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Crystallization and tile separation in the multi-agent systems

Jacques Henri Collet *, Jean Fanchon

Laboratoire d'Analyse et d'Architecture des Systèmes du Centre national de la Recherche Scientifique, 7 avenue du colonel Roche, 30177, Toulouse CEDEX, France

HIGHLIGHTS

- We consider large populations of mobile agents coupled by binary interactions.
- We study the emergence of order by only changing the interaction rules.
- We show the formation 2D hexagonal or rectangular multi-agent crystals.
- We also show the complete separation of agents in regular hexagonal tiles.

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ABSTRACT

This paper deals with the self-organization of simple mobile agents confined in a two-dimension rectangular area. Each agent interacts with its neighbors inside an interaction disk and moves following various types of force-driven couplings (e.g. repulsion or attraction). The agents do not know their absolute position, do not exchange messages, have no memory, and no learning capabilities. We first study the self-organization appearing in systems made-up with one sole type of agents, initially generated at random in the terrain. By changing the agent–agent repulsive interaction, we observe five different population reorganizations, namely, grouping, diffusion (that is classical), but especially interesting, crystallization (i.e., the agents group together on the vertices a regular hexagonal lattice), alignment along straight lines, and vortex dynamics. Then, we consider reorganization in systems made-up from two to five types of agents, where each pair of agent types has specific interaction parameters. The main result of this work is to show that, by only changing the agent–agent repulsion rules, one can generate hexagonal or rectangular multi-agent crystals or on the contrary, induce complete separation in regular hexagonal tiles.

1. Introduction

A huge number of papers have been published analyzing the properties of mobile agents, where each agent makes a move decision autonomously from the local knowledge of its environment. This approach has been applied for instance to the design of intelligent swarms in robotics [1,2], to sociology [3–8], to explain the behavior of biological systems, including bacteria populations, simulation of herds of animals, pedestrians [9], flock of birds [10–12], schools of fishes [13–15], etc. These examples show that the "agent" paradigm is generic, covering a large variety of autonomous systems that have little in common. When considering agents, it is thus of utmost importance to accurately specify which information they can acquire from their environment, whether they can communicate (via messages or pheromones [16]), whether they know

* Corresponding author. Tel.: +33 561336220.
E-mail addresses: jacques.collet@laas.fr (J.H. Collet), jean.fanchon@laas.fr (J. Fanchon).

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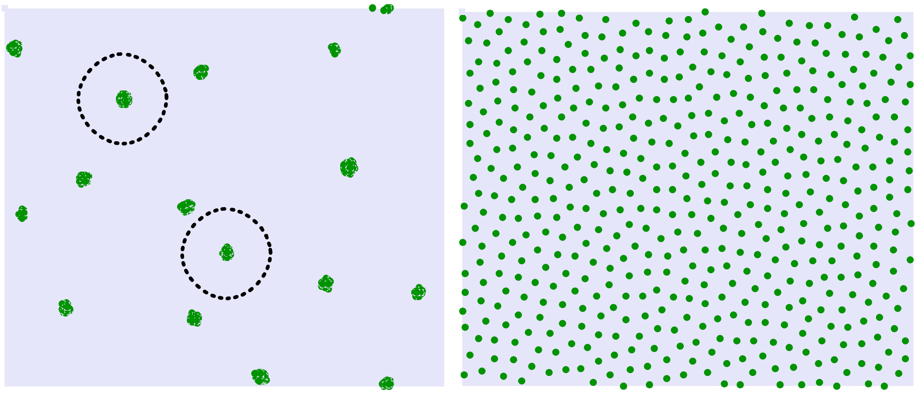

Fig. 1. *Left*: Aggregation of agents in clusters in case of agent–agent attraction. The dotted circles represent the agent interaction radius and show that the clusters are not coupled in the long term. *Right*: Diffusion and random occupation of the area in case of repulsion ($n = 2$ in Eq. (2)).

their absolute position, whether they can learn from their past experience [17–20] or adapt their policy [21]. It is also crucial to clarify how they make a decision (with the definition of collaborative policies [22,23]), etc. because all these properties dramatically determine the processing capacity of the agent, and the potential complexity of its behavior.

In this work, we focus on the crystallization and tile separation of simple mobile agents which resemble physical entities. Each agent interacts with the other agents inside its interaction disk and calculates their positions relative to it. A very important point is that the agent does not know its absolute position, does not exchange messages, has no memory and executes a simple move algorithm as will be shown below. Demonstrating the emergence of organizational properties with such crude agents is not trivial whereas, there would be no great merit to achieve the same result with agents that have significant planning capabilities and could execute any sequential algorithm to move to the correct position. Here, we address the problem of the link between the local rules and the macroscopic properties (see also in sociology [24]). The central question is: Starting from agents initially distributed at random, is it possible, just by changing the sole couplings between agents (thus local properties), to evolve the system towards stationary distributions presenting high macroscopic symmetries?

In Section 3, we first study the self-organization in a population build-up with a single-type of agents. Studies are conducted by simulation (the simulator is described in Section 2.2). We observe five basic temporal evolutions, namely:

- *Random clustering*: The agent–agent interaction is repulsive at short distance in the interaction disk, then attractive in the rest of the disk. The evolution starts with the formation of small agent aggregates (made up of a few agents) which grow in size, coalesce and progressively loose in mobility (see Fig. 1, left). This behavior is no real surprise [25].
- *Diffusion-homogenization*: Diffusion occurs when the agents have a repulsive interaction (decreasing as $1/d^2$) inside the interaction disk. It results that agents occupy the whole area in a self adaptive way, even in the presence of obstacles (not represented in this study). This behavior is also no real surprise.
- *Crystallization*: It occurs when the agents have a repulsive interaction the intensity of which is *independent* of the distance inside the interaction disk. It follows that the agents separate and aggregate exactly at the vertices of a hexagonal lattice. We already described this property in Ref. [26]. The final state is a high symmetry distribution (see Fig. 2).
- *Alignment*: It occurs when each agent follows a repulsive interaction inside the interaction disk, and takes an anisotropic move decision because it knows a reference direction. Typical alignment of agents is shown for instance in Fig. 4.
- *Vortices formation*: Vortex dynamics appears when the repulsion between two agents i and j is not collinear with the direction joining them. Typical long term distribution is displayed in Fig. 5.

Then, we study more complex systems build up from two to five types of agents. In these cases, specific interaction parameters are defined for each ordered pair of agent types. We study the *incremental* organization in Section 4. It consists in adding one or several populations (say A) to existing ones (say B) which do not detect A, while A detect B. Thus, the populations B are not disturbed, while the agents of types A occupy positions resulting from the stationary pre-existing distribution reached by B and from the way the programmer defines the interaction of agents A. The striking result observed in this section is the formation of amazing crystals coupling several agent types (see for instance Figs. 9 and 10).

Finally, in Section 5, we consider the problem of the spatial separation of several types of repulsive agents. The incremental approach is abandoned since each agent interacts with all the agents inside its interaction disk whatever the type. We show that it is possible to achieve full separation of the different types in regular hexagonal tiles (see Figs. 13 and 14).

2. Model of population dynamics

2.1. Local move decision

The agent algorithms that we consider are based on a common principle: Each individual, say the agent of index i, calculates a direction vector $\vec{V}_{ij}$ for each neighbor j inside its interaction disk. The sum of all the elementary vectors $\vec{V}_{ij}$