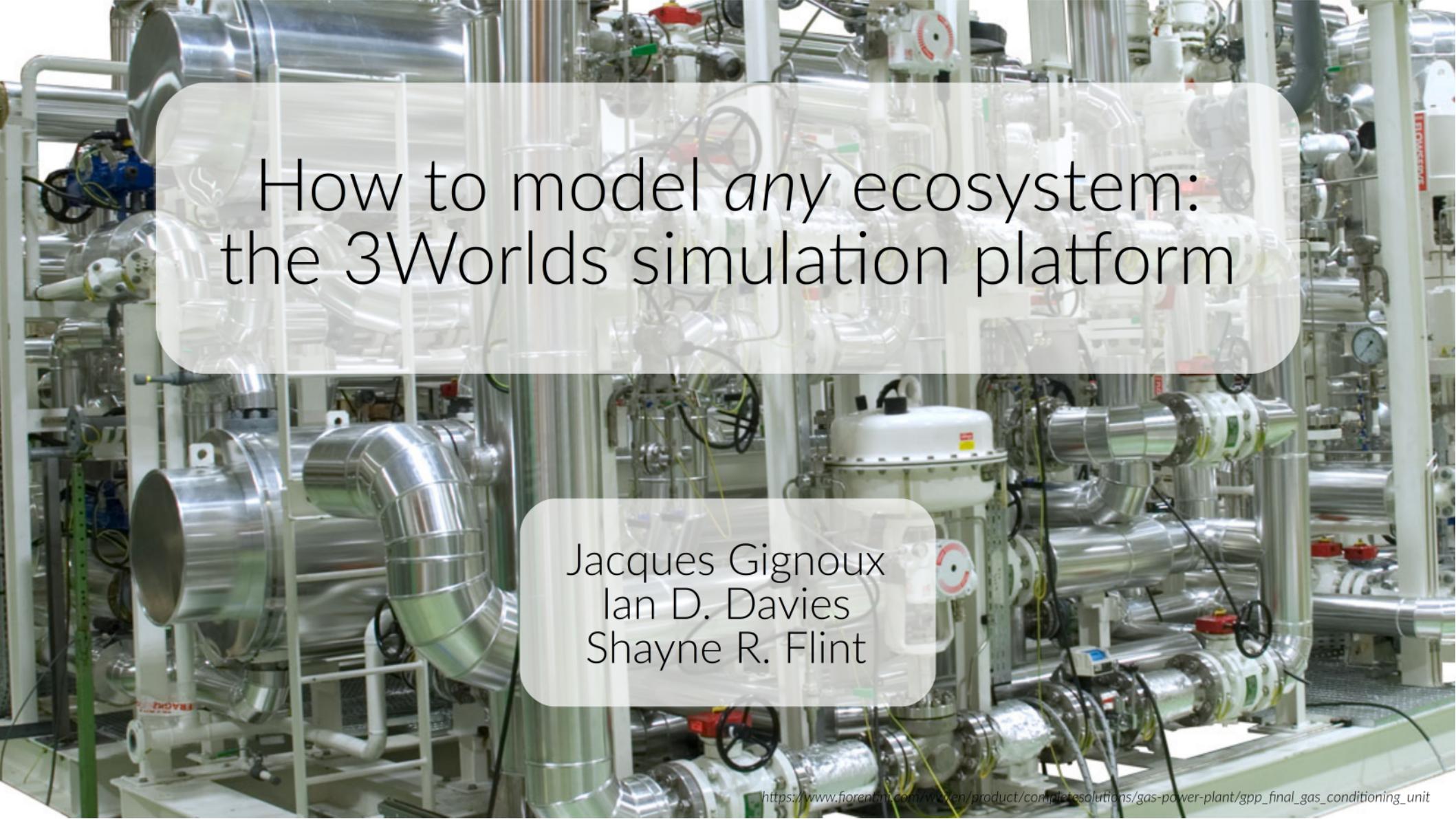




Australian
National
University



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

Jacques Gignoux
Ian D. Davies
Shayne R. Flint

Three difficulties of Ecology

Ecology:

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

A dramatic photograph of a massive ocean wave crashing. The wave's face is a bright white spray and foam, contrasting with the deep blue-grey of the surrounding water. The perspective is from a low angle, looking up at the wave's face.

Ecology looks at incredibly
different objects

...and claims to have a method



photo Jacques Gignoux





photo Jacques Gignoux

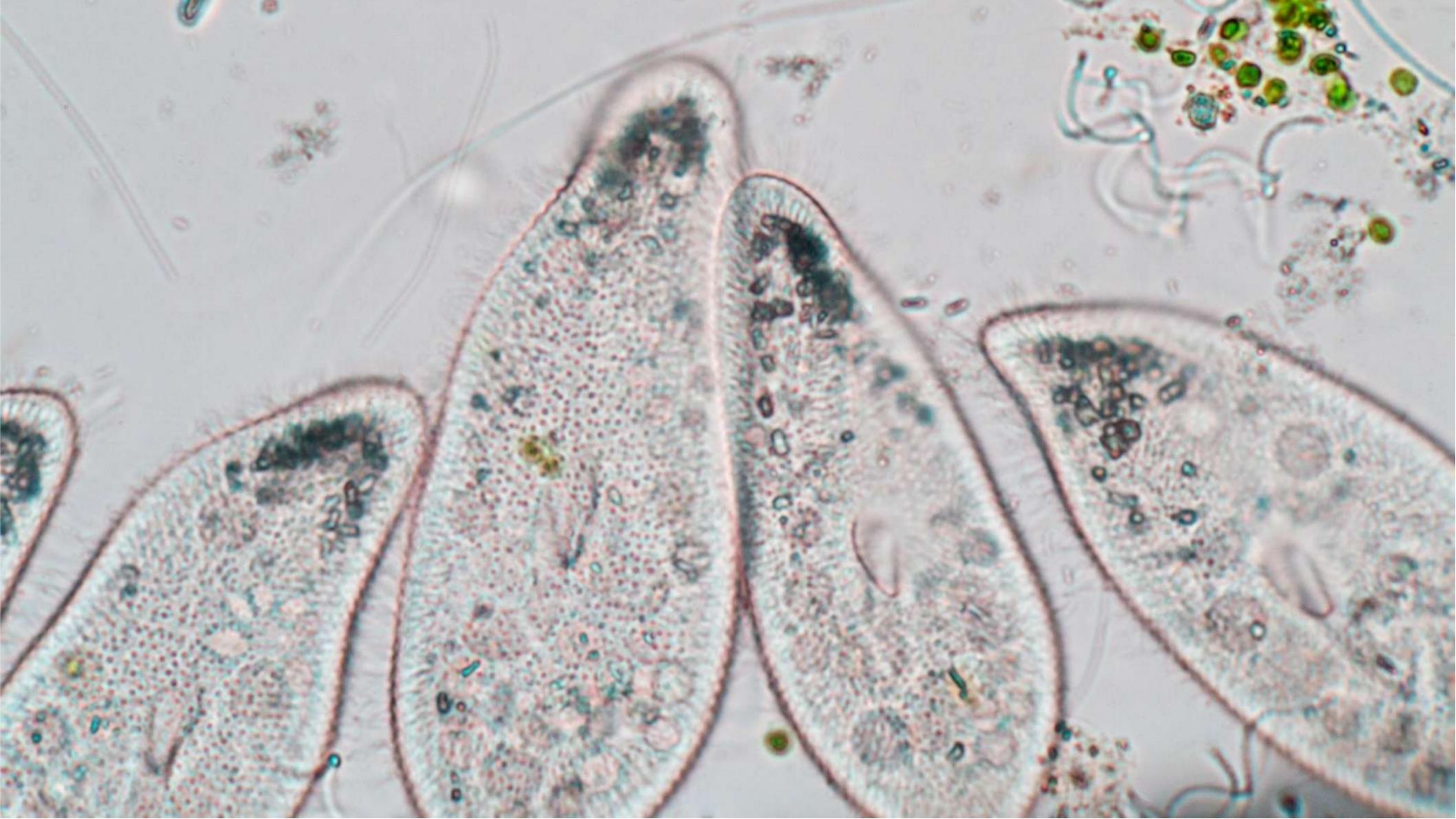








NASA AS17-148-22727

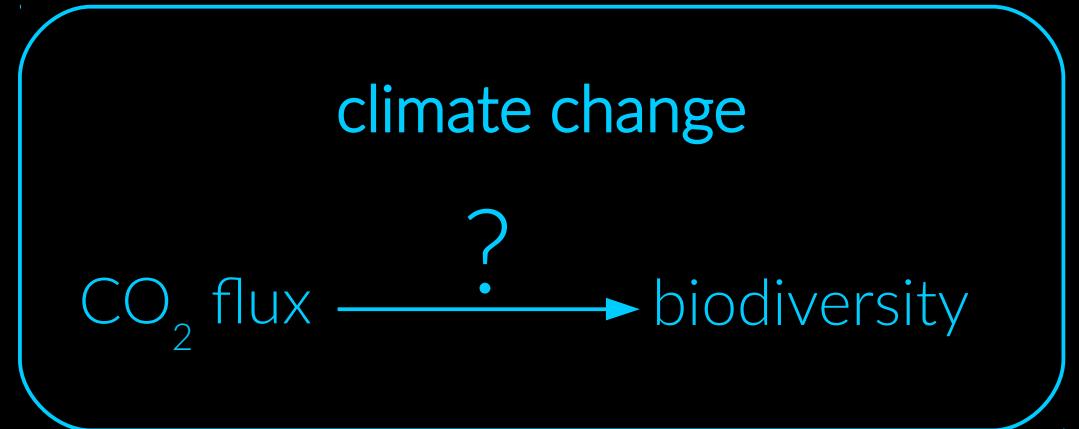


A microscopic image showing various microorganisms, including ciliates and amoebae, against a light background.

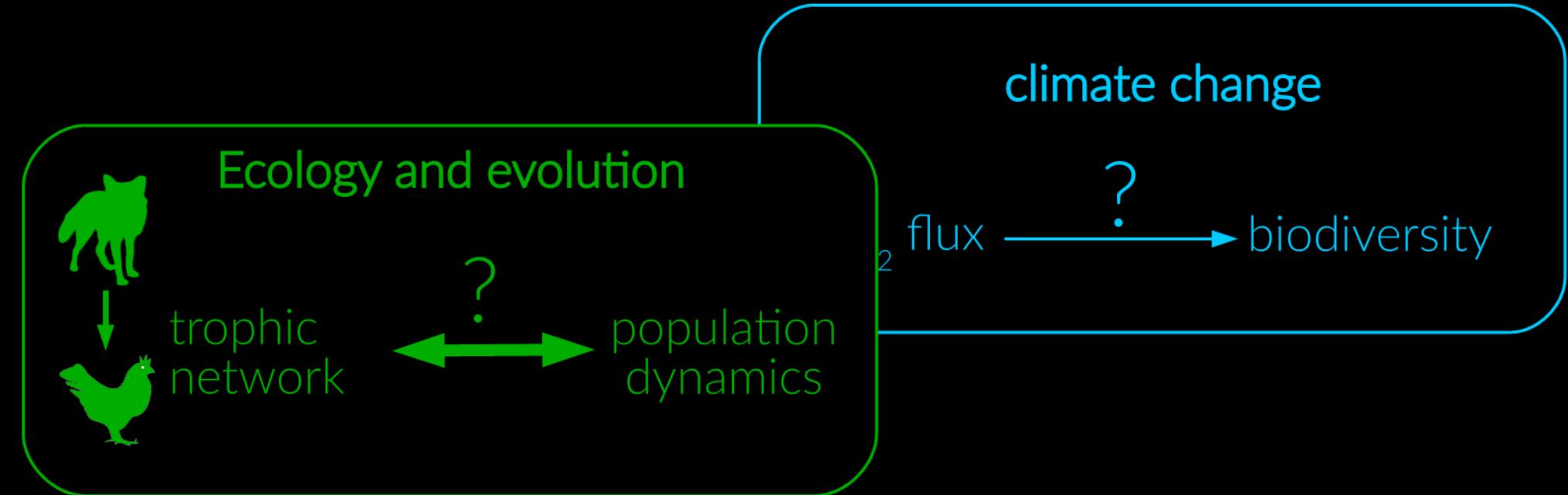
Can we find a common approach
to study all these objects?

Ecology addresses *difficult* questions:

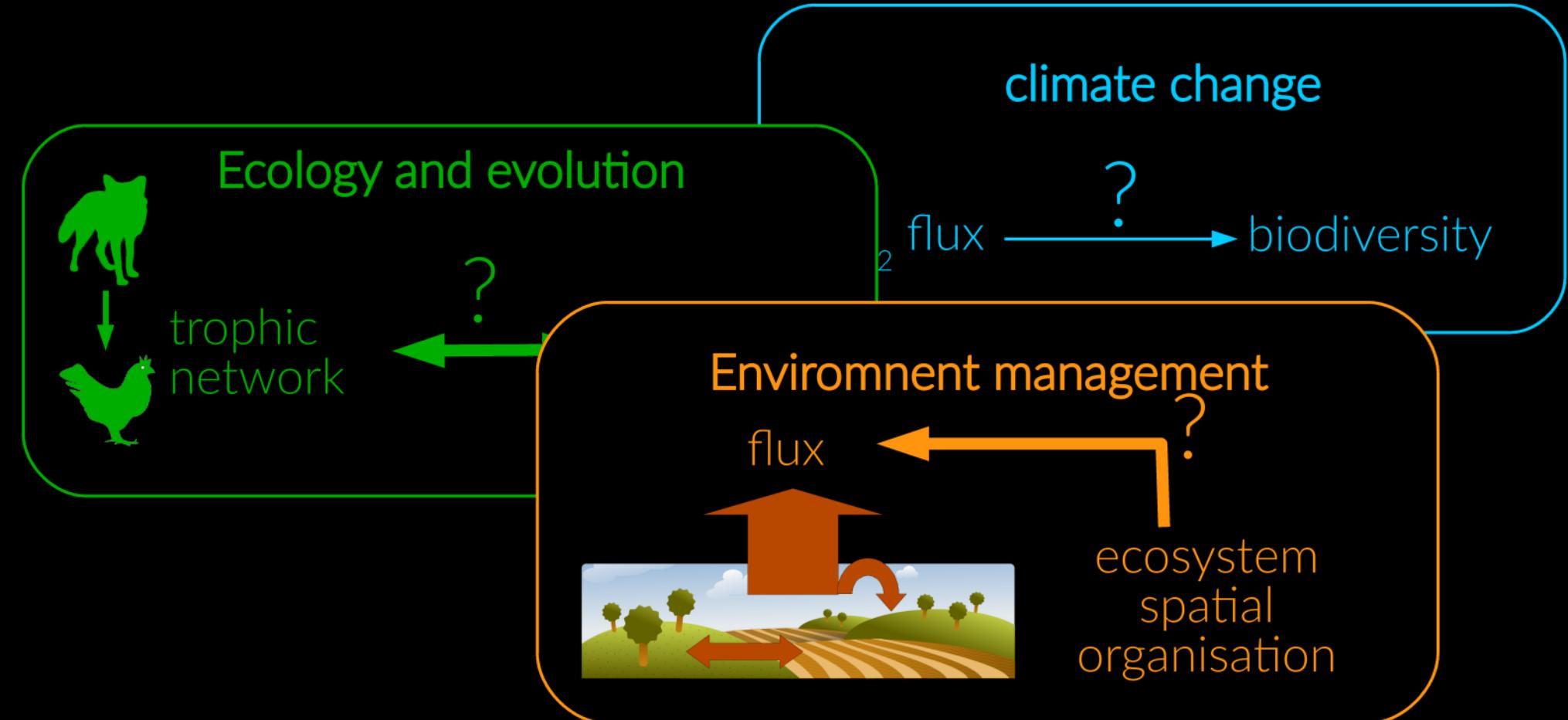
Ecology addresses *difficult* questions:



Ecology addresses difficult questions:



Ecology addresses difficult questions:



Ecology addresses difficult questions:

Ecology and evolution



trophic
network

These questions require
a coupling between
different ecological approaches

climate change

flux

?

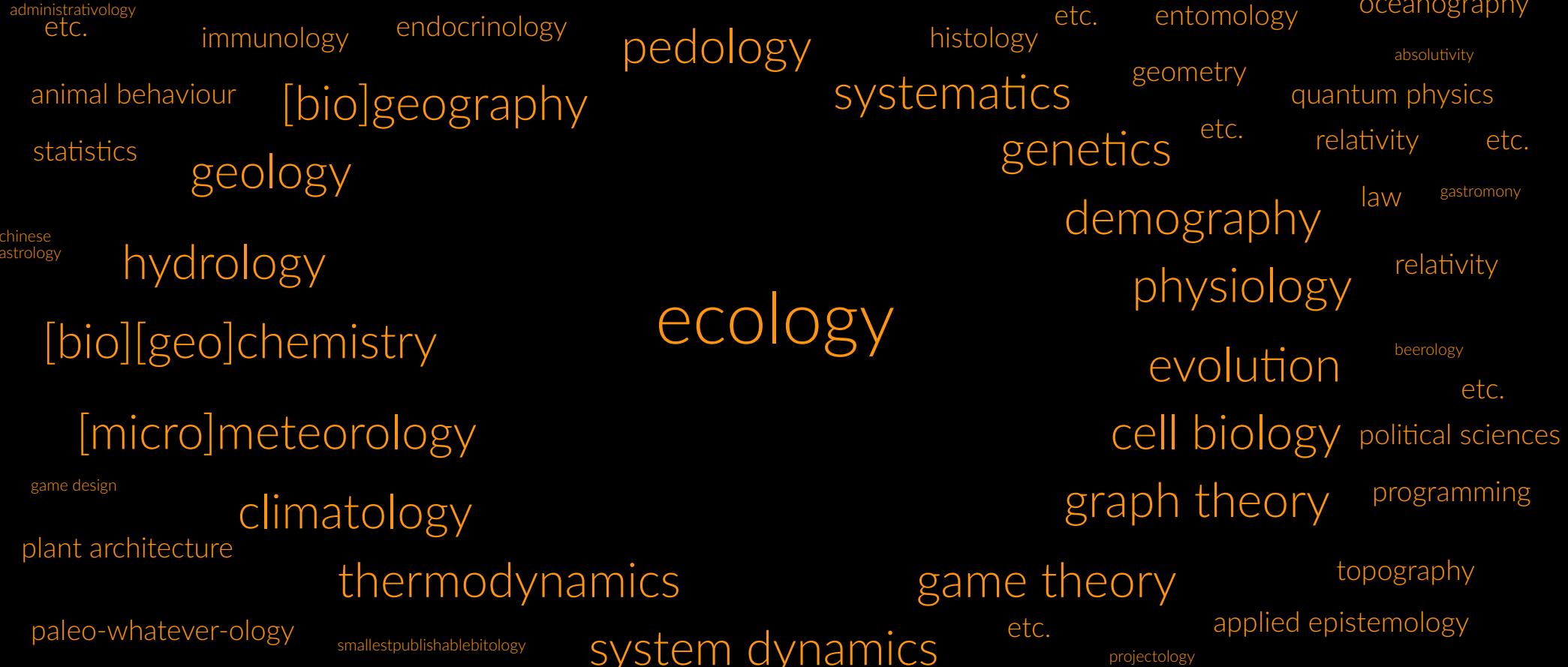
biodiversity

environment management

ecosystem
spatial
organisation



Ecology is an *integrative* science:



... borrowing methods from other sciences

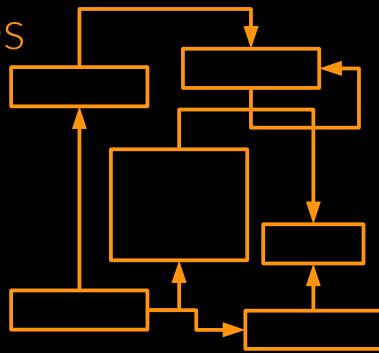
Ecological sub-fields use poorly compatible representations:

Matter and energy fluxes

Ecophysiology

Ecosystems

Dynamic systems



Ecological sub-fields use poorly compatible representations:

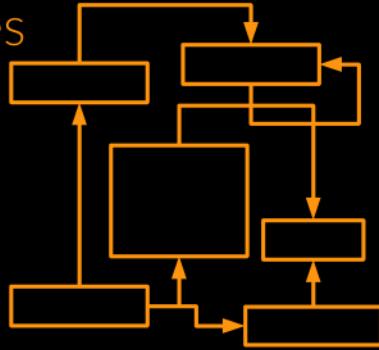
Matter and energy fluxes

Ecophysiology

Ecosystems



Dynamic systems



Demography

Genetics

Evolution



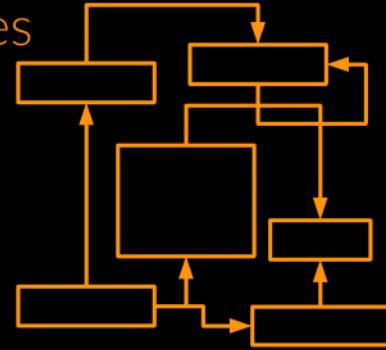
Population models



Individual-based models

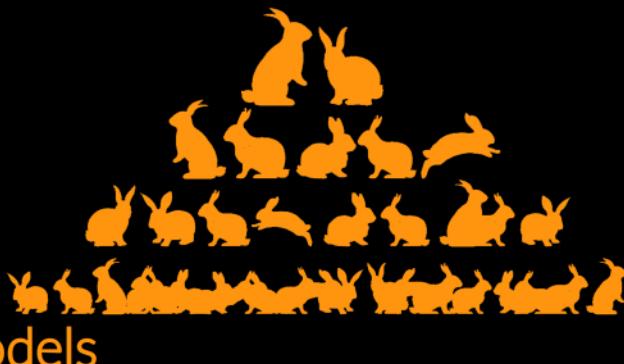
Ecological sub-fields use poorly compatible representations:

Matter and energy fluxes
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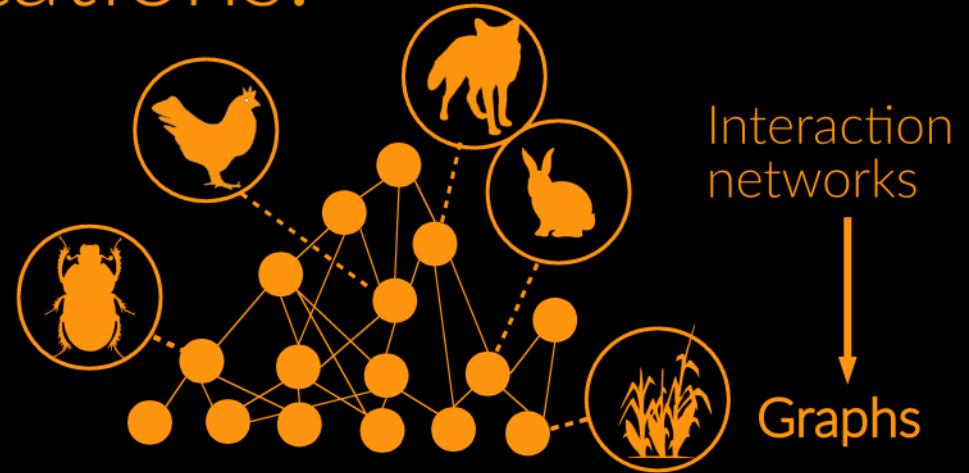


Dynamic systems

Demography
Genetics
Evolution



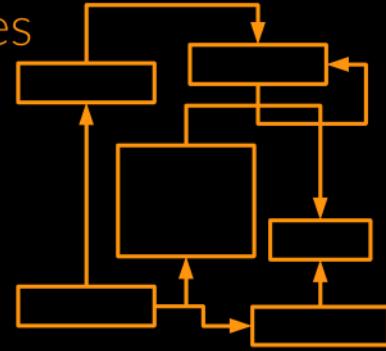
Population models
Individual-based models



Interaction networks
Graphs

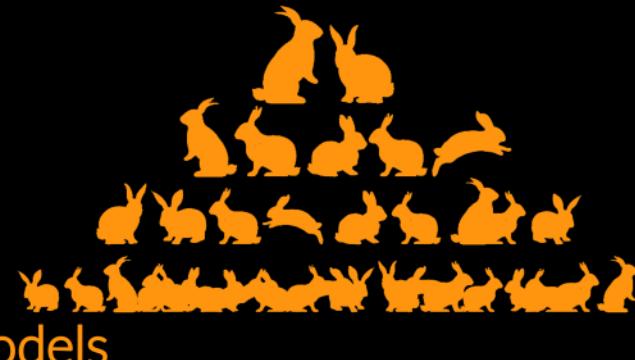
Ecological sub-fields use poorly compatible representations:

Matter and energy fluxes
Ecophysiology
Ecosystems

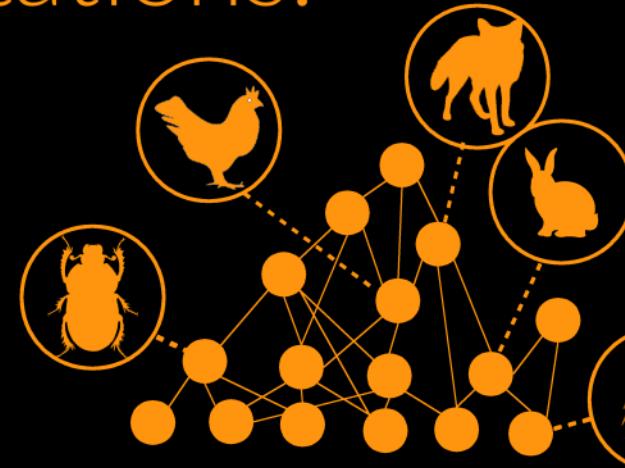


Dynamic systems

Demography
Genetics
Evolution

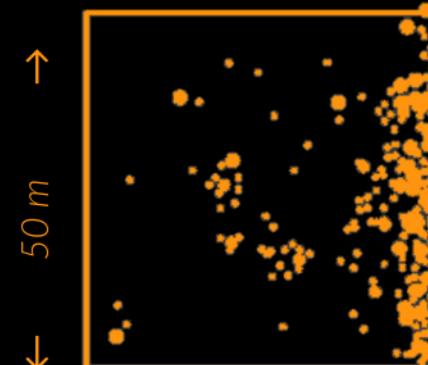


Population models
Individual-based models



Interaction networks

Graphs



Landscape ecology
Ecosystem structure

Cellular automata

Ecological sub-fields use poorly compatible representations:

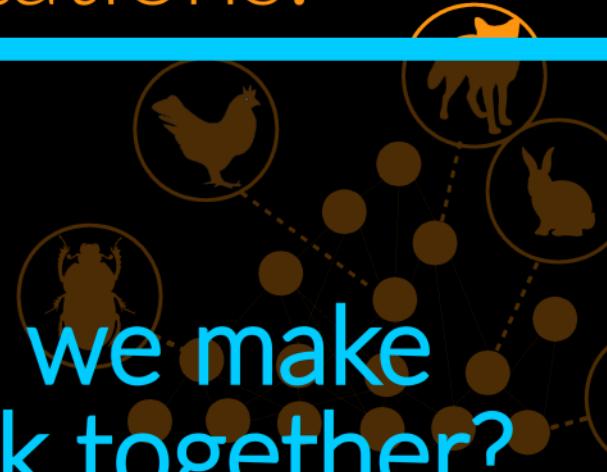
Matter and energy fluxes
Eophysiology
Ecosystems



Dynamic systems

Demography
Genetics
Evolution

How can we make
these work together?



Interaction networks



Graphs

Landscape ecology
Ecosystem structure



Cellular automata

Population models
Individual-based models



Ecology focuses on *interactions*

From various definitions:

Ecology studies **interactions** among living beings and between them and their milieu (<https://fr.wikipedia.org/wiki/%C3%89cologie>)

Ecology - the study of the environment and the **relationships** between things in it (<https://dictionary.cambridge.org/dictionary/english-french/ecology>)

Ecology - the **relation** of plants and living creatures to each other and to their environment; the study of this
(<https://www.oxfordlearnersdictionaries.com/definition/english/ecology?q=ecology>)

... that may help

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
- focus on interactions



The ecosystem concept (Tansley, 1935)

Ecosystems

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

Ecology consists in viewing everything as an ecosystem



even this:



or this:



II. The solution to the difficulty of these questions

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.**

Systems thinking



<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.

Shayne Flint



Australian
National
University

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

1. Ecosystems are commonly considered as *complex systems*
2. Complex systems are assumed to display *emergent properties*

But what is an...

emergent
properth?

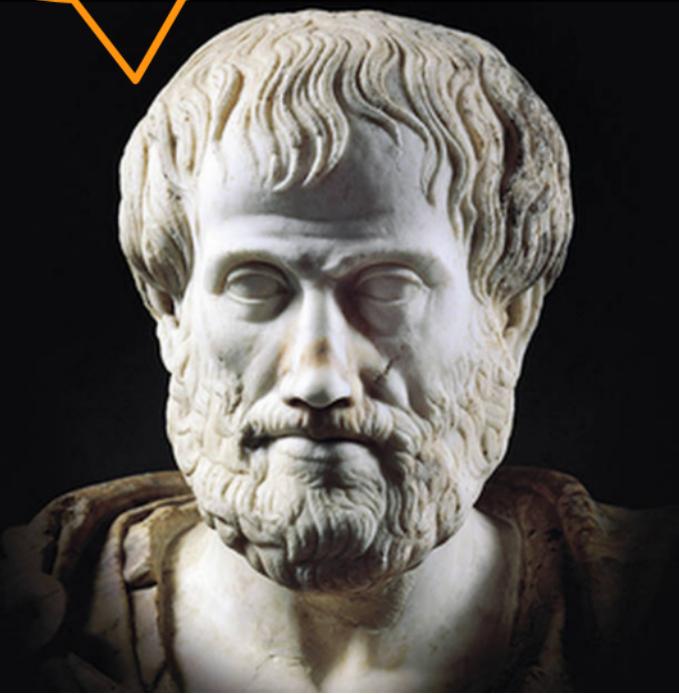


What does that mean?
(does it hurt?)

Not much:

The whole is
more than the
sum of its parts

Αριστοτέλης (-335)



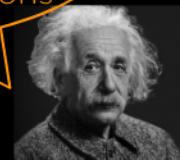
Not much:

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:

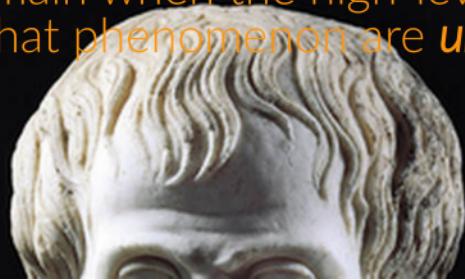
Bedau 1997: Macrostate P of S with microdynamic D is weakly emergent iff P can be derived from D and S's external conditions but **only by simulation**.

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*
2. Complex systems are assumed to display *emergent properties*
3. There are dozens of definitions of emergence (Chérel G. 2013, PhD)

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1. Ecosystems are commonly considered as *complex systems*
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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.

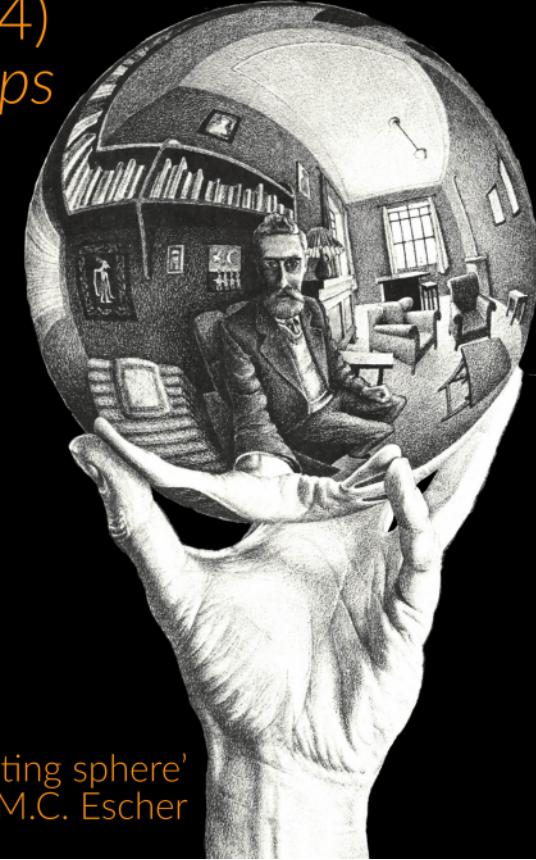
The hierarchical system

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

A hierarchical system is best represented by a 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:

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

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

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

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

$$\begin{aligned} \gamma : R &\rightarrow C \times C \\ r_v &\rightarrow (c_i, c_j) \quad i \leq n_c, j \leq n_c \end{aligned}$$

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

A hierarchical system is best represented by a mathematical graph

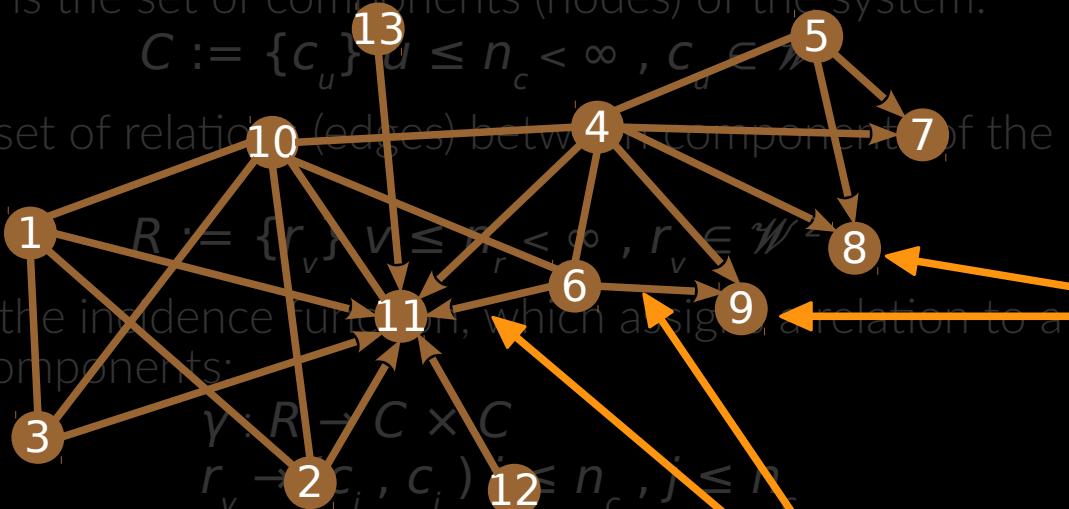
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the
system

the
components

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

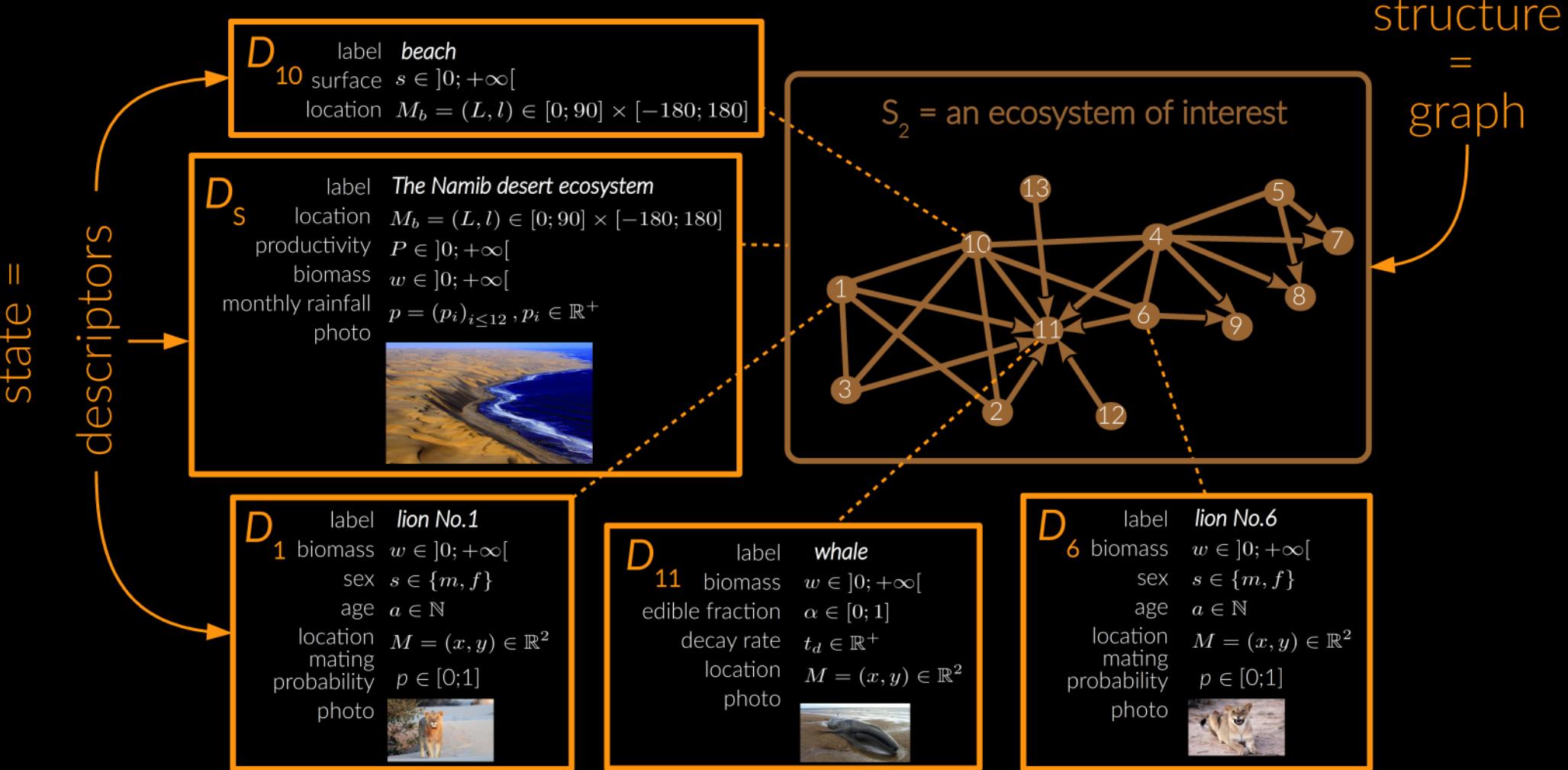
$$\gamma : R \rightarrow C \times C$$

$$r_v \rightarrow (c_i, c_j) \quad i \leq n_c, j \leq n_r$$

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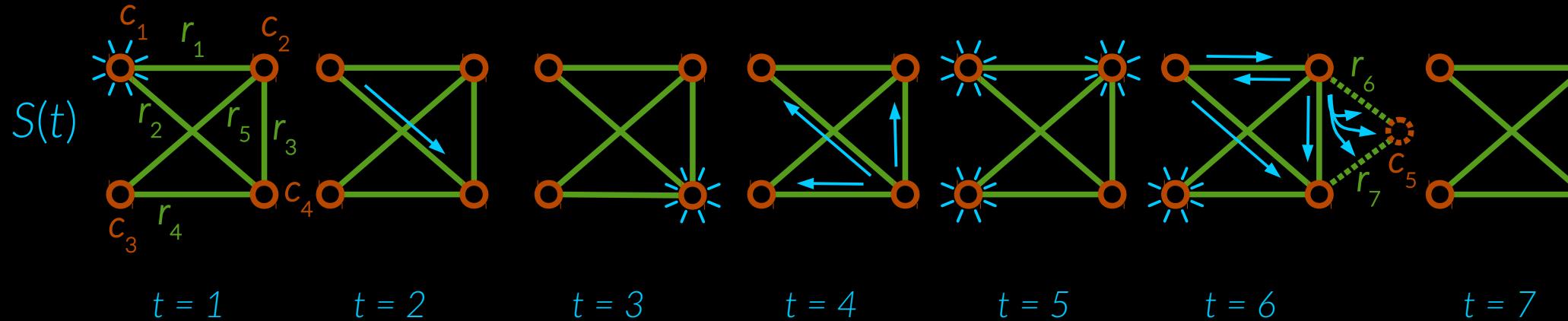
the
interactions

A hierarchical system is best represented by a mathematical graph



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

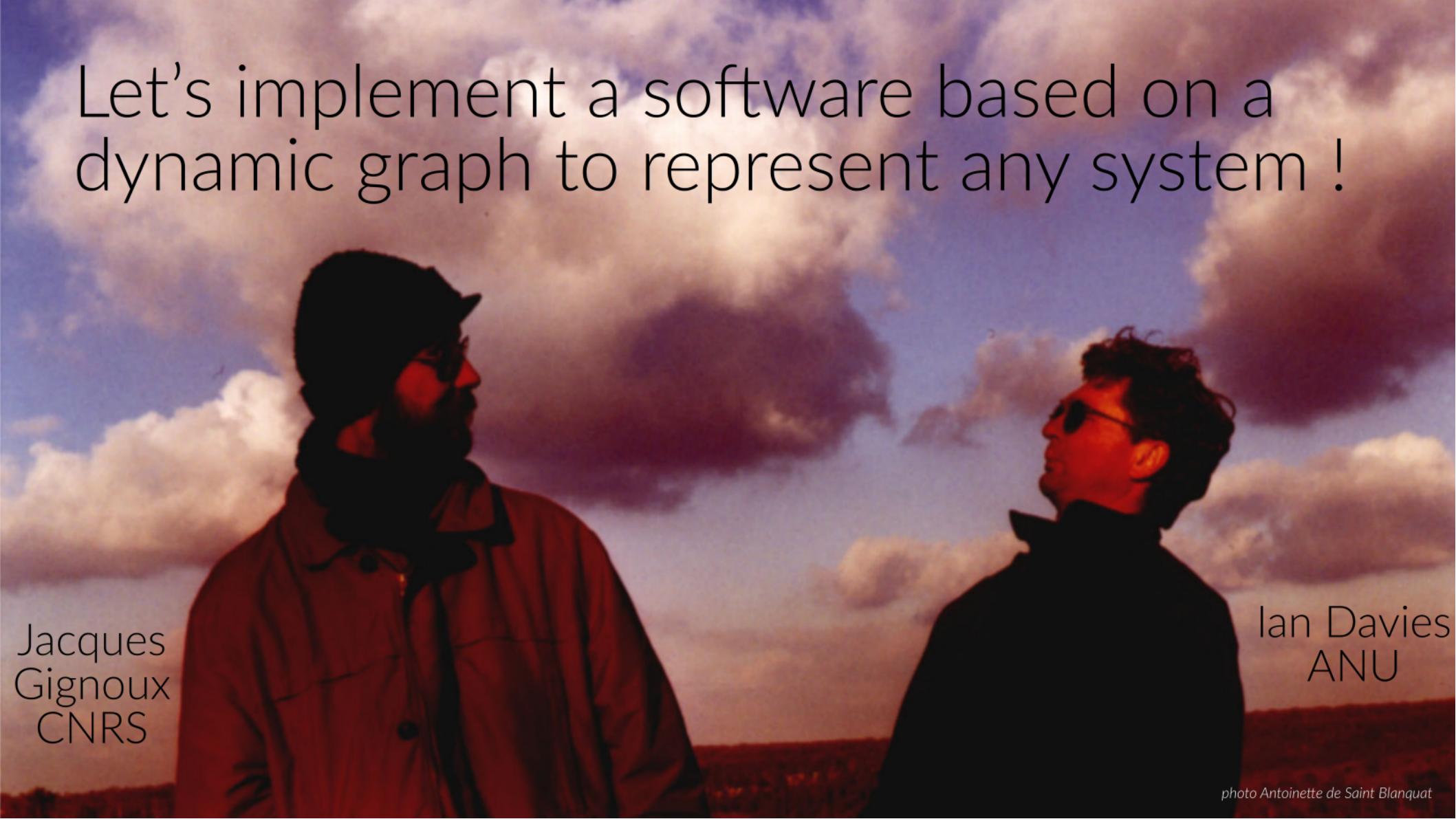
Harary & Gupta 1997. Dynamic graph models, Math. Comp. Model. 7:79-87



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 !



Jacques
Gignoux
CNRS

Ian Davies
ANU

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



Gotlib, M. (1971)
Incorrígibles rêveurs,
Rubrique à brac, 2:26-27

FYC, automatic translation:
'Then my dear, you are in the middle of science fiction!'

My translation:
'Sorry my dear, this is pure science-fiction!'

Or, more direct:
'Bullshit!'

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 }

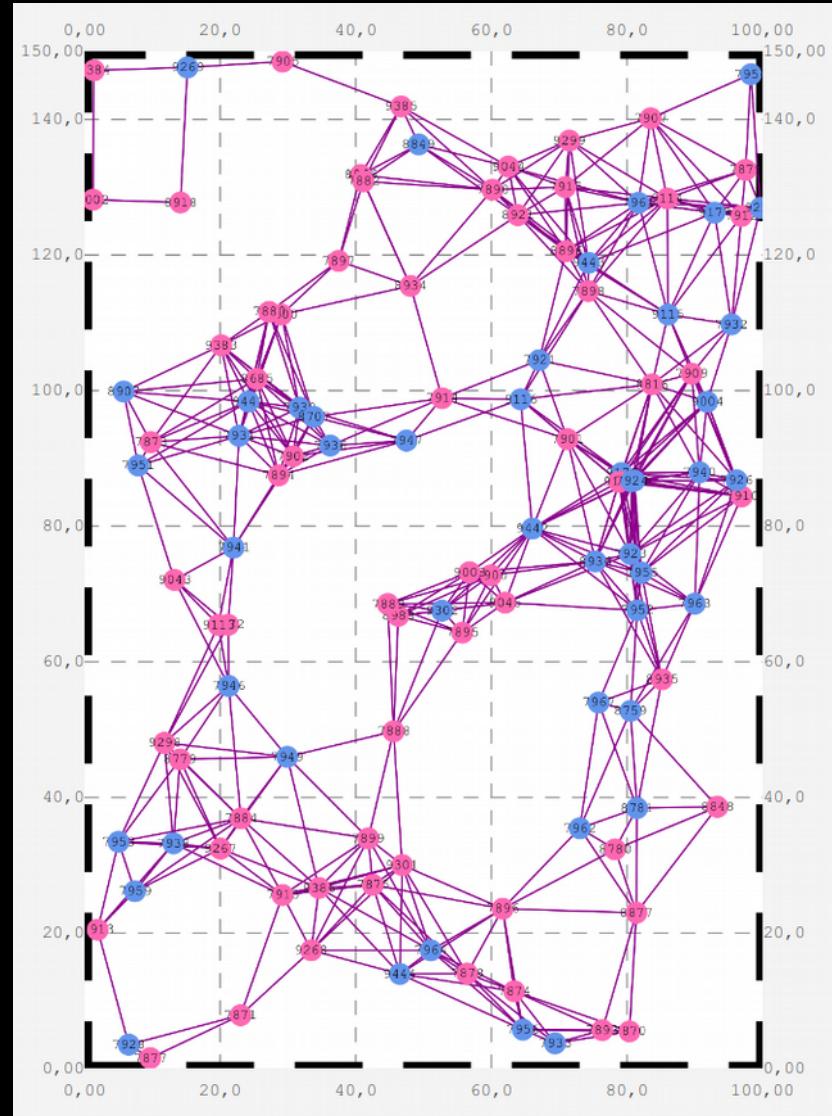
a generalisation for
individual-based models (IBMs)

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.

...but with **explicit** relations



Key design concepts

Categories to group components ‘that look like each other’

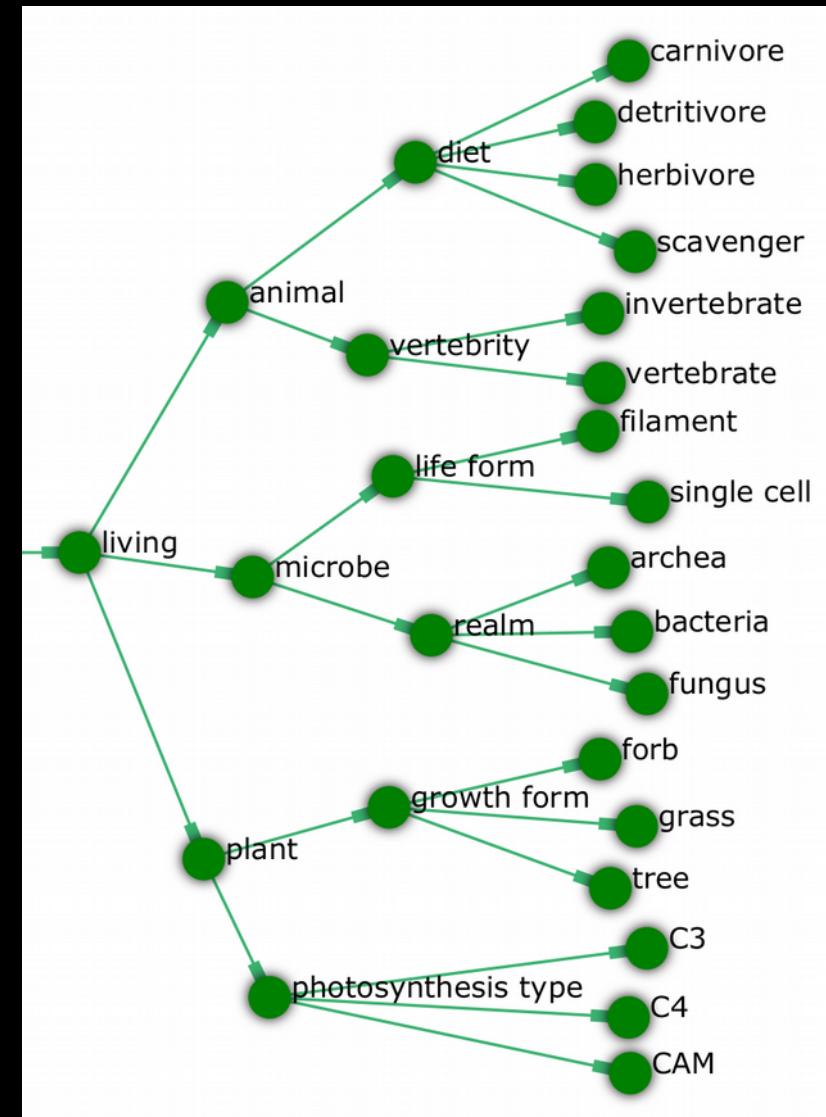
Members of a category:

- 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



How is the graph made dynamic?

Every possible *local* change in the graph state or structure is modelled by a specific function that can be modified to suit user needs:

- → ⚡ **changeState & setInitialState**: changes the descriptor values of a component
- → ⚡ **deleteDecision**: a component decides to delete itself
- → ○ **createOther**: a component creates other components
- → ○ **changeCategoryDecision**: a component becomes member of other categories

How is the graph made dynamic?

Every possible *local* change in the graph state or structure is modelled by a specific function that can be modified to suit user needs:

- ○ → ○ — ○ **relateTo**: component establishes a relation to another component
- — ○ → ○ ⚡ ○ **maintainRelationDecision**: a component decides to keep/delete a relation
- — ○ → ○ — ○ **changeOtherState & setOtherInitialState**: a component changes the descriptor values of another component to which it is related
- — ○ → ○ ⚡ ○ — ○ **changeRelationState**: components at both ends of a relation change their descriptor values

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

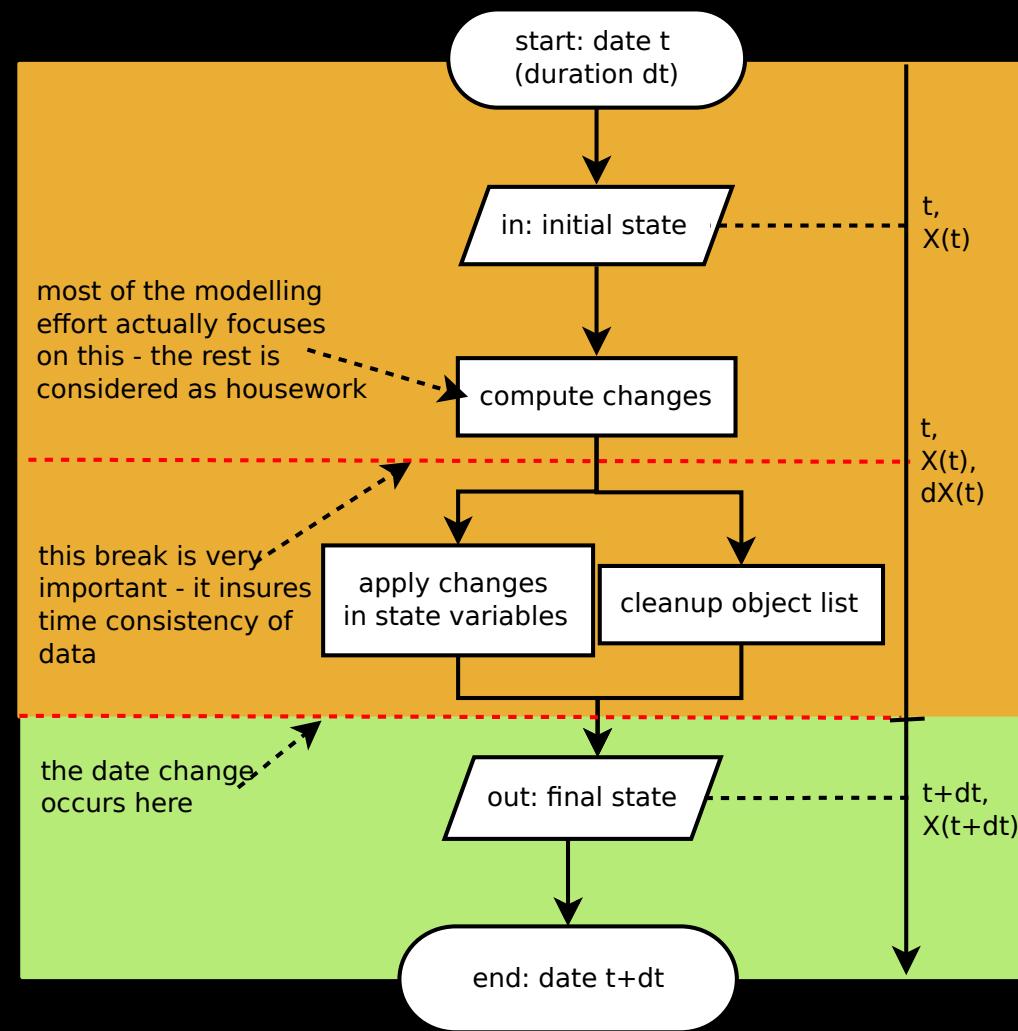
long time units only (month or longer), calendar-compatible

SHORT_TIMES

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

ARBITRARY

arbitrary time units with no predefined name



Key design concepts

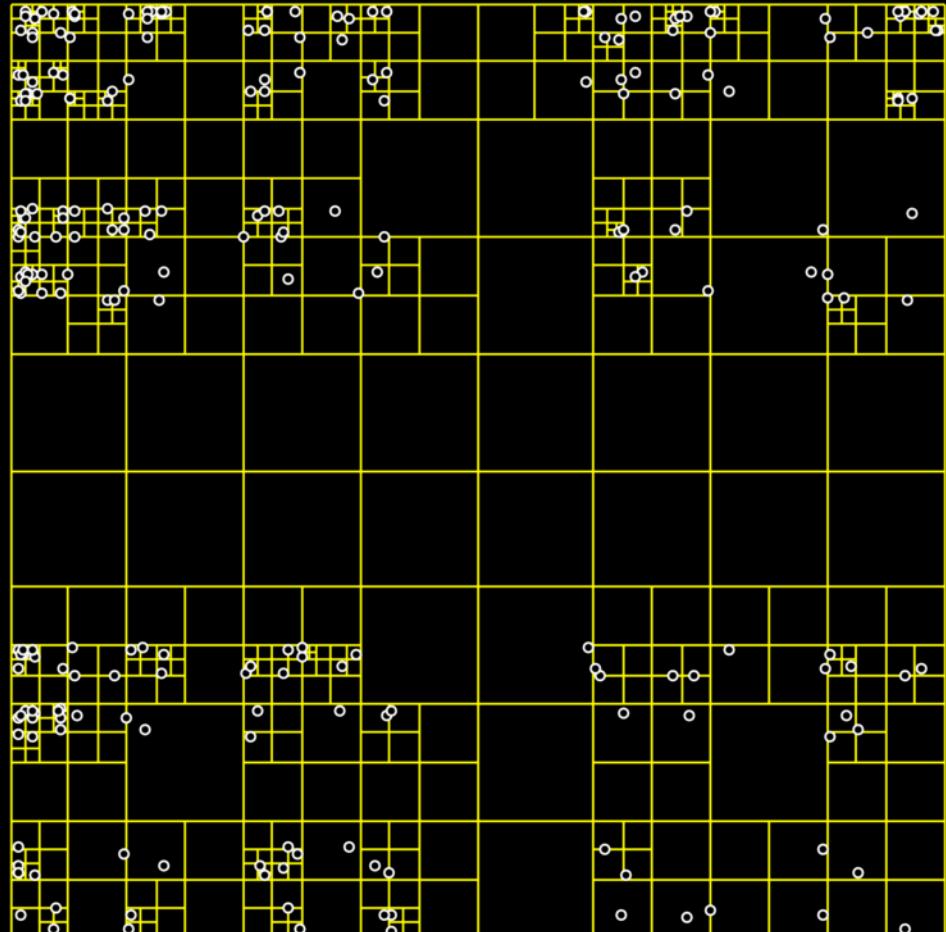
Space optional

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!]



Key design concepts

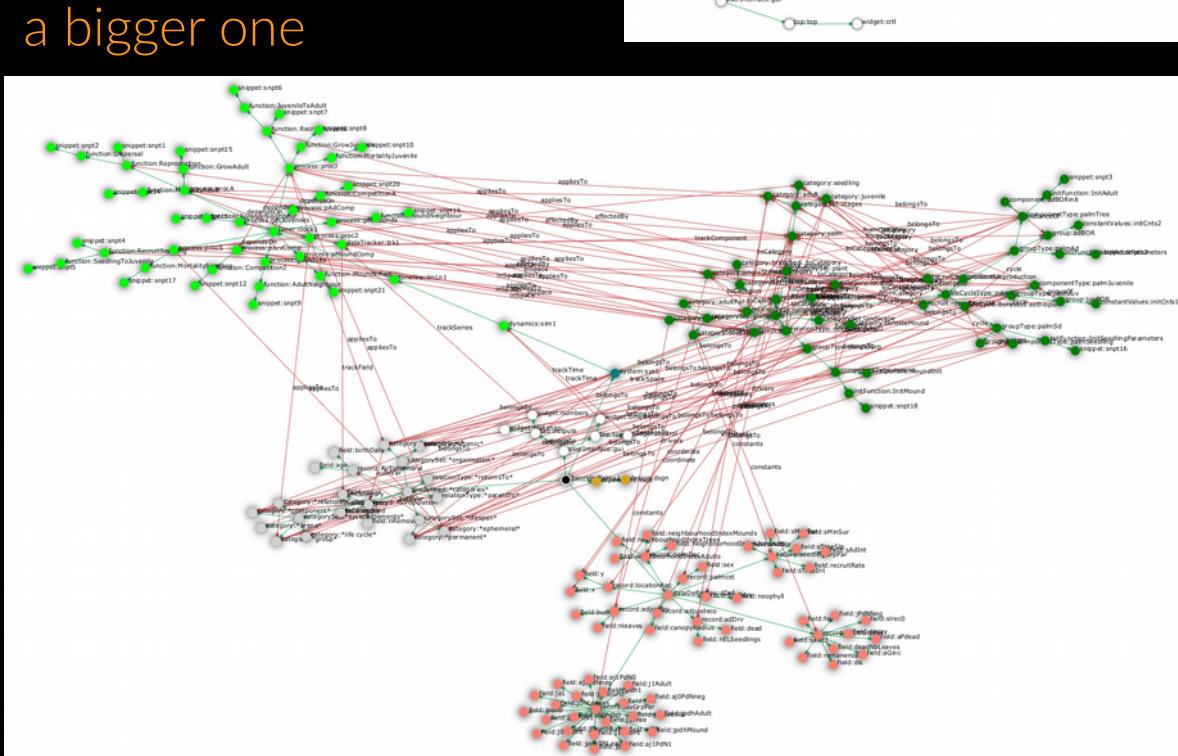
the smallest configuration graph in 3Worlds

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 CO₂ 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

Example 2 (VEMAP members, 1995, GBC 9, 107–107):

Question: Are vegetation predictions of 6 models consistent for the USA?

Method: runs of 6 models on the same datasets.

Conclusions:

**We should do better because
comparing graphs is easier**

- (a) The VEMAP results indicate that uncertainty also exists in the ability to simulate ecological responses to elevated CO₂ 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 [...]

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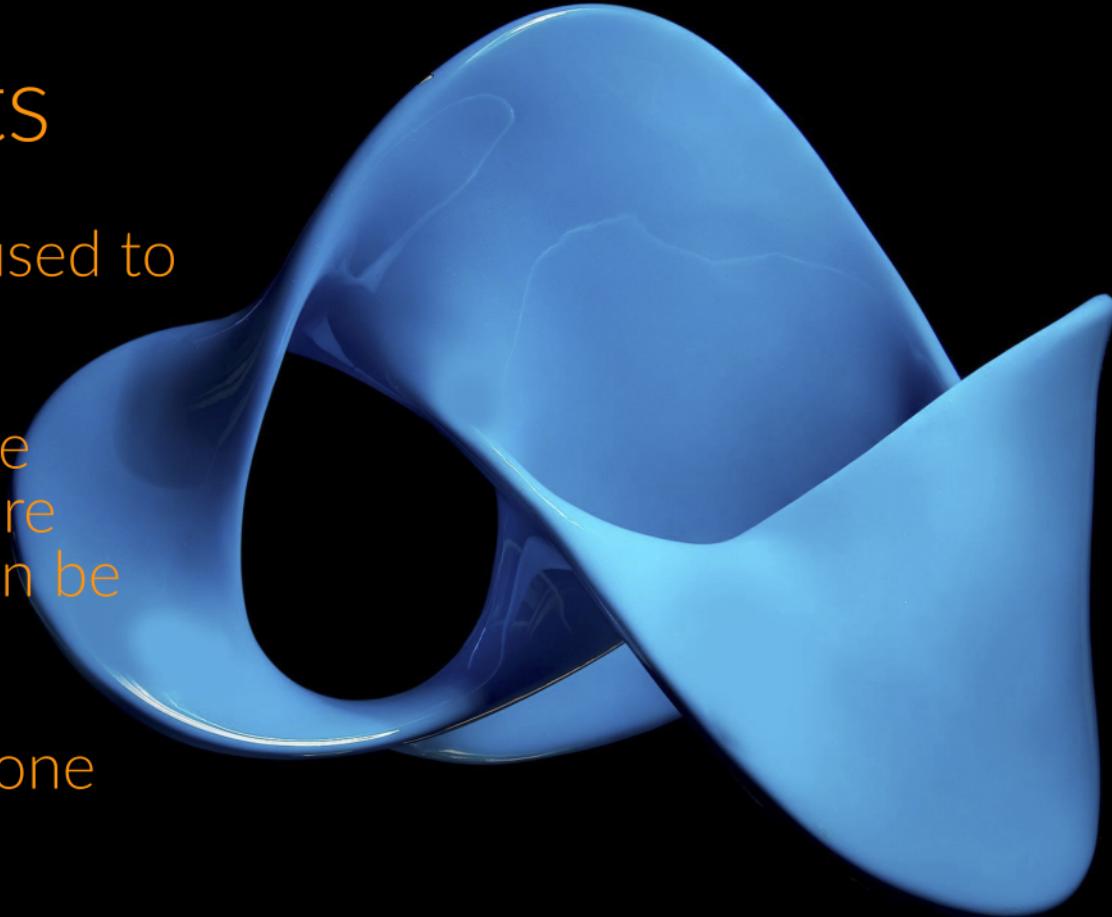
- (d) Between forest and arid regions lie grasslands and shrub-steppe regions, which exhibit complex responses.

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

Key design concepts

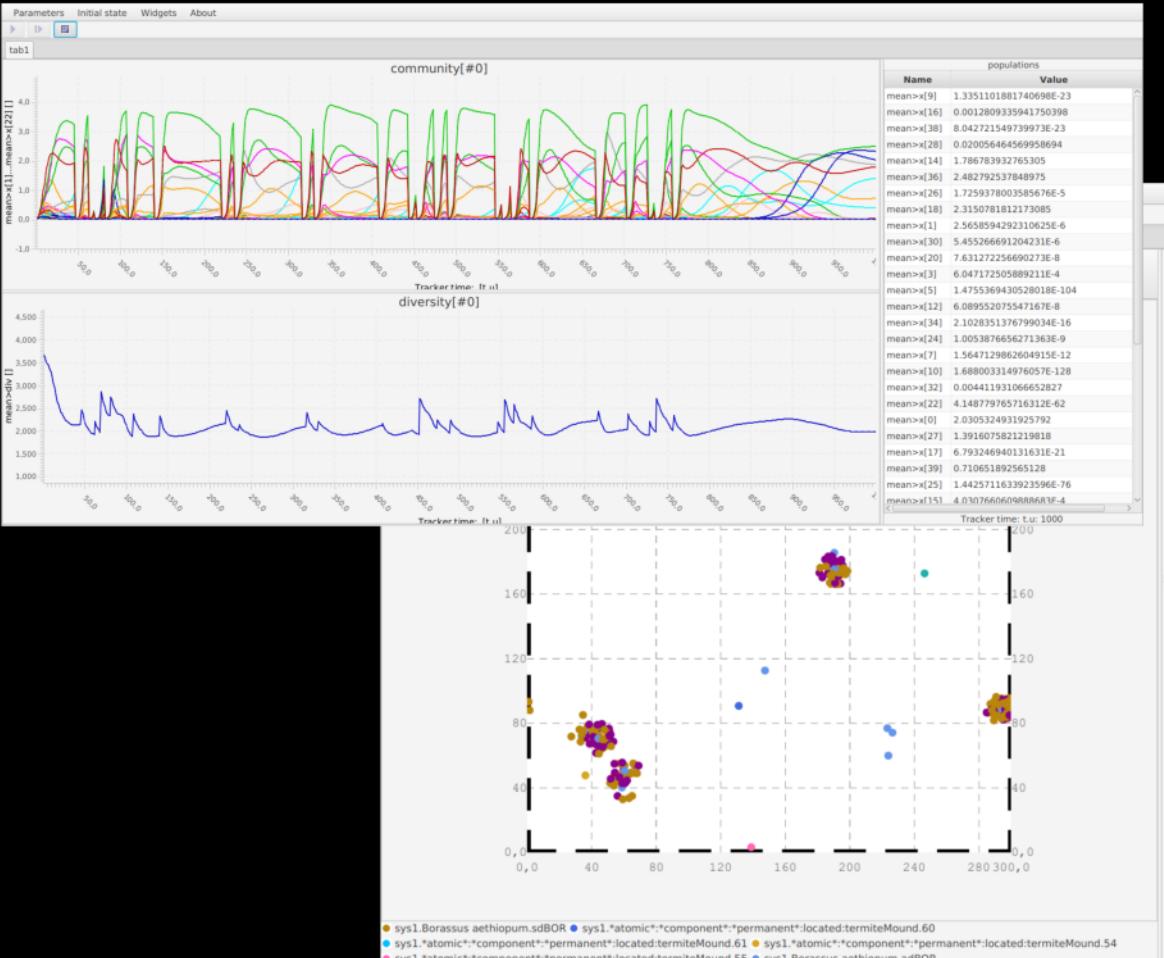
Use case 1 :
developing model
quick feedback on outputs

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 skeleton for any model as an OpenOffice file

```

edge factory = java.lang.String(au.edu.anu.twcore.root.TwConfigFactory)
node factory = java.lang.String(au.edu.anu.twcore.root.TwConfigFactory)
// TREE
3worlds Palms
authors = au.edu.anu.rscs.aot.collections.tables.StringTable(([1] ""))
built-by = java.lang.String(gignoux (21 déc. 2020))
contacts = au.edu.anu.rscs.aot.collections.tables.StringTable(([1] ""))
precis = java.lang.String()
publication = au.edu.anu.rscs.aot.collections.tables.StringTable(([1] ""))
persons = java.lang.String()
predefined *categories*
categorySet *organisation*
category *assemblage*
category *atomic*
record AVEphemeral
field birthDate
precision = java.lang.Double(0.0)
type = fr.cnrs.iees.twcore.constants.DataElementType(Double)
units = java.lang.String()
field age
interval = fr.cnrs.iees.twcore.constants.Interval(-∞, +∞[])
precision = java.lang.Double(0.0)
type = fr.cnrs.iees.twcore.constants.DataElementType(Double)
units = java.lang.String()
record AVPopulation
field count ...it doesn't yet write the article, though.
range = au.edu.anu.rscs.aot.util.IntegerRange(0..*)
type = fr.cnrs.iees.twcore.constants.DataElementType(Integer)
units = java.lang.String(#)
field nRemoved-

```

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
a **java IDE***, e.g. **eclipse** to write function details

runs on Linux, Mac, Windows

currently 13+ models [many more to come]

[optimisation to come]

* integrated development environment. A 'user friendly' software to write code

In practice

java language for portability

~125,000 lines of code

2 applications:

ModelMaker to edit configurations

ModelRunner to launch a simulation experiment

runs on Linux, Mac, Windows

currently 13+ models [many more to come]

[optimisation to come]

**This is no science-fiction
but more tests are needed**

V. Some applications



© Yves Thonnerieux
www.oiseaux.net

The starling (*Sturnus vulgaris*).
Flies.
Loves being in a (huge) group.
Is very noisy and shits while perching.

A flock of starlings



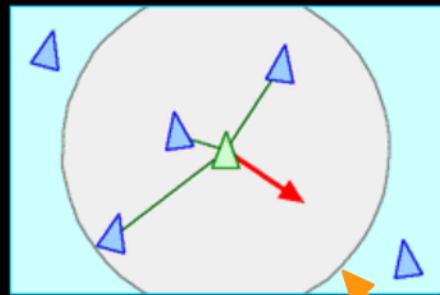
Fish also do it
(so one need not be very smart)



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

1

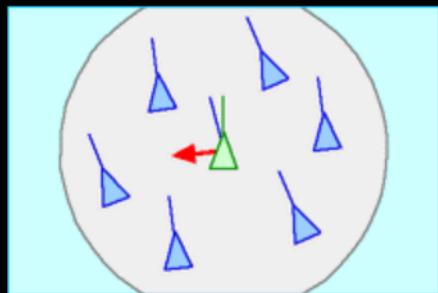
separation: avoid flockmates (close neighbours)



visual
field

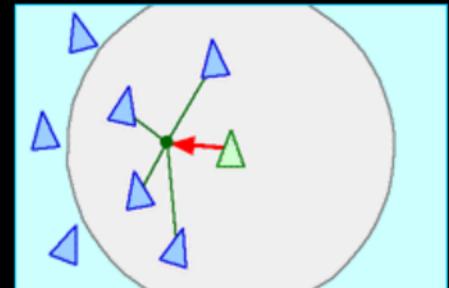
2

alignment: follow average heading of flockmates



3

cohesion: move towards barycentre of local flockmate group



Configuration:

size	153
drivers	5
constants	3
decorators	8
component types	1

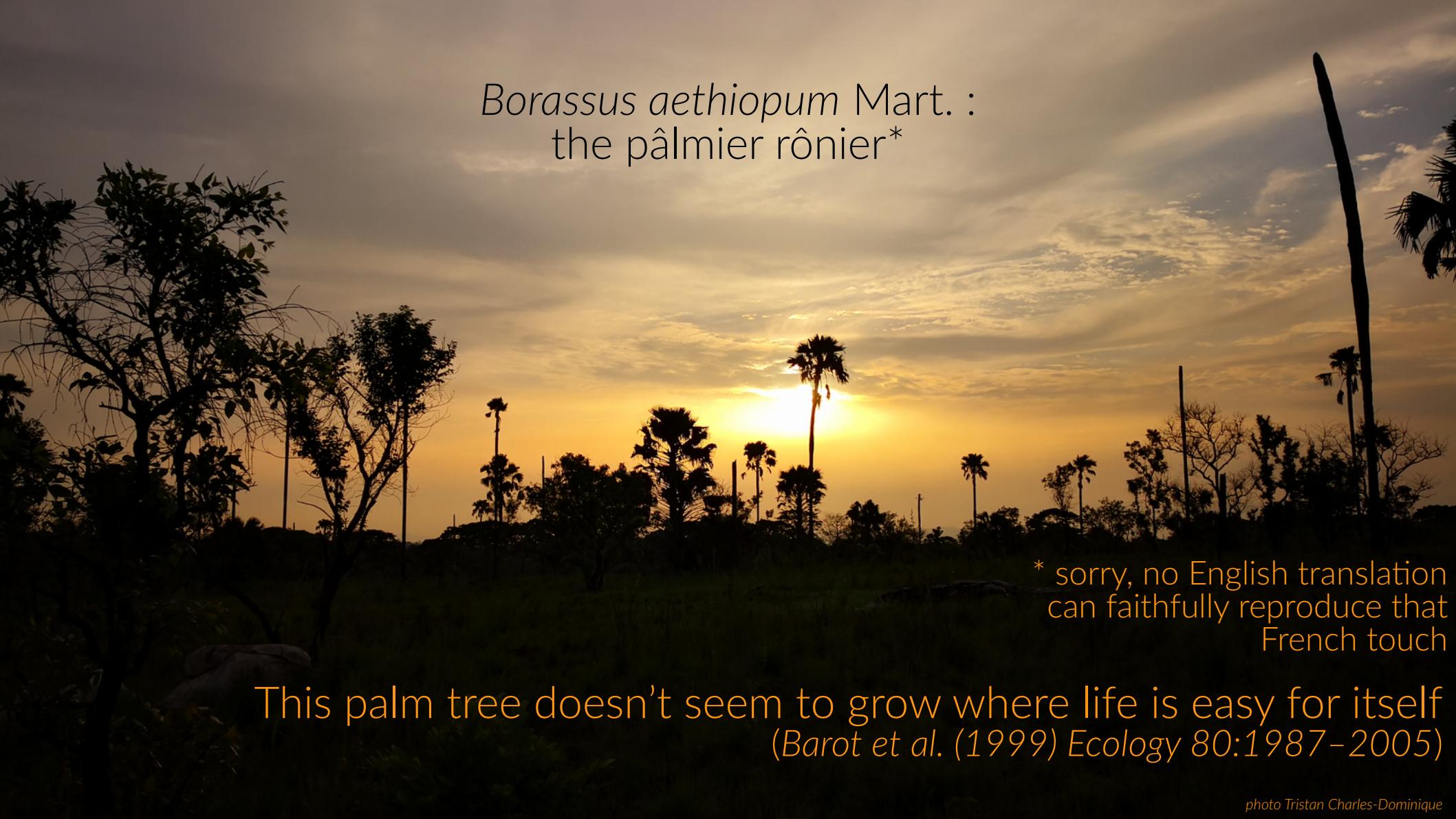
User code: 97 lines

```

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;

```

A photograph showing the silhouettes of various tropical trees, including palm trees, against a vibrant sunset or sunrise sky. The sky is filled with warm orange, yellow, and blue hues, with scattered clouds. The foreground is dark, making the tree silhouettes stand out.

Borassus aethiopum Mart. : the pâlmier rônier*

* sorry, no English translation
can faithfully reproduce that
French touch

This palm tree doesn't seem to grow where life is easy for itself
(Barot et al. (1999) *Ecology* 80:1987–2005)

A data-supported model

3 stages : seedling, juvenile, adult (categories)
adults reduce seedling and juvenile survival
termite mounds increase growth
reproduction starts at adult stage
seed dispersal is very short ranged
spatial pattern gets less aggregated with palm age

Barot & Gignoux 1999, Biotropica
Barot et al. 1999, Oikos
Barot & Gignoux 2003, JVS
Barot & Gignoux 1999, Biotropica
Barot et al. 1999, Oikos
Barot et al. 1999, Ecology

Hypotheses

1. *B. aethiopum* is lacking former dispersers (elephants and baboons) and its spatial pattern will change
2. Without termite mounds there will be no more palm trees in Lamto



Hypotheses

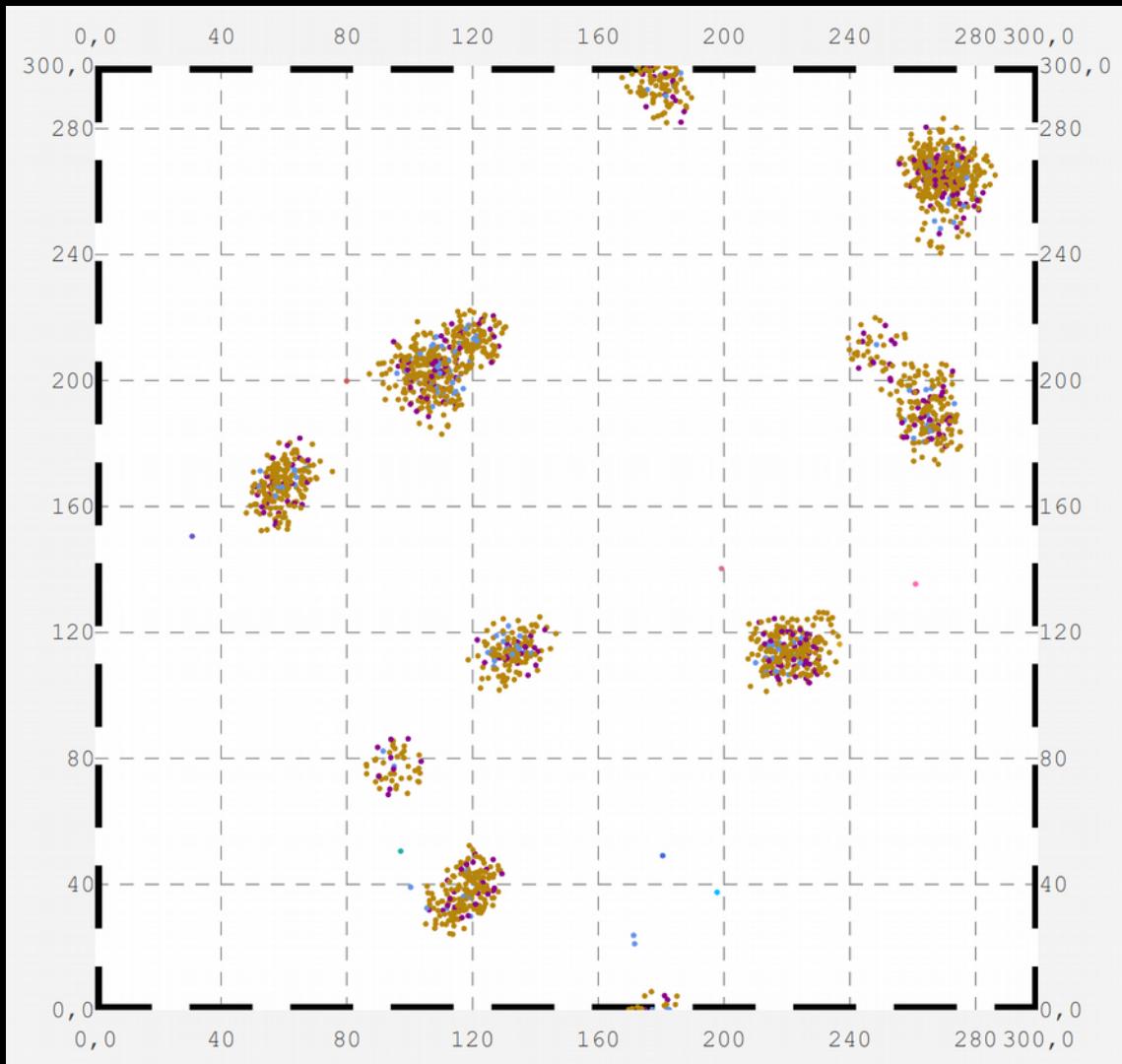
1. *B. aethiopum* is lacking former dispersers (elephants and baboons) and its spatial pattern will change

...

seedling and juveniles are still clumped around adults,

but

adults are much more clumped than in reality

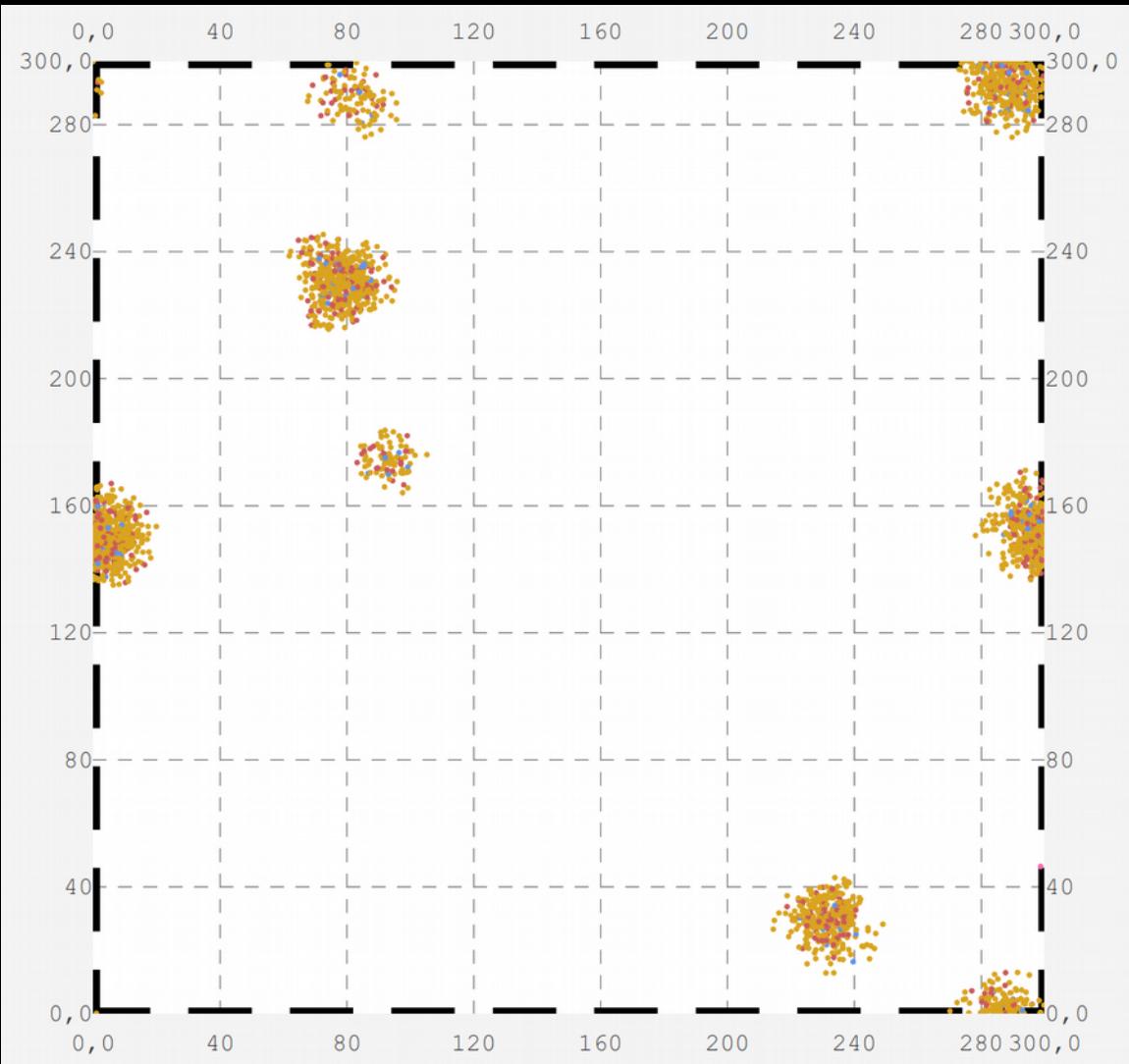


Hypotheses

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

...

The difference is not obvious.
A formal simulation
experiment is needed.



Configuration:

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

User code: 217 lines

```
moundEffect(..)
// relative distance 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_aj0PdNO;
    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_aj1PdNO;
    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



VII. Needs & future plans

testers:

develop models

check GUIs

check checks

programmers

space library

openMole integration

optimisation

graph analysis

**And, anyway, what do you
have against science-fiction
when people spend billions
to plant tomatoes on Mars?**