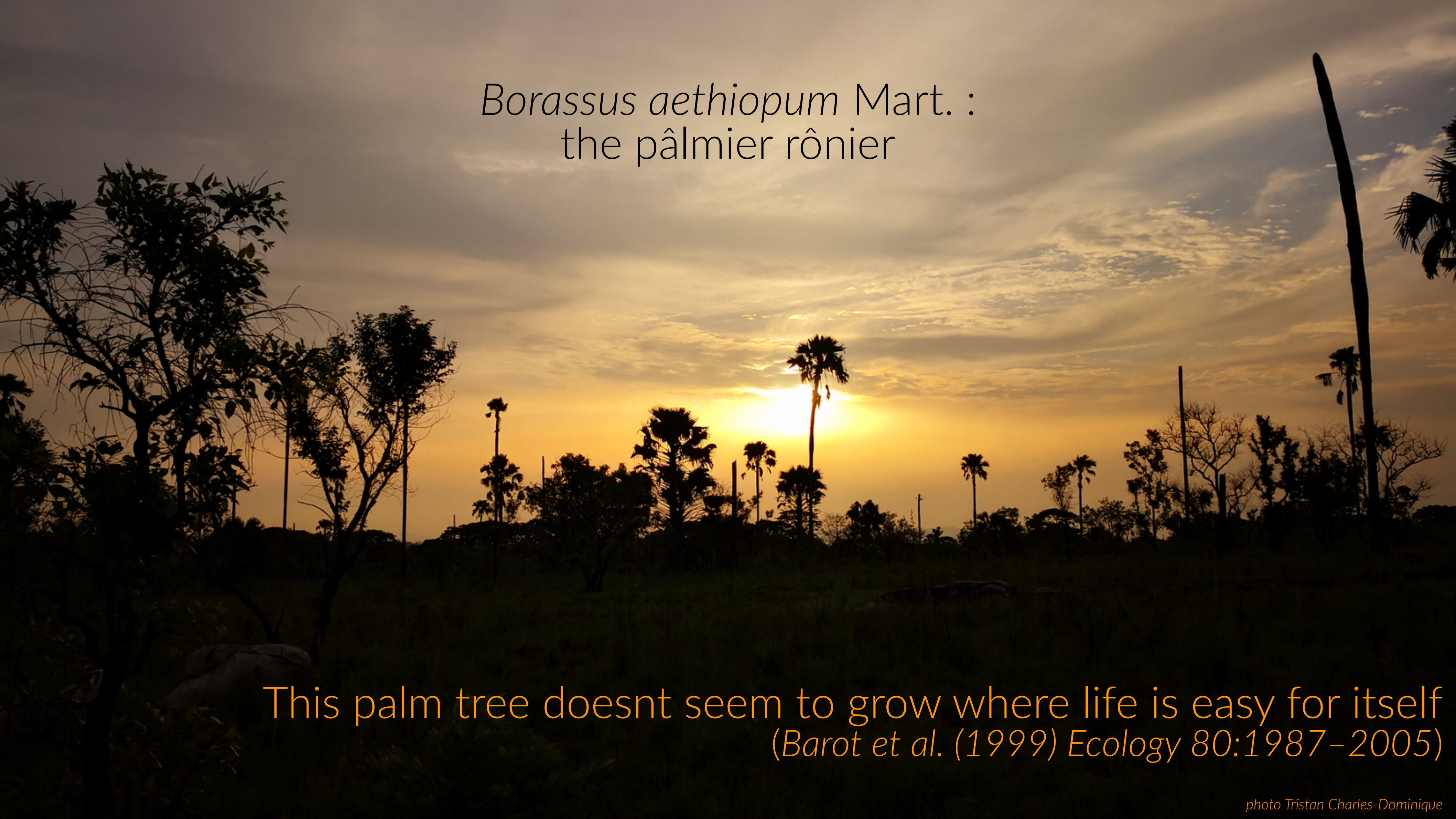
size	153
drivers	5
constants	3
decorators	8
component types	1

User code: 97 lines

```
move(...)
double x = xx;
double y = yy;
double incR = 0.0;
double incT = 0.0;
// default movement based on inertia, ie in the same direction as before + some random tilt
incR = speed;
incT = (random.nextDouble()*PI/4 - PI/8)/speed;
double radHeading = heading*PI/180+incT;
double moveX = incR*cos(radHeading);
double moveY = incR*sin(radHeading);
// if there are visible birds, add corrections:
if (nLocal>0) {
		// rule 1: cohesion - flying towards the barycentre of the local group
		// move 1% towards the centre
		moveX += (avgX/nLocal-x)/100;
		moveY += (avgY/nLocal-y)/100;
		// rule 2: separation - avoid collision with other boids
		moveX += focalDec.avoidX/nLocal;
		moveY += focalDec.avoidY/nLocal;
		// rule 3: match movement to others
		moveX += (avgdX/nLocal-dX)/8;
		moveY += (avgdY/nLocal-dY)/8;
}
focalDrv.xx = x+moveX;
focalDrv.yy = y+moveY;
focalDrv.dX = moveX;
focalDrv.dY = moveY;
focalDrv.heading = acos(moveX/euclidianDistance(0.0,0.0,moveX,moveY))*180/PI;
if (moveY<0.0)
		focalDrv.heading = 360-focalDrv.heading;

prepareMove(...)
focalDec.avgHeading += other_heading;
focalDec.avgX += other_xx;
focalDec.avgY += other_yy;
focalDec.avgdX += other_dX;
focalDec.avgdY += other_dY;
focalDec.nLocal++;
// rule 2: avoid collisions
if (squaredEuclidianDistance(xx,yy,other_xx,other_yy)<safetyRange*safetyRange) {
		focalDec.avoidX -= (other_xx-xx);
		focalDec.avoidY -= (other_yy-yy);
}
focalDrv.xx = xx;
focalDrv.yy = yy;
otherDrv.xx = other_xx;
otherDrv.yy = other_yy;
```

Borassus aethiopum Mart. :
the pâlmier rônier



This palm tree doesnt seem to grow where life is easy for itself

(Barot *et al.* (1999) *Ecology* 80:1987–2005)

photo Tristan Charles-Dominique

A data-supported model

3 stages : seedling, juvenile, adult (categories)	Barot & Gignoux 1999, Biotropica
adults reduce seedling and juvenile survival	Barot et al. 1999, Oikos
termite mounds increase growth	Barot & Gignoux 2003, JVS
reproduction starts at adult stage	Barot & Gignoux 1999, Biotropica
seed dispersal is very short ranged	Barot et al. 1999, Oikos
spatial pattern gets less agregated with palm age	Barot et al. 1999, Ecology

Hypotheses

1. *B. aethiopum* is lacking former dispersers (elephants and baboons) and its spatial pattern should change

2. Without termite mounds there should be no more palm trees in Lamto

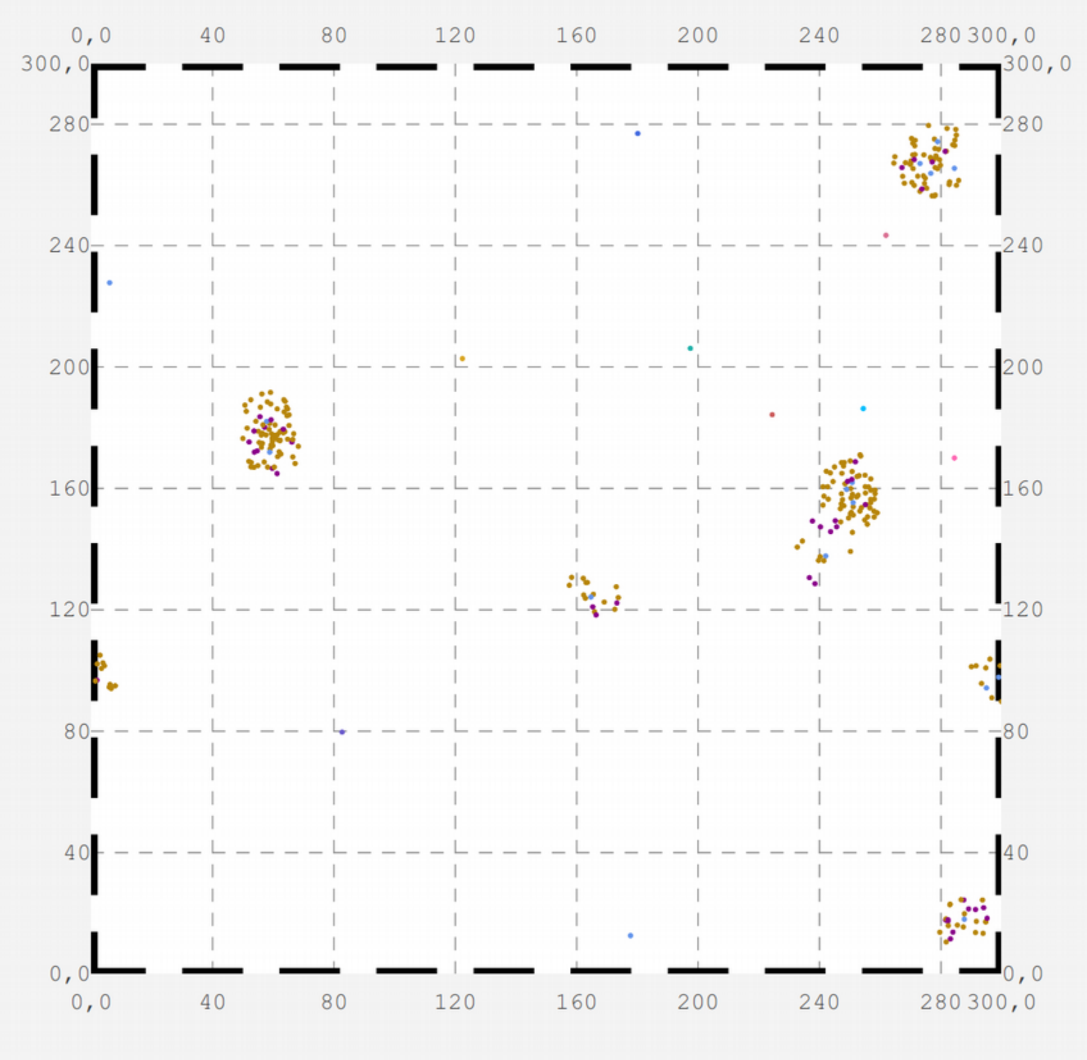
Hypotheses

1. *B. aethiopum* is lacking former dispersers (elephants and baboons) and its spatial pattern should change

...

seedling and juveniles are clumped around adults

adults are much more clumped than in reality



Hypotheses

2. Without termite mounds there should be no more palm trees in Lamto

...

[TO DO]

Configuration:

size	627
drivers	5
constants	43
decorators	5
component types	4
relation types	3

User code: 217 lines

```
moundEffect(...)
// relativedistance weight, ie = 1 if at focal location, =0 at searchRadius distance
double weight = 1-euclidianDistance(x,y,other_x,other_y)/searchRadius;
focalDec.neighbourhoodIndexMounds += weight;

mortalityAdult(...)
if (dead>=group_remanence)
        return true;
else
        return false;

juvenileNeighbour(...)
return true;

growJuvenile(...)
double crownSurface = PI*sqr(canopyRadius);
double niMound = neighbourhoodIndexMounds/crownSurface; // TODO: replace by
neighbourhood index
double niTree=0;
double niAdult = neighbourhoodIndexAdults/crownSurface;
double niJuv = neighbourhoodIndexJuveniles/crownSurface;
// increment in number of leaves
double[] proba = new double[3];
if (budHt>0.0) {
        double neighb = group_j0Mound*niMound + group_j0NLeaves*nleaves;
        double logit = neighb + group_aj0PdNneg;
        proba[0] = 1/(1+exp(-logit));
        logit = neighb + group_aj0PdN0;
        proba[1] = 1/(1+exp(-logit));
        logit = neighb + group_aj0PdN1;
        proba[2] = 1/(1+exp(-logit));
}
else {
        double neighb = group_j1Tree*niTree + group_j1Adult*niAdult +
group_j1Juvenile*niJuv + group_j1BudHt*budHt;
        double logit = neighb + group_aj1PdNneg;
        proba[0] = 1/(1+exp(-logit));
        logit = neighb + group_aj1PdN0;
        proba[1] = 1/(1+exp(-logit));
        logit = neighb + group_aj1PdN1;
        proba[2] = 1/(1+exp(-logit));
}
double real = random.nextDouble();
int result = 3;
for (int i=0; i<3; i++)
        if (real<proba[i]) {
                result = i;
                break;
}
int dN = result-1; // possible outcomes: -1,0,1,2
```

VI. Conclusions

efficient modelling requires
good concepts

any ecosystem can be
modelled with a dynamic graph

3Worlds is there*, use it!

*Well... come and see me after the talk

VII. Needs & future plans

testers:
- develop models
- check GUIs
- check checks

programmers:
- space library
- openMole integration
- optimisation
- graph analysis

https://valerianpierret.artstation.com/projects/e0m4eJ

VII. Needs & future plans

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programmers:
- space library
- openMole integration
- optimisation
- graph analysis

And, anyway, what do you have against science-fiction when people spend billions to travel to Mars?

https://valerianpierret.artstation.com/projects/e0m4eJ