SEE EMERGENCE AS A METAKNOWLEDGE
A Way to Reify Emergent Phenomena in Multiagent Simulations?

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Abstract: Emergence is a fascinating concept for most scientists, and multiagent simulations are known to allow and facilitate its representation. Research in this area yield to several definitions and classifications of emergent phenomena, but only a few of them offers a solution for a concrete reification of emergence in simulation.
This paper deals with this important notion of emergence reification that, as we know, does not have yet formal mathematic definition, if any could be expressed. We need to progress on the conceptual meaning, leading to more global definitions but allowing to give a general conceptual framework that makes possible the reification of emergent phenomena in multiagent simulations. We define emergence as being a metaknowledge and we present a conceptual framework in which emergent phenomena can be detected and injected into simulation systems and be handled like other entities.

1 INTRODUCTION

Simulation of natural and social systems is a cross-disciplinary activity in which computer scientists work with many other researchers who are the experts of their fields (geography, biology, economics, etc.). These experts, that we call *thematicians*, define the models that lie at the core of any simulation: they input the properties and functional descriptions of the system entities. Their goal is to use computer simulations to imitate operations of real-world processes or systems over time (Banks, 2000) and then improve the collective knowledge about the system. They are the owners of the knowledge on the models, and for them computer science is simply seen as a tool.

However, most of them have to face the question of emergence during the design of simulation models. Early defined by greek philosophers with the now-famous phrase “the Whole is more than its Parts” (Palmer, 2000), the emergence concept is present in most scientific fields. Many are the real-world examples that thematicians try to understand and explain: collective behavior among ants colonies, regulation of stock markets, flocking of birds, etc. In this context, the scientists try to find answers to a series of recurring questions (Di Marzo Serugendo et al., 2006; Fromm, 2005), including: *What does emerge? What are the properties of the phenomenon that has emerged?* or *Can we understand the emergence of this phenomenon?* that are all linked with the most general one: *What is emergence?*

This question, which arises for real-world phenomena, also arises for the virtual simulations we create to imitate them. That is why working on the concept of emergence, its representation and its integration in simulations is therefore essential to improve our understanding (i) of the simulation itself and (ii) of the real phenomena that are represented.

Emergence is so an extensively studied concept in the complex systems field. Many work has been done in software engineering (Hu et al., 2007; Abbott, 2007) and many definitions and classifications have been proposed by the multiagent community (Deguet et al., 2007). Multiagent Simulation (MAS) constitute for emergence a very good expressing place whenever emergent phenomena are known to be unilateral or bilateral (Castelfranchi, 1998), weak or strong (Dessalles et al., 2007), synchronic or diachronic (Stephan, 2002), intrinsic or causal (Boschetti and Gray, 2007). Thus, MAS are particularly suited for the emergence concept. They allow us to discover and highlight the phenomena that emerge in the system.

A good and simple example is the one of ant-agents who try to link their nest to a food source (Drogoul and Ferber, 1994). The ants have a very simple behavior but after a while all ant-agents follow the

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shortest path between their nest and the food source. This shortest path has "emerged" from the collective behavior of agents and its existence is due to the system consideration as a whole.

But emergence should not be considered as a simple observation result and emergent phenomena should have a real place in simulation. For example, if we want to simulate a lagoon and its fishes, it would be better to detect potential shoals of hundred fishes that can be formed, and then being able to inject them into the system instead of any of the hundred fishes belonging to the shoals. That is called *emergence reification*. There would be there a significant interest for the system comprehension and in terms of complexity drop during the simulation. But for computer scientists emergence is often manipulated thanks to their knowing of simulation platforms and specific concepts while for thematicians it is often seen only as a result.

According to this, we propose in this paper a first step toward a formalism which is useful but for which we still need progress. In the next section, we will make a key proposition by defining emergence as a metaknowledge. Then, we will take advantage of this definition to propose a conceptual framework in which emergent phenomena can be reified through emergent structures. Within this framework, emergent phenomena can be detected and injected in the simulation system through mechanisms of introspection and intercession to then be manipulated like any other entity.

2 EMERGENCE AS METAKNOWLEDGE

Attempting to reach a possible reification of emergent phenomena, we focused on a concept that appears in many scientific fields related to the design of systems and to artificial intelligence: metaknowledge (Pitrat, 1990; Paguette, 1998; Kalfoglou et al., 2000).

We found in literature that metaknowledge is linked with many philosophical concepts or theories which are very close to our point of view about emergence, like meronomy or mereology, research fields that deal with relations between a Whole and its Parts (Keet, 2006). And when we talk about Parts and Whole, emergence is never far away. In the example "the rum of this punch", the punch is more than the sum of its parts (rum, sugar, fruits, etc.), because these ones can not be separated since the punch was created (and irreducibility is a characteristics of some emergent phenomena (Stephan, 2002)). This encouraged us in order to find a link between emergence and metaknowledge.

Metaknowledge is a tool to work on knowledge and it has been defined as "knowledge on knowledge rather than knowledge about a particular area such as mathematics, medicine or geology" (Pitrat, 1990). The concept is very broad but it can be refined so we can consider among others:

- the metaknowledge describing knowledge;
- the metaknowledge on the use of knowledge;
- the metaknowledge to discover knowledge;
- the metaknowledge to manipulate knowledge.

Thus, seeing metaknowledge as a tool to discover, describe, utilize and manipulate knowledge is in full fit with the fundamental concept of emergence, including the ones of radical novelty (knowledge discovery) and of interdependence levels (use and manipulation of knowledge) (Stephan, 2002). According to this, in our approach we consider the following definition.

Definition. Emergence is a metaknowledge.

This is a key proposition of this paper. Metaknowledge is at the heart of the process of transforming information into knowledge. It offers a greater variety of attitudes and a better way to adapt changes occurring in environments (Luzeaux, 1997) and in that sense this concept is particularly suited to the study of emergence in MAS. So this definition of emergence as a metaknowledge enables us to have new approaches for simulation modeling in order to take into account the emergence of phenomena as best as possible.

3 CONCEPTUAL FRAMEWORK FOR EMERGENCE REIFICATION

3.1 Modeling Approach

To reify emergent phenomena that do occur, we need to built knowledge and metaknowledge on the simulation, even if we do not forget that metaknowledge is only a supplementary knowledge: the difference lies in the levels of abstraction that can be obtained for example through a subjective external observer.

We know that MAS provides knowledge on studied systems, and it is the study of this knowledge that will provide us metaknowledge on the initial systems. For the sake of genericity, this proposal takes place in a MAS model that is most general as possible. We conceive that agents are entities acting through mechanisms of perception, influence and interaction within one or more environments. The proposal is at a conceptual level that allows us not to take into account the specific concepts that are integrated and handled the different multiagent simulation platforms.

As shown on Figure 1, the idea is to construct the knowledge about the MAS by using mechanisms of observation on the simulation. This will provide us the useful elements about the agents, their environment(s), and their evolutions. The metaknowledge about the MAS, and so the emergent phenomena that may occur in simulation, is then defined using the elements of the constructed knowledge. That means that all the emergent phenomena will be described using combinations of whatever happened (or may happen, or... may have happen) in the simulation system. Moreover, and by definition of metaknowledge, when some phenomena emerge, their belonging to the metaknowledge about the MAS means that they belong to the knowledge about it too, and of course to make sense they have to be add to the MAS itself.

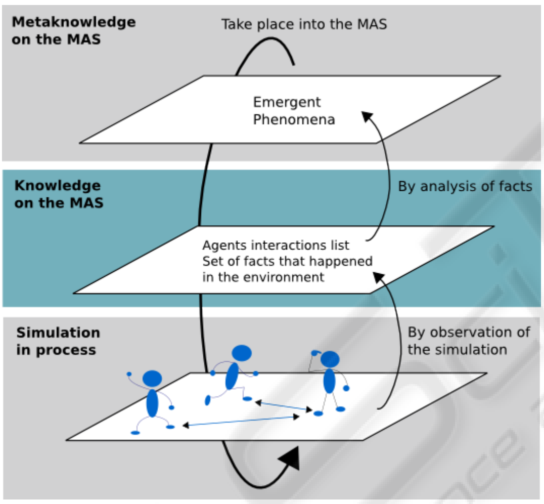

Figure 1: From the MAS to the metaknowledge.

This modeling approach makes possible to thematicians to think about the simulated systems at more abstract levels. Indeed, emergent properties cannot be expressed with the same level used to define the system entities. For example, it is not possible to express the notion of shortest path in the simulation of ants colonies moving to a source of food with the same parameters used to define ants behaviors.
Moreover, it offers the possibility for thematicians to inject into a simulation the properties, behaviors and patterns that emerged. In order to make this conceptual framework intent to detect and learn emergent properties of the simulated systems, we propose in the followings a first step toward a useful formalism of these two aspects of emergence reification. Drawing on works found in philosophy and about reflection and metaobjects (Kiczales, 1991), we called them introspection and intercession processes.

3.2 Introspection Process

In philosophy, introspection is a method of observation and analysis to study one's own person and to acquire self-knowledge. To yield to the detection of emergent phenomena, the MAS has to do its own introspection. Obviously, this process is based on the analysis of the facts that are happening in the simulation. So in the context of our study, we define the introspection process as follows.

Definition. The introspection process consists in creating and expressing knowledge and metaknowledge on the simulation in order to detect phenomena that do emerge.

To detect the emergent phenomena that appear in a simulation, we need to know the set (or a set) of all the facts that are occurring (or have occured in the case of a post-simulation analysis) in the MAS. As we said before, these facts are related to the agents behavior and to their environment. They are function of space, time, communication, and, more generally, they depend on the different entities and the different metrics present in the MAS.

Using the observation mechanisms offered by simulation platforms (probes, publish/subscribe mechanism) to observe the interactions of the agents and the evolutions of the environment(s) in which they evolve, we can build $\mathcal{K}$, a set defined as follows:

$$\mathcal{K} = \{facts\}$$

This set represents the useful knowledge (for emergent phenomena analysis) that can be studied on the MAS. Moreover, we can refine $\mathcal{K}$ as follows :

$$\mathcal{K} = \mathcal{K}_A \cup \mathcal{K}_E$$

where $\mathcal{K}_A$, which gathers the facts produced by agents, is defined by:

$$\mathcal{K}_A = \{influences, perceptions, interactions\}$$

and where $\mathcal{K}_E$ is the set of all the facts produced within the environment.
The emergent phenomena are defined through the study of the set of facts $\mathcal{K}$ that represents the knowledge on the system. Such an analysis of $\mathcal{K}$ consists to establish relations between facts. This helps to highlight the changes that occur in the simulation and that

represent emergent phenomena. To detect these potential changes, we propose to define an extensible set of functions $\mathcal{R}_E$ defined as follows:

$$\mathcal{R}_E = \{f : \mathcal{K}^n \rightarrow boolean\}, \quad n \in \mathbb{N}$$

Each function of this set detects if combinations of parameter facts define an emergent phenomenon. We define these functions as *emergence revelators*.

Using these emergence revelators, we can now define the $\mathcal{P}_E$ set of emergent phenomena:

$$\mathcal{P}_E = \{f \in \mathcal{R}_E / f = true\}$$

It is important to notice that these mechanisms of knowledge construction and analysis do not limit themselves to simple conjunctions of facts: time, space, or communication events can be considered together, as any other types of facts, to reveal complex emergence situations. For example, back to the intrinsic emergence (as defined in (Boschetti and Gray, 2007)) example of the lagoon and its fishes, we can consider that the emergent phenomenon "shoal of fishes" only occurs when hundred fishes are in the same neighborhood, during a minimum period, and when the fish agents interact to know in which direction they should evolve. Thus, our approach is very powerful because we give the possibility to detect emergent phenomena that occurs in complex situations mixing informations on space, time, communication, or whatever.

3.3 Intercession Process

Once emergent phenomena have been detected in simulations, we need to "give them life". In our conceptual framework, this is done during the intercession process that we define as follows.

Definition. The intercession process consists in the injection into the MAS of the emergent phenomena that have been detected during the introspection process.

Most of the time, emergent phenomena that occur in the real world are at least materialized or characterized. Their existence impact directly on other entities of the real world. Some of them may take part of the emergent phenomena, others are influenced by these phenomena, and others have their perception of world modified from the presence of these phenomena. We decided to set up such mechanisms in the virtual world of simulations. Thus, the detection of emergent phenomena sometimes yields to the definition of entities that will directly influence agents behaviors in the MAS. These entities manifest themselves through different kind of elements that we define hereafter : *emergence agents* and *interposition elements* managed by *emergent metastructures* with which they constitute *emergent structures*.

An **emergence agent** is an agent that runs on a MAS platform. It thus evolves in the same environment as all other agents of the system and interacts with them through the mechanisms of influence and perception offered by the platform. Several emergence agents can be created to reify the same phenomenon.

An **interposition element** is a modification of one or several environments. It changes (as appropriate by altering, improving, restricting, etc.) the perception or influence mechanisms associated with one or more agents.

These two elements are controlled by **emergent metastructures** that we call ms_E, which are themselves governed by laws of emergence. These emergence laws are all the elements of the set $\mathcal{L}_E$ defined as follows:

$$\mathcal{L}_E = \{f : \mathcal{P}_E{}^n \rightarrow \mathcal{S}_E\}, \quad n \in \mathbb{N}$$

where $\mathcal{S}_E$ represents the set of all the emergent structures.

An **emergent structure** is defined by a tuple *<emergent metastructure, emergence agents, interposition elements>*. Each emergent structure is managed (created, modified, deleted) by its own emergent metastructure.

An emergent phenomenon $p_e \in \mathcal{P}_E$ is materialized in the MAS through an emergent structure $s_e \in \mathcal{S}_E$ in function of the laws defined in $\mathcal{L}_E$. Depending of its properties, this emergent phenomenon p_e is concretely injected inside the simulation as a one or more emergence agents, as one or more interposition elements, or as a combination of both.

The independent or complementary use of emergence agents and interposition elements allow us to take into account different types of emergence that could occur in MAS. Thus, in the shoal of fish example, the shoal will be represented directly in the system by an emergence agent. The fishes that constitute the shoal of fishes may continue to evolve in their environment, but will have their influences and perceptions changed by elements of interposition controlled by the ms_E corresponding to the shoal of fish. Here, as soon as the thematicians are able to observe and then characterize the behavior of the shoal of fish, it is possible to keep it into the system and to remove each one of the hundred fish-agents that may constitute it. At least we can imagine that the fishes that evolve in the shoal will not need to exchange messages to find collectively the best direction for mov-

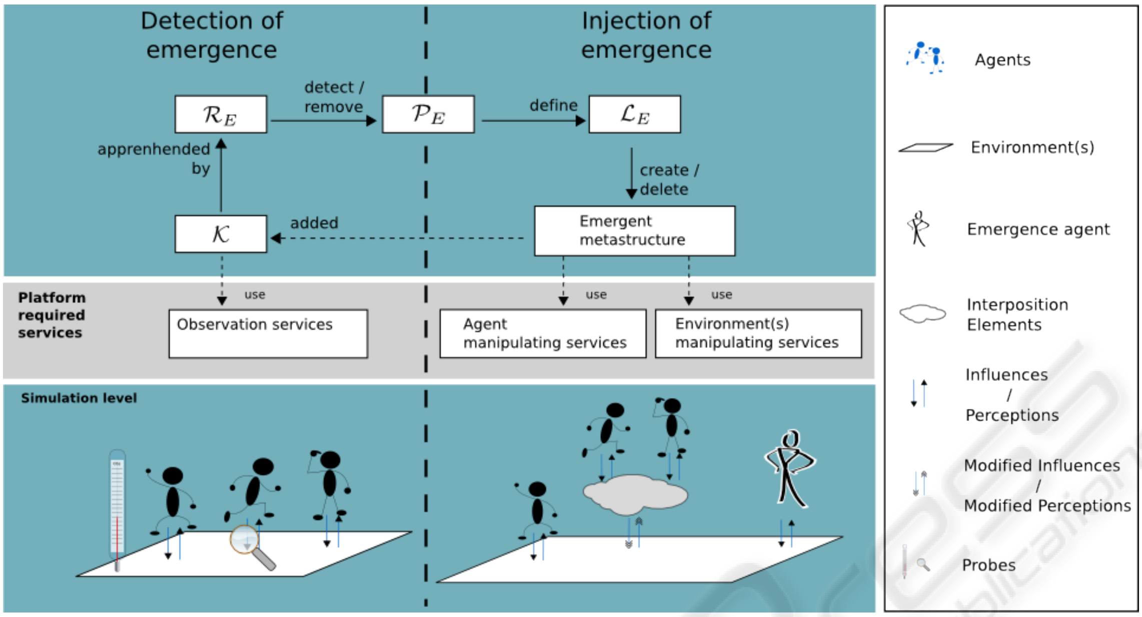

Figure 2: Complete framework for emergence reification.

ing, but that the shoal will take this decision for all of them. No more interactions to deal with for hundred agents : the complexity drop is important.

Notice that this approach supports the dynamism of emergent phenomena, especially their volatility: when an emergent phenomenon is no longer observed, its corresponding emergent structures are deleted from the MAS. Indeed, the functions in $\mathcal{P}_E$ (the ones that activated the corresponding laws in $\mathcal{L}_E$) are no longer defined.

3.4 Emergence Reification

As said in introduction, emergence should have a better place in the design cycle of models and simulations. Figure 2 shows a summary of our proposal, with both the "inside simulation" aspect and the conceptual vision for the complete cycle of emergence reification that we define as follows.

Definition. The emergence reification consists in doing the complete cycle of the introspection and intercession processes

We can also see on Figure 2 that because emergent structures can have their own behavior, they also contribute (via their own influences and perceptions) to create new knowledge that can be added to the set of facts. Once more, this contributes to refine the knowledge on the MAS.

At the junction of the conceptual works and the MAS representation, we identified three services that simulation platforms should have to reach such a reification of emergent phenomena:

- observation services (to set up the observation mechanisms useful to build knowledge on the MAS);
- an agent manipulation service (to create, delete and modify agents cycle of life);
- an environment manipulation service (to manipulate the interposition elements).

Notice that the MAS platform that we develop in our lab fits with the conceptual framework we defined in this paper. This argues for the feasibility of our approach. Because of the genericity of the proposal, it is a reuse advantage that would benefit to other simulation platforms that would like to set up such emergence reification mechanisms.

Before concluding, it is important to remind that with this conceptual framework, thematicians have a new role to play during the modeling cycle of simulations: thinking about the $\mathcal{R}_E$ and $\mathcal{L}_E$ sets that appears in the processes of introspection and intercession. This is consistent with what happen in the real world: thematicians do not have any innate knowledge on emergent phenomena and it is only from observation that they have learn to recognize, characterize or name them. The first phenomena that emerge and that may be detected by mechanisms of observation are the result of the descriptions initially provided by the thematicians. So forth, the detected emergent phenomena will constitute a kind of new knowledge, that it is important to add to the global knowledge of the system. This will yield to a better understanding of the simulation system itself and to the discovery of new emergent phenomena that could not have been identified with the thematicians initial knowledge.

4 CONCLUSIONS & DISCUSSION

In this paper, we focused on the emergence issue and on its representation in MAS. We consider that we need to improve the way this concept is taken into account in simulations and we proposed a conceptual framework that enables the reification of emergence in simulations.

Actually, this is allowed by the analysis of the knowledge on the simulation. That is why the main issue of our approach is the definition of emergence as a metaknowledge on the MAS: it is the key concept that we used to propose and describe a conceptual framework for the detection and injection of the different kinds of emergent phenomena. Thanks to this, we identified the services that should be available in simulation platforms to take emergence into account.

Our experience on large-scale simulation projects and our long-time wondering about the representation of emergence in MAS (Marcenac et al., 1998) has led us to make this conceptual framework the most simple and generic as possible. In that sense, we consider it as a first step (i) toward a formalism which is useful but for which we still need progress and (ii) in the way of designing models and programming with emergence.

In future works, we will use the conceptual framework we described in this paper to improve a multiagent application of energy simulation under development on our simulation platform GEAMAS-NG, in the context of a research program financed by the Reunion Island. Drawing on this conceptual framework we will also extend our platform in order to take emergence into account as soon as we start the conception of the simulation agents, while keeping a clear separation between initial behaviors and emergent ones. This would improve agents capacities by giving to them the possibility of reasoning on themselves and so on emergent phenomena that will get back some piece of magic.

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