CHANGING THE LEVEL OF DESCRIPTION IN ECOSYSTEM MODELS: AN OVERVIEW

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ABSTRACT

Aquatic ecosystems are natural open holarchic systems. They are crossed by energy fluxes that give them structure. One of these fluxes is mass transport, which is carried by the fluid flow. This flow is the essential vector for interaction inside the system and thus one of the main contributors to emergent formations structuring these ecosystems. Furthermore, to follow ecosystem evolution, because of their holarchy, it is necessary to observe and represent organizations that span over different scales. We finally present a fluid flow simulation which dynamically detect emergent formations, then manage them on different scales.

INTRODUCTION

France Ministère de la culture has been fighting an increasingly difficult battle against the Lascaux cave since 1963. Discovered in 1940, this rich item of our cultural heritage was opened to the public in 1948. It would then be closed in 1963 because of the proliferation of algae and their bacteria on the painted walls. Since then, the commission in charge of the preservation of the cave has tried to bring it back to a steady biotic state akin to what it was before the discovery of the cave. So far they haven't succeeded, as each solution to one problem was the cause of the next. For instance, the formol used to get rid of the algae was the food used by a *fusarium* mushroom to colonize the caves. Each time they tried to alter a factor to right a perceived wrong, the ecosystem of the cave adopted a new unforeseen trajectory.

This is an example of why ecosystems are tough to handle scientifically. By their size and complexity, they resist reductionist approaches. Ecosystem theories are near impossible to prove formally, as is often the case in life science, and experiments range from very difficult to impossible to carry upon them, because of both structural and moral problems.

Simulations remain therefore among the best tools to validate the models specialists of ecosystems create. Nonetheless, the models are necessarily huge and complex, and computer science must help provide said specialists with tools adapted to running this kind of simulation. This is what we are going to try to describe here.

First, we will describe how, from the original notions of ecosystems, we have now reached a description using advances in systemic and thermodynamics, and how this holarchic description, in the meaning of Koestler, guides the way we must simulate things.

We will then describe how these multiple scales are handled in other parts of science and simulation, in both global and local approaches to modeling.

We will conclude with describing another way of handling scale transfer and an application to the simulation of a fluid flow in an estuarial ecosystem.

REASONS FOR CHANGING THE SCALE IN A SIMULATION OF AN ECOSYSTEM

Ecosystems are ecological systems.

From ecology to ecosystems

The British botanist Tansley coined the word ecosystemks in 1935. This is how he defined them: "The more fundamental conception is … 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. We cannot separate them (the organisms) from their special environment with which they form one physical system ...It is the system so formed which [provides] the basic units of nature on the face of the earth … There ecosystems, as we may call them, are of the most various kinds and sizes."

Following this line of thought, ecosystems are often roughly described by the synthetic equation: "Ecosystem = Biotope + Biocoenosis". They are therefore tackled through a reductionist approach, as is common in science. In this method, each part of the subject of the study is divided in smaller parts, then again until it is estimated that dividing it further wouldn't provide anymore simplicity or clarity. Then, a holistic approach of each part is taken, trying to put back together everything divided during the analysis.

This method works for instance in many sub-domains of physics. However, it does not, work well for ecosystems.

One problem comes from the synthetic, holist part, which proves too vast to handle. But also the first part, the reductionist analysis, through its simplifying way that is at the core of its principle, "breaks" what it studies when it divides it. Unlike massive systems whose division gives more systems whose sum of the masses gives the original mass, ecosystems are more akin to living systems, where dividing leads to unliving systems, not to smaller live ones. The coupling between the different scales is just not subtle enough to represent in an appropriate way what exists in ecosystems.

Event though Tansley used the word "system" in its thermodynamic acceptation, we will now see how this domain alone, if necessary to describe ecosystems, is not sufficient. We must further develop it thanks to Von Bertalanffy systems.

Ecosystems as "General System Theory systems"
Von Bertalanffy introduced a new meta-scientific discipline called General System Theory (Von Bertalanffy 68). This method has later been developed, refined and used by such as Le Moigne (Le Moigne 94) or, as for the domain of our interest, the Odum brothers (Odum and Odum 53).

A system in General System Theory is a set of interacting elements that verify three principles (Frontier and Pichot-Viale 98):

- *Principle of mutual dependence.* At least some of the structures and dynamics of the elements of the system depend one from another. As a consequence, if you isolate one of these elements, you modify it, and if you act upon one of them, you influence some others
- *Principle of an emerging entity interacting with its environment.* From the interaction of some of its elements emerge a "new" entity, which differs from its components by its structure, relations and dynamic.
- *Principle of a retroaction of the emerged entity on its components.* The set modifies the way its composing elements behave; this principle can somewhat be seen as a specialization of the first principle.

Following this definition, ecosystems are "General System Theory systems".

Ecosystems as thermodynamic system
In thermodynamics, systems are parts of matter singled out from their surroundings. These surroundings are the rest of space around the singled parts. Material systemic systems are therefore thermodynamic systems. Ecosystems are always in part material. They therefore incorporate subsystems that are thermodynamic.

When our focus of study of ecosystems is precisely its thermodynamic part, we may abusively call the ecosystem a thermodynamic system, thus neglecting for instance the information relations inside the ecosystem. This is the way it is usually done, as in [Jorgensen et al. 00]. This practice works fine as long as the study is kept to structures little influenced by entities with perception like animals, whose interactions are poorly handled by thermodynamics.

Ecosystems are crossed by flows of matter and energy. If some of these flows are entirely internal to the system, some of them originate from or continue into the environment of the system. Ecosystems are therefore open thermodynamics system.

Furthermore, their trajectory seldom includes equilibrium states, unless the ecosystem is in decline (Frontier and Pichod-Viale 98). The flows of matter and energy may lead them to oscillate around stable states: ecosystems are dissipative systems.

Ecosystems are SOHOs
Ecosystems are therefore what Koestler calls SOHOs, for Self-Organized Holarchic Open systems (Koestler and Smythies 69). A holarchy is an extension of the notion of hierarchy, where the top/down influence is not privileged. Each member of the holarchy is called a holon.

A model of an ecosystem must consequently include this SOHO aspect. Its holarchic part will lead to a multi-level features for the model, while the openness will put an emphasis to the modeling of flows.

Simulation of complex systems

Complexity vs. reductionism
As explained in (Adami 98), to study how mass works in a material system, dividing this system into smaller parts is a good method. Indeed, each of his subsystems is massive, and therefore the study, the reductionism, can continue.

This is not so with living systems. If you divide a living system into smaller parts, the odds are good that all you reap is a heap of dead things. That's because the life question of a live system is *complex*. This means that what is important is not so much the parts of the systems, nor the parts of these parts, but the functioning relations that exist between them.

This is one of the two main reasons why one may want to integrate the multiple possible scales of description into a simulation. When you enquire about a complex question in a system, you need to choose carefully the needed levels of description, as you can't simplify them. Furthermore, these needed levels may change during the simulation, and it would be a fine thing if the simulation could adapt to these variations.

Thus changing the scales of description during the simulation could be useful for the accuracy of the answers to complex questions regarding the system the simulation may provide. And then there is the understanding of these answers.

Clarity of the simulation
Users of a simulation *question* it. Final users ponder about the future of the thing simulated in various circumstances, developers try to ascertain the validity of their model and of its implementation, but all use it with a purpose in mind.

Choosing the right level of description is then important to give a useful answer. If the simulation is able to adapt its descriptions to what is needed by its user, lowering the noise and strengthening the signal, by choosing the right level(s) of description, it will be a better tool. For example in our application, a simulation of a fluid flow in an ecosystem, this help takes the form of hiding tiny perturbation and putting forward the main structures of the flow that emerged during the simulation

METHODS FOR CHANGING THE SCALE IN A SIMULATION

Law-based vs. rule-based models

Classifying the various ways science can tackle problems is an arduous task. We will nonetheless distinguish two rough categories of models.

Law-based models are the most used in science, most notably in physics. They are often continuous, especially in their handling of time and space, and based on a differential formulation whose resolution, ideally formal but often numerical, computes the values of state variables that describe the studied domain. Those methods are sometimes also called *global* or *analytical*.

In rule-based models, the studied domain is discretized in a number of entities whose variations are computed through the use of rules. There is therefore no longer a global description of the domain, nor is there a priori continuity. Cellular automata fall in this category of course, and so do objects/actors/agents. Those models have had a strong influence on game theory, and from there directly on social models, and later on other domain through computer science for instance, at least by way of metaphors. Those models have other names depending on the domain where they are used, ranging from *micro-analytical* in sociology, to *individual-based* in life sciences or just simply *local*.

Both kinds of models can be deterministic or stochastic. Finally, so as to blur the distinctions a bit more, models may include sub-parts falling in any of these categories. This is often the case with ecosystems for instance.

Changing the scale in law-based models

Accessing different levels of description in these models is often done through integration. Indeed, as said before, state function in these models are often continuous, and can therefore be integrated. New state functions are then valued or even built, on another domain and based on different phenomenological equations. For example A. Bourgeat (Bourgeat 97) describes fluid flows in porous milieus, where, from Navier-Stokes equations, through integration and the addition of an extra parameter, he builds a Darcy law. These changes of equations description from one level to another alter sometimes drastically the linearity of the models and may lead to the introduction of new parameters that act as a memory of the local domain inside the global one.

In a similar way to this example, the change of level of description in analytical models is often performed *a priori*, at the building of the model.

Changing the scale in rule-based models

Models based on rules offer a wider variety of ways of changing the levels of description. Indeed, local approaches are better designed to integrate particularities of very different entities and their mutual influence, as is the case when entities of various scales interact.

Cellular automata
The first individual based computer science structures may have been cellular automata. If they were created by Stanislas Ulam, Von Neumann self-replicating automata may have been the foundation of their success. Ulam himself already noticed that complex geometric shape could appear starting with only simple basic blocks. Von Neumann then Langton (Langton 86) expanded this work with self-replicating automata.

If shapes and structures did appear in the course of these programs, it must be emphasized that it were users, and not the programs themselves, that perceive them. Crutchfield (Crutchfield 92) aimed at correcting that trend, by automating the detection of emergent structures.

Detecting structures has therefore been tried, but reifying these structures, meaning automatically creating entities in the program that represent the detected structures has not been tackled yet, as far as cellular automata are concerned. It could be that the constraint on its geometry and the inherent isotropy of the cellular automata are in this case a weakness.

Ecology
Since the beginning of the use of individual based models in ecology, the problem of handling the interactions between individuals and populations occurred (De Angelis and Gross 92). The information transfers between individual was handled either statistically (Caswell and John 92) or through the computing of action potential (Palmer 92).

DAI uses.
Most software architectures designed to handle multiple levels of description are themselves hierarchical. They often have two levels, one fine grained and the other coarse grained. Communication between these two levels could be called decomposition and recomposition, as in (Marcenac 97).

In 1998, members of the RIVAGE project remarked in (Servat et al. 98) that it was necessary in multi-agent simulations, to handle the emergent organizations, by associating them with behaviors computed by the simulation. Before that, were handled only border interactions between entities and groups (Gasser 92).

This led in D. Servat PhD thesis to a hydrodynamic model incorporating in part these notions. In his Rivage application, water bowls individuals are able to aggregate in pools and rivulets. The individuals still exist in the bigger entities. The pros are that it enables their easily leaving the groups, the cons that it doesn’t lighten in any way the burden of computing. Furthermore, these groups do not, to our knowledge, have any impact on the trajectories of the water bowls.

APPLICATION TO THE FLUID FLOW OF AN ESTUARIAL ECOSYSTEM.

Ontological summary

The fluid flows that constitute the ocean currents on the planet are the result of an important number of vortexes of different scales. Turbulent movement can also be decomposed into vortexes, on scales going down to the near molecular. Viscosity then dissipates kinetic energy thus stopping the downward fractal aspect of these vortexes (Lesieur 87). There are qualitatively important transfers of energy between these various scales of so different characteristic length. Representing these is a problem in classic modeling approaches.

In classic, law based models, turbulent flows are described as a sum of a deterministic mean flow and of a fluctuating, probabilistic flow. These equations (Navier-Stokes) are not linear, and space-time correlation terms must be introduced to compensate for that. These terms prevent any follow up of the turbulent terms, and thus of the energy they transmit from one level to another.

A pure law based approach is therefore not capable of a qualitative analysis of the transfer of energy between the different scales of a turbulent flow. A multi-level model, where multiple scales of vortexes would exist, and where they would be able to interact, would be a step in this qualitative direction.

Treatment of multiple scales

Fluid mechanic model and its structures
There are a number of models used to describe fluid flows. The set we use here are based on a discretisation of the flow, and are called vortex methods (Leonard 80).

In vortex methods, the flow is separated in a number of abstract particles, each being a local descriptor of the flow. These particles indicate the speed, vorticity etc… of the flow where they are located.

These particles are not fixed: they are conveyed by the fluid they describe.

This model is of interest to us as it is a local model, hence better able to deal with local heterogeneities. The values of the properties the particles describe are computed through the interactions between the particles, most notably through Biot-Savart formula. More details on this computation can be found in (Bertelle et al. 00).

The vortex method we use is of $O(n^2)$ complexity. Finding ways of lightening this calculus is therefore important. One lead is through making our model multi-scale, and only computing entities at the scale we need them. This is our second motivation for our using different levels of description.

In order to have different levels of description, we will have to use an adapted description of the simulation entities.

These entities come and go during the simulation, and thus we need a method to change the level of their description *during* the simulation, and not beforehand the way it is usually done.

In our fluid flow, the main entities as we explained are vortexes. Not only do we therefore need to detect emerging vortexes by monitoring lower level vortexes particles, but also, as these vortexes aggregate among themselves to form even bigger vortexes, make this detection process iterative.

Detecting the structures is not enough: we also need to create them in the simulation once they are detected. We must make these new entities live in the simulation, interacting with its various inhabitants (most notably particles, vortexes). They must evolve, whether it is growing or decaying to its possible disintegration.

Let us now describe our recursive detection-creation–evolution-destruction cycle.

Detecting emergent vortexes among the vortex particles
Structures are detected as clusters of particles sharing some properties. For vortexes these properties are spatial coordinates and rotation sense.

As described in the following figure, the process is:

- Delaunay triangulation of the particles
- Computation of a minimal spanning tree of this triangulation
- Edges that are too much longer than the average length of edges leading to the particles are removed. So are edges linking particles of opposite rotational.
- The convex hull of the remaining trees is computed
- An ellipse approximates the hull through a least square method

Further details on this process can be found in (Tranouez et al. 01).

Scale transfer : making simulation entities of the detected structures
Detected structures are created in the simulation where they take the place of the particles whose interactions gave them birth.

The vortex structures are implemented through multiplicity automata (Bertelle et al. 01). These automata handle both the relations between higher level vortexes and the relations between them and the basic particles.

The relations between vortexes and their environment are handled through a method based on the eco-resolution model (Drogoul et al. 92), in which entities are described through a perception and combat metaphor. The associated perceptions and actions are:

- Perceiving an intruder means being on a collision course with another vortex.
- Attacking another vortex means sending it a message.
- Being attacked means receiving such a message.

- Fleeing means being destabilized: the vortex structure shrinks and creates particles on its border. Too much flight can lead to the death of the structure, which is then decomposed in its basic particles.
- Getting satisfaction means aggregating surrounding particles of compatible vorticity. This calculation is done through a method close to the initial structure detection: Delaunay triangulation, spanning tree, removal of edges. Compacity criteria are then used to estimate whether the tree should be added to the vortex and thus a new ellipse be computed or not. For instance in figure 1, the particles on the lower left will be aggregated while those on top won't.

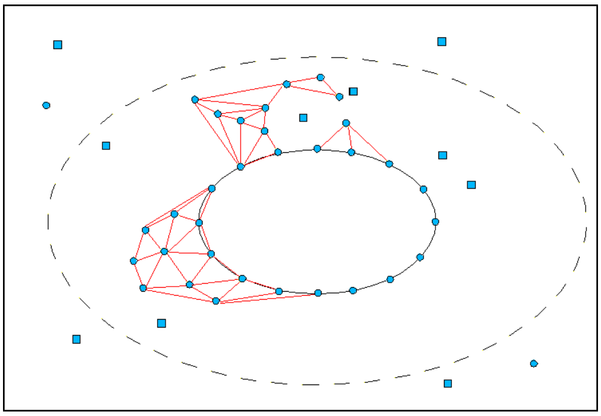

Figure 1 : to aggregate or not to aggregate

The described process is then iterated. New structures are detected and implemented, while others grow, shrink or disappear altogether.

CONCLUSION

A promising approach of ecosystem modeling nowadays is through their representation by holarchic thermodynamic dissipative systems.

The thermodynamic side of this description imposes an appropriate handling of flows in the ecosystem. The holarchic side imposes a software model able to handle multiple level of description, not only in their existence but also in their functioning, which means detecting and managing structures that may appear during the simulation.

The detection part has been attacked for the past 10 years, but the ensuing simulation of the structures is not so densely described.

We propose an essentially rule-based model, with a Navier Stokes law-based bottom foundation that has these properties in our simulation. It is also infinitely recursive, and not limited to just two levels. This is possible because of the fractal nature of the model used to describe the fluid flow.

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