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Diversity and survival of artificial lifeforms under sedimentation and random motion

Nicolas Glade¹  · Olivier Bastien² · Pascal Ballet³

Abstract Cellular automata are often used to explore the numerous possible scenarios of what could have occurred at the origins of life and before, during the prebiotic ages, when very simple molecules started to assemble and organise into larger catalytic or informative structures, or to simulate ecosystems. Artificial self-maintained spatial structures emerge in cellular automata and are often used to represent molecules or living organisms. They converge generally towards homogeneous stationary soups of still-life creatures. It is hard for an observer to believe they are similar to living systems, in particular because nothing is moving anymore within such simulated environments after few computation steps, because they present isotropic spatial organisation, because the diversity of self-maintained morphologies is poor, and because when stationary states are reached the creatures are immortal. Natural living systems, on the contrary, are composed of a high diversity

of creatures in interaction having limited lifetimes and generally present a certain anisotropy of their spatial organisation, in particular frontiers and interfaces. In the present work, we propose that the presence of directional weak fields such as gravity may counter-balance the excess of mixing and disorder caused by Brownian motion and favour the appearance of specific regions, i.e. different strata or environmental layers, in which physical–chemical conditions favour the emergence and the survival of self-maintained spatial structures including living systems. We test this hypothesis by way of numerical simulations of a very simplified ecosystem model. We use the well-known *Game of Life* to which we add rules simulating both sedimentation forces and thermal agitation. We show that this leads to more active (vitality and biodiversity) and robust (survival) dynamics. This effectively suggests that coupling such physical processes to reactive systems allows the separation of environments into different milieux and could constitute a simple mechanism to form ecosystem frontiers or elementary interfaces that would protect and favour the development of fragile auto-poietic systems.

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Introduction

Artificial environments where synthetic lifeforms (numerical creatures, simulated biological systems, or hardware imitations of the living) “live”, constitute experimental numerical platforms where hypotheses on physics, chemistry or other aspects expected to play a role in the functioning of life can be tested (Rennard 2004). Although

extremely simplified and obviously far from real systems, numerical experiments of simulated biological or biochemical systems somehow reflect the nature of the living, giving access to what it could be or could have been (Sims 1994a, b; Bedau 1999; Feitelson 2006; Dowek 2011; Varenne et al. 2015). Artificial life is also naturally used to test hypotheses on the origins of life. Moreover, the understanding of how such artificial or synthetic golems¹ behave and can be controlled allows the development of several branches of unconventional computation, from bioinspired computing to natural or physical computing (MacLennan 2014, 2015; Varenne et al. 2015; Courbet et al. 2015; Adamatzky 2017).

What is fascinating when thinking to the nature of life, especially at its origins, is how semantically closed functionality, the self and its functional elements that Pattee calls “symbol vehicles” (Pattee 2015), emerges from disorganised matter and then self-replicates (Maturana and Varela 1974, 1988; Varela 1989; Vareto 1993, 1998). Nature, from single biochemical systems to evolved life-forms, needs driving forces to self-organise at a macroscopic level but also other mechanisms to control and differentiate such self-organisation in space and time. At the least, self-organising structures and processes have to be contained in space by boundaries to pretend to belong to the living: this is the self-defined topological domain where the emerging auto-poietic network “lives” as defined by Varela (1989), or the “gabarit” in insect societies (Grassé 1959); living cells are limited by a membrane and ecosystems often by geographical boundaries. By this way, proto-cells first and then living systems are prevented from being diluted or isolated, are able to differentiate throughout space, and can support functionalities (from “simple” auto-poietic loops to complex metabolisms) over time (Langton 1984; Mange et al. 2004; Ho and Ulanowicz 2005; Sayer 2007).

Original soups of randomly produced elements [e.g. Miller’s experiment (Johnson et al. 2008)] start to assemble to form functional structures [e.g. in artificial auto-poietic system (Kauffman 1986; Vareto 1993; Ray 1994)]. However, they do not satisfy the sustainability condition in space: molecules naturally diffuse in such a way these emerging systems cannot maintain themselves over long periods nor reproduce. In this context, at the origins of life, but also within ecosystems, many physical milieux or processes are seen as candidate micro-environments to protect such emerging micro-ecosystem, by preventing

¹ This term, used by Rennard (2008), refers obviously to our wishes to give life to amorphous matter, but it probably also hides additional meanings: the facts that such models have a purpose (not only to “be themselves” but to serve our understanding), that we control them and that they are designed as reflects of our own limited knowledge of what is life.

their dilution, allowing them to complexify and differentiate in such a way they progressively get close to current living systems. This can be achieved by the aggregation of molecules in the form of *composomes*, self-assembled hyperstructures in which function and structure are interdependent (Hunding et al. 2006; Norris et al. 2007), by the containment between self-organised membrane layers (Langton 1984; Cornish-Bowden and Cárdenas 2008), the formation of microcosms due to water evaporation of ponds or mud puddles, by condensation within clay stacks or at the surface of crystals or metallic particles (Cairns-Smith 1990), or even by sustainment at the frontiers between regions of different nature. The last corresponds to fuzzy boundaries that delimit small regions where life can develop. One can find examples in the strong gradients of temperature in the neighbourhood of dark smokers (hydrothermal vents) in the deep ocean where life is suspected to have appeared (Whitfield 2009) and in the surrounding of geysers like those of Yellowstone park. Other examples are the periodic variations of composition or concentration in self-organised chemical or biochemical reactions such as Turing-type spatially self-organised reactions where stationary patterns form (Turing 1952; Castets et al. 1990), or the wave fronts of excitable media (moving waves or spots) like in the Belousov–Zhabotinsky reaction (Vavilin et al. 1967a, b; Zhabotinsky and Zaikin 1973; Zhabotinskii 1974; Kagan et al. 1983; Vanag and Epstein 2003), as proposed in Zeng et al. (2004) and Abbas et al. (2009).

Gravitational sedimentation of organic and inorganic materials and their deposition on a surface (or other forms of differential separation and containment due to other directional fields or forces, e.g. in vortice) is a very efficient process in nature to form dense bio-active sediments and sludges. Sea or lake muds are composed of mineral and decomposing organic matter, of gas and organic oils, but also of living matter. They are places where very interesting dynamical processes occur. An example of this is the stratified ecology of oceans and forests. In such environments, very diverse lifeforms develop on the ground (ground of the forest, continental plateau in the ocean, bottom of lakes...), escape from the ground toward the diluted and less diverse milieu above, die and fall to the ground, and are finally recycled in an active mud. Deep ocean landscapes are deserts punctuated by oasis of life: whales’ cadavers that offer about 50 years of resources (Smith and Baco 2003), volcanic dark smokers,..., constitute local environments where a very diverse life develops. Below marine grounds, degradation of organic compounds and dying organisms produce organic oil layers or gas bubbles that can themselves constitute new interfaces (Mason et al. 2010), or travel toward the surface of the mud and cause its bubbling. Other internal processes reinforce the mixing of sediments and their degradation

process. The so-called bioturbation process is due to numerous macroscopic creatures like worms or shellfishes that travel vertically and horizontally within sediments (Janson 2007).

In real systems, stratification by sedimentation is expected to produce 3 different milieus having 3 different biodiversities and densities: (1) a very active one (at the ground's surface) where life is produced, where new and various configurations of lifeforms can emerge, but where predation is intense and lifetimes short due to a substantial density of life, (2) a diluted one (far above the ground) towards which autonomous lifeforms escape, where they are less subject to predation, allowing to save the most prolific and stable configurations, and (3) the last one below the ground where organic matter decomposes and serves as substrate or food for creatures in the strata above. Moreover, thermal agitation and directed flows produce collisions between passive lifeforms so that they can interact (or react if they are chemical particles instead of lifeforms).

The same process of stratification of the environment under the action of gravity coupled to thermal agitation could also have played an important role at the origins of life. Above the surface, in a soup of biochemical particles, large supra-molecular structures and aggregates form and sediment depending on their size and density, the medium being progressively depleted. Actually, particle sedimenting depends on the intensity of their interaction with the gravitational field compared to the motion of matter due to thermal agitation and potentially to flows (like the convective flow). At the surface of the sediment itself, whose boundaries are not necessarily precisely defined (i.e. it looks like a fuzzy interface with a certain thickness), most of molecular aggregates deposit on the ground and can react with the others, while some others remain suspended above in the solvent. They can escape from the interface due to thermal agitation, to the bubbling of the interface, to hydrodynamic flows and convection that confer them a certain kinetic energy. Moreover, some particles can possess their own energy-dependent motility and escape the interface by themselves. They are often biotic ones (complex organisms with limbs or fins, ciliate cells or propelling bacteria), but also possibly abiotic ones [some very simple synthetic or simulated systems can move, like gliders and crawlers in the Game of Life, the Langton's ant or Karl Sims' creatures (Langton 1986; Sims 1994a), but also some supra-molecular dynamical assemblies like microtubules or synthetic DNA tiled assemblies present an apparent displacement due to threadmilling (Margolis and Wilson 1978; Rothmund et al. 2004)], or even decanol droplets showing chemotactic activity moving from one part of a glass slide to another, in a salt gradient, towards the highest salt concentration levels (Čejková et al. 2014). These movements of matter ensure a certain turnover of the

interface (e.g. ground's surface), help some 'structures of interest' to survive, i.e. by favouring the survival of the most represented particles (lifeforms, prebiotic compounds...) generated at or coming from the interface. The most represented structures (those that naturally form faster than others) that can escape the boiling ground, towards the diluted milieu far above the interface, will be the most represented and those that will survive longer in the whole environment. Although physical boundaries like membranes (or their numerical abstraction) are usually thought as the principal manner to obtain closed and autonomous organisms, we think that the stratification of environments into different adjacent milieus favouring different levels of biological richness, is one of the most basic processes having permitted the appearing of life on earth and its development.

Artificial life approaches and, in particular, deterministic cellular automata are often used to explore the numerous possible scenarios of what could have occurred at the origins of life and before, during the prebiotic ages, when very simple molecules started to assemble and organise into larger catalytic or informative structures, or more simply to simulate ecosystems. In cellular automata, the artificial spatial self-maintained structures that emerge sometimes may represent biological particles from molecules to living organisms (we will call them "creatures" in the article). Deterministic cellular automata simulations converge—at best—to homogeneous stationary soups of still-life or periodic creatures. For an observer, it is hard to believe that such soups of too simple numerical emerging creatures could constitute good models of the living, in particular because (1) none of the creatures is still moving through the environment after few iterations, (2) they present homogenous and isotropic spatial organisations, (3) the diversity in self-maintained morphologies is poor, and (4) when a stationary state is reached the creatures are then immortal. Natural living systems, on the contrary, are composed of a high diversity of creatures in interaction, having limited lifetimes. The environments where they live present heterogeneous distributions of species and their spatial organisation is often anisotropic (stratification of the milieu).

In this article, we propose that the presence of random motion of the milieu may maintain a self-organising ecosystem far from equilibrium while a directional weak field such as gravity may counter-balance disorder and prevent the appearance of physical-chemical conditions that are not favourable to the emergence of life-like systems. We test this hypothesis using a toy-model of ecosystem, derived from the well-known Conway's *Game of Life* (Gardner 1970; Berlekamp et al. 1982) to which we added rules simulating both sedimentation of particles and their thermal agitation. We show that the addition of both sedimentation and random motion leads to a more active

(vitality), diverse (richness) and robust (survival) Alife system. The richness of such Alife environments is measured as a combination of both the diversity of species and density of individuals, while a survival analysis (expected lifetime of creatures as a function of time) informs on their robustness.

Model and measurements

The main idea of our article is the following. The presence of thermal agitation may maintain a self-organising system farther from equilibrium than a pure catalytic system (without any movement and where reactions occur only in the immediate neighbourhood, i.e. by direct contact). It is one of the elementary features of all natural suspensions of particles including many living systems. In addition to catalysis (reactions), the presence of directional weak fields such as gravity may counter-balance the disorder generated by random motion (diffusion) and prevents a chaotic behaviour that is not favourable to the emergence of behaviours showing some characteristics of life. Here, as a generator of artificial lifeforms in a spatial environment, we use a common deterministic cellular automaton, the well-known Conway's *Game of Life* (Gardner 1970; Berlekamp et al. 1982; Rennard 2002). It has the advantage to provide still-life and periodic morphologies that can be associated with creatures in our study. We identify all the morphologies that develop at each time step, and apply onto them both gravity and/or random motion. Then, we measure the density, the diversity and the survival of a selection of different still-life and periodic morphologies along time, depending on physical conditions applied.

Numerical experiment

Reactions

We performed numerical experiments using a boolean cellular automaton with Conway's Game of Life rules, i.e. boolean cells are alive (cell value set to 1) or not (dead or empty cells are set to 0). Time and space are discrete ; the space is organised into a square array of cells with a Moore neighbourhood of range 1 (9 cells including the central cell and its 8 nearest neighbours). This automaton's rules (reactions) are such that if a living cell is surrounded by 2 or 3 other living cells, it survives, otherwise it dies, and if an empty cell has 3 living neighbours, there is a birth event. All cells are updated in parallel. From an initial uniform random distribution of living cells, transitory and periodic structures composed of several cells form in the Game of Life (see Fig. 7A). The classical finite-space automaton always reaches a stationary state constituted by only still-

life morphologies (like 2×2 squares of period 1), oscillators (like the 3×1 blinkers of period 2) and sometimes moving spaceships (like the 5 cell gliders of period 4) that can survive only in toric environments. Any other ecosystemic and evolutionary Alife system for which a classification and survival analysis of species can be done may be also used instead.

Identification of creatures

Every structure composed of contiguous living cells even the smaller one, a single cell, even if it lives during one time step, is considered as a creature. In the game of Life, periodic morphologies composed of several disjoint cells can form. We, however, do not consider them as creatures. In our model, creatures are limited to morphologies made of contiguous cells. At each time step, we browse the set of living cells and look at their living neighbours. All contiguous cells belong to one creature which is considered as an instance (an individual) of a morphology that potentially belongs itself to a studied taxon (see paragraph below). When two creatures collide, they form another morphology that can belong to another taxon or to a transient morphology. The characteristics (number of cells and their relative coordinates, and the dimensions of the creature) are used as keys to classify them in a hash table (a dictionary) so as to record each of them at each time during the simulation. In practice, we recorded only some 'interesting creatures' (defined in the following section). The times of birth and death of each interesting creature are recorded.

Selected species

The Game of Life generates a huge variety of contiguous morphologies that can be classified into three groups: (1) stable cyclic morphologies including still-life ones (cycle of period 1), oscillators and space ships, (2) transient morphologies that either reach cyclic states or die, (3) gardens of Eden that cannot be reached from any previous state. Two morphologies belong to the same taxonomic group if they are equivalent by any operation of symmetry (rotation and reflection) that can transform the one into the other. For example, glider's taxon is constituted of 16 morphologies (4 states in one cycle \times 4 symmetries), blinker's taxon of 2 morphologies and blocks correspond to only 1 morphology.

Among the possible generated creatures, we selected only 20 well-known still-life species from those most frequently encountered to the less ones. They are shown in Fig. 1 and their corresponding names [according to Silver and Martin's Game of Life lexicon (Martin and Silver 2009)], number of morphological configurations and number of cells are given in Table 1. Note that we counted together beehive and ship morphologies since they are similar (same number of

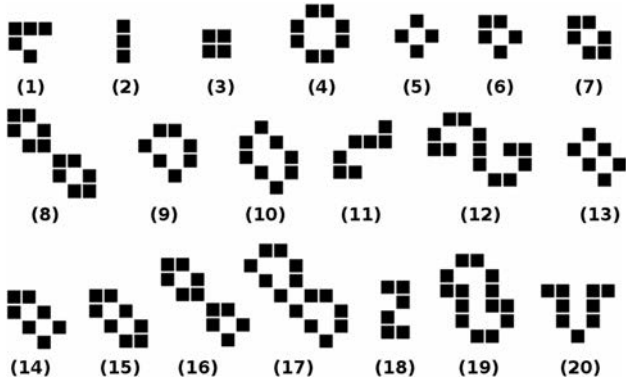


Fig. 1 Selected morphologies in the Game of Life. Their identification in the environment includes their possible other conformations (for cycling creatures), as well as all their *symmetrical shapes*. Their characteristics are given in Table 1

elements, same shape, although their dynamics is not the same) after a rotation of 45° . Some (gliders, blinkers, blocks, boats. . .) are very common, while others (mango, eater, snake, paperclip, hat) are rare.

Interaction between creatures and forces: sedimentation and random motion

In our numerical experiment, two forces are applied on the creatures: sedimentation (noted G for gravity) and random

Table 1 Names and characteristics of the selected morphologies (see Fig. 1)

| # Morphology | Name | Period | Configurations | Cells |
|--------------|------------------|--------|----------------|-------|
| 1 | Glider | 4 | 16 | 5 |
| 2 | Blinker | 2 | 2 | 3 |
| 3 | Block | 1 | 1 | 4 |
| 4 | Pond | 1 | 1 | 8 |
| 5 | Tub | 1 | 1 | 4 |
| 6 | Boat | 1 | 4 | 5 |
| 7 | Ship and Beehive | 1 | 4 | 6 |
| 8 | Ship tie | 1 | 2 | 12 |
| 9 | Loaf | 1 | 4 | 7 |
| 10 | Mango | 1 | 4 | 8 |
| 11 | Eater1 | 1 | 8 | 7 |
| 12 | big S | 1 | 4 | 13 |
| 13 | Barge | 1 | 2 | 6 |
| 14 | Long boat | 1 | 4 | 7 |
| 15 | Long ship | 1 | 2 | 8 |
| 16 | Ship tie boat | 1 | 4 | 11 |
| 17 | bi-Loaf | 1 | 4 | 14 |
| 18 | Snake | 1 | 4 | 6 |
| 19 | Paperclip | 1 | 4 | 14 |
| 20 | Hat | 1 | 4 | 9 |

motion (TA, for thermal agitation). Here, sedimentation and random motion are probabilistic moves along vertical and horizontal axes (e.g. 0.5 meaning an event that may occur half of the time). The probability of a creature sedimenting along the vertical axis in a timestep is proportional to the number of cell it contains (its mass). The probability of a creature moving in any random direction is inversely proportional to the number of cells it contains.

Environment and boundary conditions

Because this work is based on the Game of Life 2D-automaton, we use here a 2D-environment. The vertical direction along which particles sediment is the y vertical axis. The two lateral sides (along the x horizontal axis) of the environment are connected together, so that it forms a cylindre. In several simulation conditions (conditions c , e , f , g ; see Table 2 below), the top boundary has Dirichlet conditions: it is composed of still-dead cells. The bottom mimicks a soil where living cells can accumulate. The presence of gravity causes the death of automaton' cells (and of associated creatures) at the bottom of the environment if nothing is done to maintain life. We introduced random Dirichlet boundary conditions at the bottom of the environment and call them 'active ground boundary' (AGB): in the border line at the bottom, at each time step we distribute spatially, with a certain probability (equal to 0.5 in our simulations), a pool of living cells. These cells are not allowed to react between each others (this part of the environment is kept inert) but contribute to the life of the creatures above that take into account their presence when updating the neighbourhood of the automaton' cells. A physical analogy of our active ground boundary would be an energy supply from the ground, like heat coming from Earth's ground. In some other simulation conditions, however (conditions a , b , d ; see Tab. 2 below), the top and

Table 2 Physical conditions parameters used in our simulations

| Condition # | G | TA | AGB |
|-------------|------------|-------|-----|
| a | 0 | 0 | 0 |
| b | 0 | 0.5 | 0 |
| c | $\simeq 0$ | 0.5 | 0.5 |
| d | 0.005 | 0 | 0 |
| e | 0.005 | 0 | 0.5 |
| f | 0.005 | 0.005 | 0.5 |
| g | 0.005 | 0.5 | 0.5 |

These parameters correspond to probabilities that an event of sedimentation (G for Gravity) or random motion (TA for Thermal Agitation) occurs for each creature during one step, and to the probability that an event of production of matter from the ground (AGB for Active Ground Boundary) occurs for each position x of the ground during one step

the bottom (axis y) are connected, so the environment forms a torus.

Data analysis: survival analysis, vitality and biodiversity

For each studied condition (see Table 2), we collected the data of 6 simulations run in $x \times y = 400 \times 100$ 2D-environments during 30,000 iterations, yielding the complete “life” (time of birth and death, and successive locations) of about 5.4×10^6 creatures. It has to be reminded that there is no genetic evolution process working in our simulations (our creatures do not possess any genome), so that new creatures cannot appear as a result of evolution and that creatures that have one appeared can re-appear (i.e. a species cannot go extinct).

Kaplan–Meier estimate of taxon average lifetime

In order to estimate the average lifetime of our taxa, we computed the survival curves of species using the Kaplan–Meier estimate. Survival analysis studies are frequently used in epidemiology, e.g. in the follow-up care for cancerous patients, using death events as real random variables to construct the survival curves $S(t)$. Similarly to infant mortality studies, many birth and death events occur during our simulations, so we used creature birth times as events and estimate the probability to reach the age Age .

The Kaplan–Meier estimator (Kaplan and Meier 1958) provides a non-parametric maximum likelihood estimate of $S(t_j)$ which is the product over time (from the initial time t_0 to the current discrete time t_j) of the ratio of the difference of the number of survivors and dead creatures $n_j - d_j$ divided by the number of living creatures n_j at time t_j :

$$S(\hat{t}) = \prod_{t_j < \hat{t}} \frac{n_j - d_j}{n_j}$$

Practically, because of the possible long-life of certain creatures, it is convenient to use the logarithm of age as random variable. Using the random variable $\log(\text{age})$, n_j and d_j , respectively, denote the number of creatures having reached the $\log(\text{age} = t_j)$ and the number of creatures that did not reach this value.

Vitality

The vitality of the system should inform on its ability to favour life, but it should also inform on its ability to favour new births. The density of living creatures in the environment (its biomass) gives a good idea of its vitality: high birth rate coupled to long lifetimes (survival) maintain numerous creatures alive in the environment. Figure 5A, B

shows, respectively, the kinetics of creature density and the average density of living creatures at steady state. However, this can be biased by conditions in which collisions between creatures (i.e. that can cause their death) are very rare, like conditions a and d , and where creatures can live for very long times. In these conditions, we only count the same long-living, sometimes immortal, creatures instead of new ones; this is not what can be called a lively system. Another manner to measure the vitality is to count the accumulated number of new creatures over time, i.e. the sum of birth counts, per cell, over time. This informs on the ability of the system to produce high numbers of creatures by favouring new births (turn-over). This is shown by Fig. 5C, D). However, high birth rates could be counter-balanced by high mortality rates, so a strong vitality must be understood as a combination between high creature densities and high birth rates.

Biodiversity

There are several manners to understand biodiversity (Zak et al. 1994; Ulanowicz 2001; Ricotta 2007). Here, we distinguish at least two. *Stricto sensu* ‘biodiversity’ corresponds to the number of species at a given time or during a certain period of time. This can be obtained here by simply counting the number of existing species during the simulation. However, we wished to take into account the vitality (number of creatures for each species) in the biodiversity indicator to give a certain measure of the robustness of the system. Shannon’s biodiversity index $H(t)$ takes into account both the number of species (specific diversity) and the size of their respective population (calculated here as the product of the number of the creatures composing them (vitality) with their mass, as to say the biomass per species).

If at a given time only one taxon is present, whatever the number of individuals and their importance in the environment (occupation of the environment in terms of mass), H should be small. As a first consequence, H must take into account the unoccupied space in the environment. In our study, we consider the—unoccupied—environment as a—virtual—unique creature and convert its available space into a corresponding “biomass” (number of empty cells) to include it in the calculation of H . This is to consider legitimately the environment as a part of the ecosystem: a real environment provides organic and inorganic mass available for living creatures and, as it is subject to predation (matter and energy are took off it) or on the contrary takes energy and matter from living creatures (degradation of creatures, secretion of products by living organisms. . .), it shall not be distinguished from other creatures. Conversely, H should be large when lot of species constituted of numerous individuals occupy broadly the environment.

Moreover, the indicator H must also take into account the vitality of the system. In the calculation of our biodiversity indicator, we however chose to take into account the accumulated biomass per species over time (i.e. the accumulated vitality) because it allows a more regular representation of the biodiversity trend instead of showing all the small variations of entropy.

Let us consider $S = \{1, 2, \dots, s + 1\}$ that denotes the set of s species' accumulated biomass, plus the total number of empty cells in the unoccupied environment (biomass of the taxon $s + 1$), α_k the set of automaton conditions used in the k^{th} experiment, and $Q_{\alpha_k}(t_j)$ the random variable which takes its values in the set S and meaning: "a new living cell appears and belongs to one of the selected species". $Q_{\alpha_k}(t_j)$ values represent the different taxon frequencies $v_i(t_j)$ accumulated until time t_j in the condition α_k . Frequencies at time t_j are obtained by dividing the accumulation of creatures in each taxon by the environment mass (width \times height) accumulated over time. It is natural then to use Shannon's entropy of random variable $Q_{\alpha_k}(t_j)$ as a biodiversity estimator:

$$H(Q_{\alpha_k}(t_j)) = - \sum_{i=1}^{s+1} v_i(t_j) \log(v_i(t_j)),$$

where H is a function defined on $\Omega \times \mathfrak{R}^+$, Ω being the complete set of conditions in the automaton.

Simulation results

Survival

We first performed an age-survival analysis of the 20 selected species taken together, depending on simulation conditions (Fig. 2). We also estimated the age-survival of some common species (Blinker, Glider, Block, Boat and Loaf) (Fig. 3). We did the same for some less common species such as Mango, Eater and Snake (Fig. 4). Of course, in the classical Game of Life, all still-life and periodical creatures have 'infinite' lifetimes once the stationary state is reached (lifetimes are limited only by the simulation time).

As shown in Fig. 2, the average age survival of selected species is clearly increased in the presence of sedimentation and with an active ground boundary, compared to conditions in which only random motion is present. In conditions of sedimentation, a very reactive deposit (an active mud) forms at the bottom, while the environment above becomes diluted. In the diluted medium, collisions become rare events, so the average lifetimes are increased for still-life and periodic species. When no phase separation occurs, for example when sedimentation is too slow to

counterbalance random motion or when no sedimentary deposit can form (absence of ground in toric conditions), conditions are similar to random motion conditions and the respective behaviours too. When only sedimentation occurs (no active ground boundary and absence of random motion), the behaviour is similar to the one in very weak random motion.

During our simulations, we observed a difference of age survival behaviour between common species (Fig. 3) and rare species (Fig. 4). All individuals belonging to common species benefit strongly from phase separation, which allows them to live in a diluted medium over long times. This should be similar for rare species. Nevertheless, these rare species need many collisions to emerge. Birth events of rare species are too much rare in the basic conditions of the Game of Life. On the contrary, the intense turn-over at the bottom of the environment as well as conditions of strong random motion favour their birth. Such conditions allow to observe their formation during the simulations and measure their survival. Random motion does not, however, favour long lifetimes, so their survival is limited in time compared to common species. One can notice particularly the age-survival of Snake. This taxon is very rare in the classical Game of Life, whereas it can form more frequently from a Beacon oscillator undergoing random motion (shown in gray in Fig. 4).

Vitality and biodiversity kinetics

Population kinetics (Fig. 5A, B) inform on the vitality of simulated systems. Figure 5C, D shows the corresponding values when the steady state is reached (near 4000–5000 iterations). The density of species (in Fig. 6A the average density of species at steady state) and the entropy of their cumulative distributions (Fig. 6B) give information on their capacity to maintain a certain diversity and to allow rare species to live.

As a first observation, it seems that the creature density in the system is largely lower when the creatures sediment and form a deposit (Fig. 5A, B, conditions e, f, g) compared to the conditions in which they stay suspended in the milieu (Fig. 5A, B, conditions b, c); condition d is comparable because, in this case, the environment has no fixed boundaries at the top and the bottom (toric environment), so sedimentation plays approximately the same role as Brownian motion in condition b . This apparent low vitality in conditions of sedimentation is due to the fact that the diluted medium is taken into account. Moreover, the density (Fig. 5A, B) of individuals belonging to selected species is higher in the classical Game of Life (condition a , initialized with a density of 15% of living cells) once the system has reached its stationary state than in other conditions. This is because, once the steady state is reached,

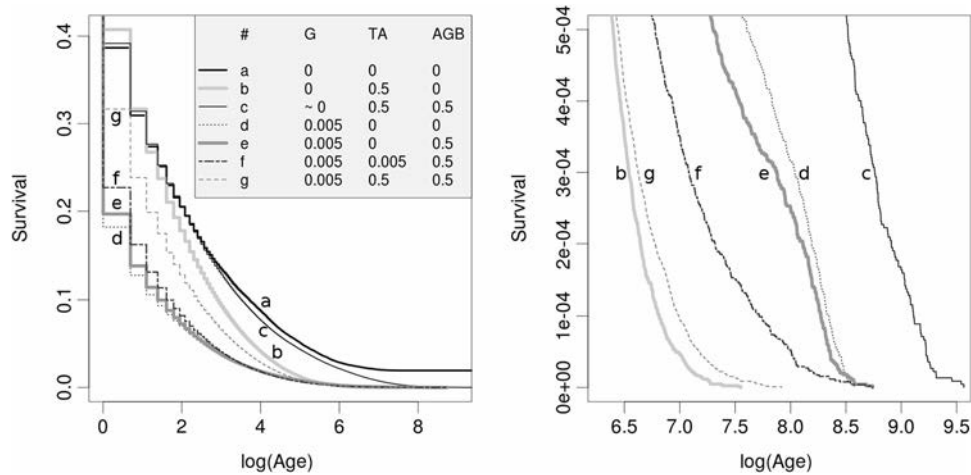


Fig. 2 Survival curves of selected species' populations depending on physical conditions. (*Left*) complete curves of the average age survival of the 20 selected species given in Table 1, depending on different conditions of gravity G , Brownian motion TA and production of matter from the ground AGB (conditions refer to those showed

in Table 2). On the (*Right*), are shown the details of the same survival curves for long lifetimes. Both *curves* use a logarithmic scale for the age of creatures; many creatures have short lifetimes, especially when living in dense regions, but some others can live up to 10,000 iterations

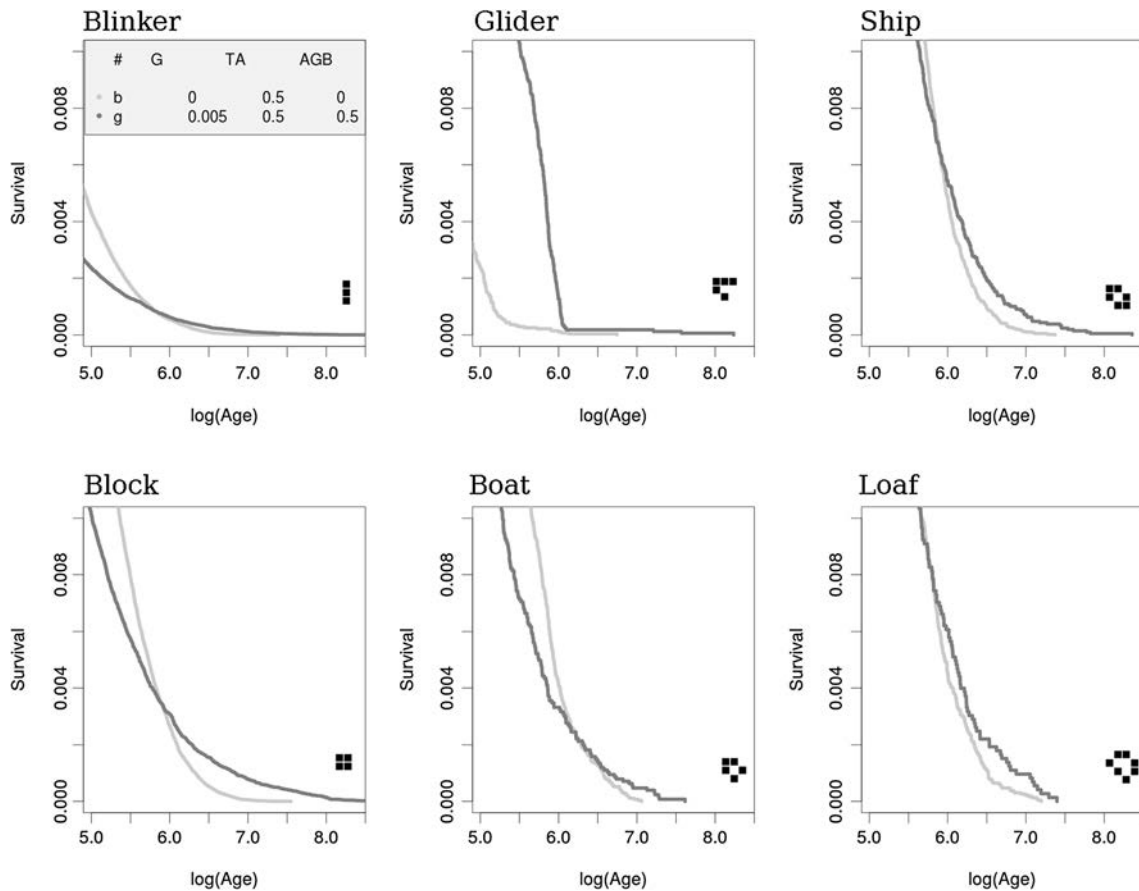


Fig. 3 Survival curves of some common species depending on two physical conditions: under Brownian motion only, or under conditions of Brownian motion coupled to sedimentation and active ground boundary conditions

the creatures in the classical Game of Life cannot collide anymore and are immortal. In a certain manner, this is the same for condition d in which collisions between creatures

are very rare. To avoid this bias, we can look at the accumulated density of new living creatures (Fig. 5C, D) because it informs on how much an environment favours

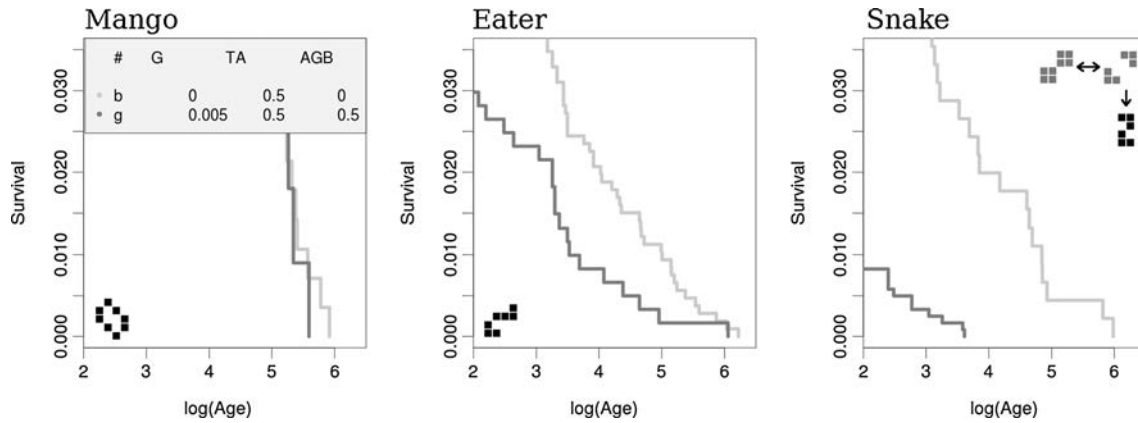


Fig. 4 Survival curves of some rare species depending on physical conditions as in Fig 3

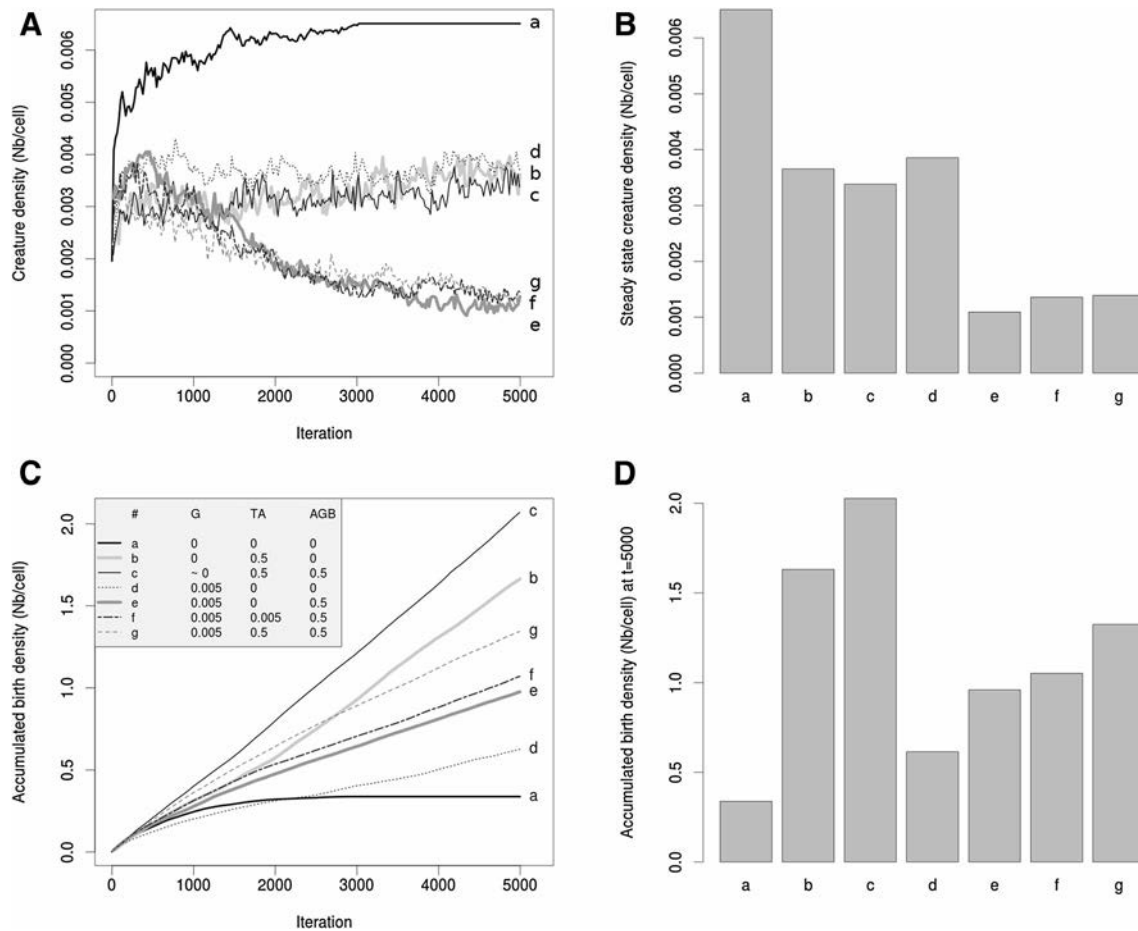


Fig. 5 Measurements of vitality depending on different physical conditions. **A** Creature density kinetics and **B** the average creature density at steady state, i.e. calculated as the mean creature density

sustainable high birth rates. All conditions (*b*, *c*, *e*, *f* and *g*) in which a sufficient “energy” is furnished to the system in the form of gravity, Brownian motion and active ground, present high creature formation rates, on the contrary to the classical Game of Life (condition *a*) in which no new

creature appears at steady state (and in a certain manner, it is the same in condition *d*).

We can also compare the biodiversity (in the very strict sense, the number of different species, as defined previously in 2.2) in different conditions by counting the

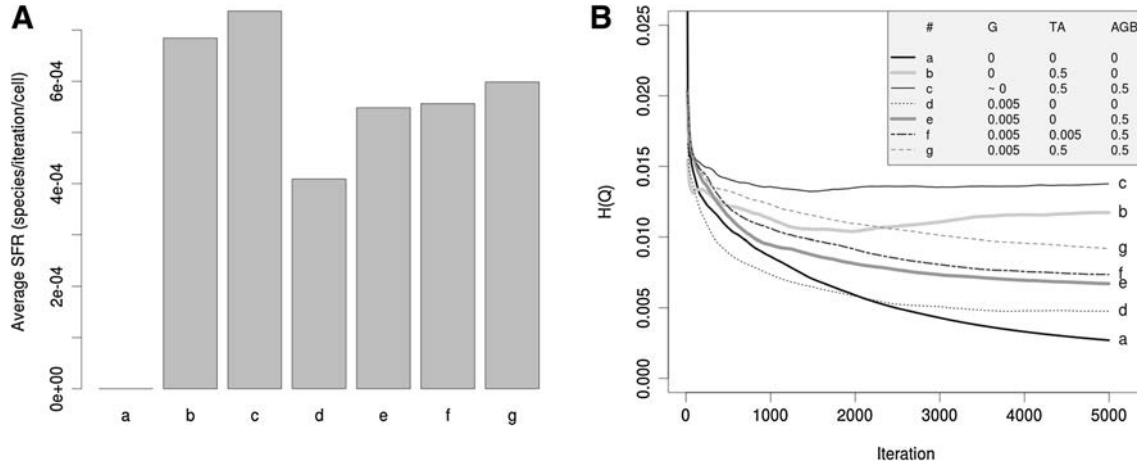


Fig. 6 Measures of biodiversity depending on different physical conditions. **A** Average density of species at steady state. **B** Kinetics of the Shannon's biodiversity index, i.e. entropy of the accumulated

average number of selected species that can be found in the environment at steady state (Fig. 6A). This time again, biodiversity is largely higher when the system receives energy from random motion and is ordered by sedimentation forces than when the system is purely deterministic.

This result is confirmed by Fig. 6B, which corresponds to $H(Q)$, the variation of the Shannon's biodiversity index (including species and environment). The larger is $H(Q)$, and the larger is the biodiversity. Whatever the condition, entropy starts to decrease strongly because the order increases in the system after its random initial state. Then, the curves progressively reach a steady state. Once again, in terms of biodiversity, conditions of sedimentation are intermediate between those with random motion alone and that of the classical Game of Life.

Gravity combined to active ground boundary leads to both containment and vitality

Figure 7 shows the effect of adding sedimentation and/or random motion in a strong catalytic system, here the Game of Life. Whereas the classical Game of Life rapidly reaches a stationary state presenting a very low vitality and biodiversity, without any form of containment (Fig. 7A), once random motion is added, both intense vitality and biodiversity emerge (Fig. 7B). However, if random motion alone increases life in the cellular automaton, it cannot allow the formation of any different parts in the milieu by confinement or stratification, necessary to ensure the survival of creatures. In natural systems, this can arise from symmetry breaking processes, possibly due to the presence of weak external fields like gravity. This is what is shown in Fig. 7C, where both sedimentation and active ground boundary are present. The bottom of the environment behaves as an active sludge where an intense turn-over occurs (in particular in the

distribution of creatures into their taxonomic classes. All measurements are normalized for one cell of the environment

case of this automaton, the Game of Life being extremely catalytic), from where regular 'eruptions' spread—artificial—life towards the diluted medium above.

In the presence of sedimentation and active ground boundary, two regions progressively emerge (see Fig. 7C): the diluted medium (about 80% in the top of the environment), and the active mud (about 20% in the bottom of the environment). Bottom and top of the environment have different behaviours: although vitality and biodiversity are largely more important in the active mud (bottom) due to the numerous collisions that generate new creatures (Fig. 8), the survival of selected species is clearly increased in the diluted milieu above (Fig. 9).

Discussion

In this article, we presented a toy model of a simplified ecosystem where some creatures are born, live and die, and undergo the effect of sedimentation and random motion. This model has several limitations. Among them, the geometry is an important one: our simulation environment is a true 2D-environment. We chose to stay in two dimensions, because it is the same environment as in the classical Game of Life, where 2D-creatures live and, of course, collide in 2D, so they cannot benefit from an additional degree of freedom to more frequently avoid the collisions. Another limitation is the simplicity of the creatures: they have no genome, nor metabolism and, therefore, no differentiated behaviour. It would be quite easy to develop other artificial life systems in 3D-environments, where creatures would have a genome and a related behaviour. However, this would imply more complicated work on the taxonomy of such creatures having various genomes and behaviours as compared to our

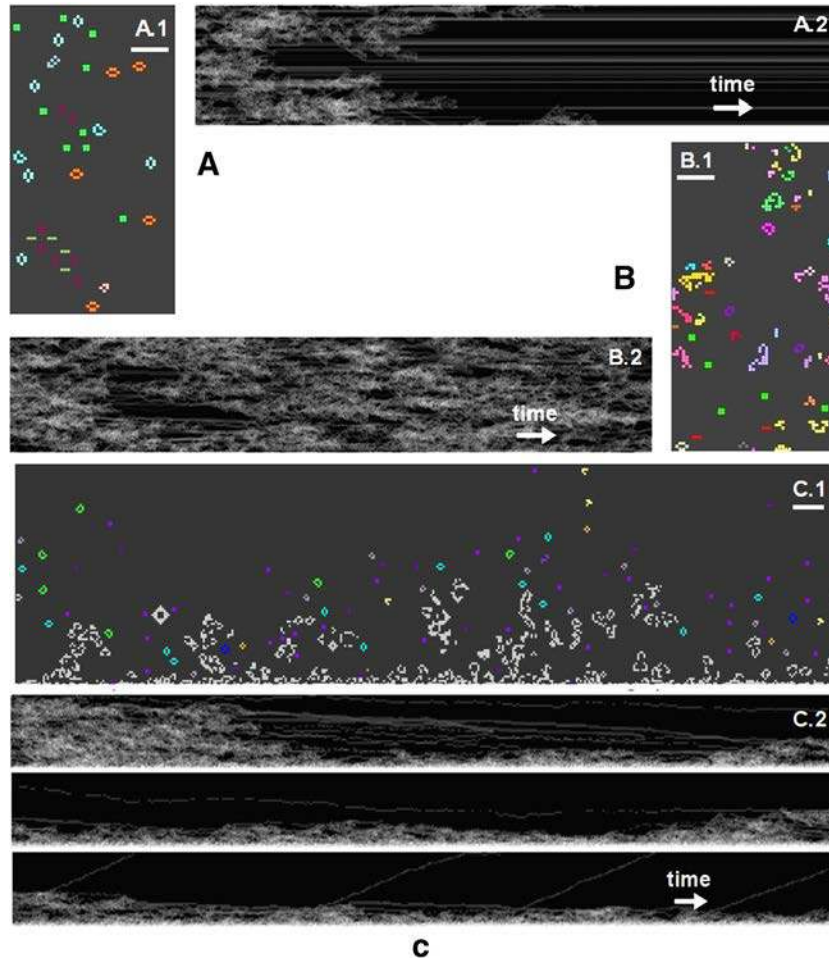


Fig. 7 Evolution of the density along the y axis depending on physical conditions. **A** The classical Game of Life is a pure auto-catalytic system that reaches a stationary state very fast: **a.1** shows some still-life creatures once the stationary state is reached (*bar* 10 cells) and, **a.2** shows the evolution of density of living cells belonging to the selected species along the y axis. After few iterations (430 here), the steady state is reached and nothing interesting occurs anymore. **B** Random motion is added. Creatures can collide and start new burst of life as illustrated in **b.1** (*bar* 10 cells) and followed over time in **b.2**. The steady state cannot be reached, life is very rich ... too much rich and ephemeral: still-life creatures are subject to

collisions and cannot last for a long time. **C** When random motion, sedimentation and active ground boundary are added, a kind of order progressively rises, punctuated by local bursts of life coming from the bottom of the environment. The environment (*bar* 20 cells) is clearly divided into two states (see **c.1**): an active mud full of transient creatures, where many collision occur providing a strong turn-over, and a diluted milieu above where still-life creatures can last for long periods. As seen in **c.1** and **c.2**, bursts of life occur from time to time and generate new still-life creatures far above the active mud. On the last graphics in **c.2** one can also see 4 *diagonal lines*; they are gliders that escape the active mud

present model. The advantage of the Game of Life is that it provides a limited number of identifiable creatures, which facilitates taxonomy and the subsequent studies (survival).

Our study shows that the diversity of such emerging numerical species is increased when individuals are allowed to collide due to the random motion, and that this increase is not only due to their intrinsic dynamics. When gravity makes them fall, the medium, as a whole, is drained out and a kind of active sediment accumulates at the bottom of the environment. This ‘active sludge’, a sedimentary deposit wherein catalytic elements are concentrated and where the turn-over is increased, is a continuous source of diversity from where some self-maintained artificial

living species can escape and swim toward a more diluted medium (e.g. as it is the case for self-driven moving gliders in a cellular automaton) or fall again until being recycled once more in the sedimentary bottom of the environment (e.g. as for motionless particles like blocks, boats or blinkers).

Alife studies mainly focus on the behaviour of artificial creatures (moves, strategies. . .), on the interaction between them (reactions, exchanges of matter, predation. . .). Works on the origins of life address in addition the problem of individuation of self-maintained microsoms, mainly by the formation of membranes. One often forget the fact that the only Life we know only developed under Earth’s

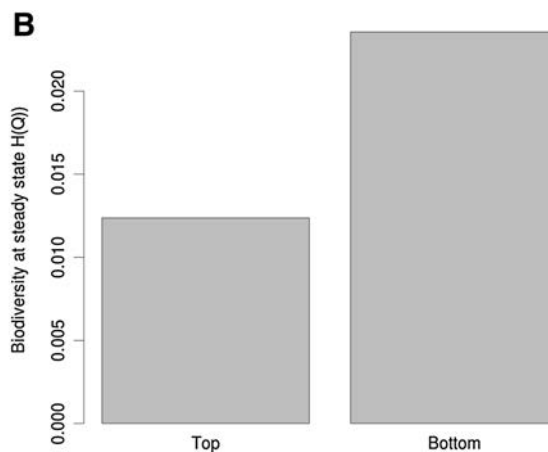
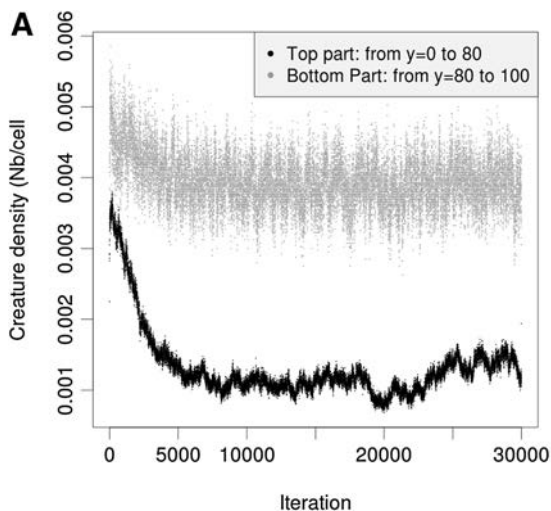


Fig. 8 Density kinetics and Biodiversity depending on the region in the environment. **A** Kinetics of the creature density. **B** Average Shannon's biodiversity index at steady state, $H(Q)$. The measurements were made in the two different states of the environment, i.e.

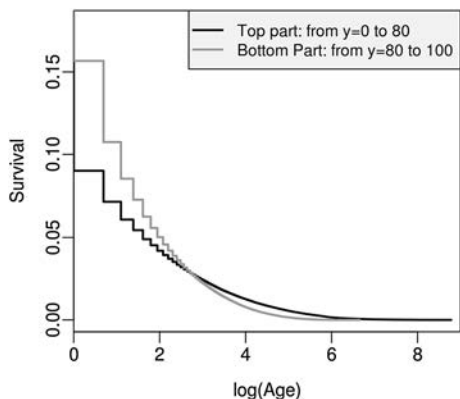


Fig. 9 Average age-survival curves of populations of selected species depending on their location in the environment. Automaton's creatures live longer in the diluted milieu than in the very reactive bottom of the environment

gravity. Sedimentation of active particles as a motor of spatial self-organisation is indeed not usually considered in Alife nor in works on the origins of life, although it is a very simple spatial symmetry breaking mechanism that concerns every system able to interact with gravity.

In several cellular automata like Conway's Game of Life, artificial lifeforms develop in a very fast turnover. Most of the "lifeforms" are very labile and exist during only a very small number of time steps, often only one. Others like gliders, blocks or blinkers are frequently encountered and often survive during long periods until they collide with or are hit by other moving structures. All these structures are very fragile because practically every collision between living cells is a success, i.e. produce a local reaction between cells, which is not the case in

the diluted milieu corresponding to the upper part that covers 80% of the environment, and the active bottom that covers only 20%

natural systems where numerous and efficient collision events are necessary to succeed in a reaction. It is tempting to make an analogy between this toy-model of life and the also very labile prebiotic soup (as it is usually though) where many different structures and functional aggregates may have formed and disassembled continuously. Nevertheless, although the first hundred steps of a Game of Life show a fast turnover, no macroscopic organisation of this Alife system appears; on the contrary, a sparse environment develops. Such strong catalytic artificial systems lack a driving force (like gravity) that would help their self-organisation at a macroscopic scale.

On the contrary, weak catalytic systems exist in which gravity plays an organising role, but their activity and reaction rules are too limited to produce any life-looking behaviour. Ventrella's so-called 'Gravity Tetris' (Ventrella 2005), a *gravitational Tetris game*, is an illustration of a system where a weak catalysis coupled to the fall of the particles (the Tetris puzzle pieces) produces a kind of active mud at the bottom of the environment. In the Tetris game, various shapes formed by several assembled squares, fall one after the other, forming a deposit in the bottom of the environment. Their horizontal position and orientation are controlled by the player. Once a shape touches the ground formed by other accumulated squares, it stops. The only possible reaction in this system occurs when a line composed of cubes is completed: it is a limited and rare reaction. In Ventrella's version of this game, shapes fall continuously by gravity, and can bounce on the top of the deposit of squares. Sometimes, even when they are not controlled by any player, they can fit in the holes of the stack of cubic elements and, like in the original game, once

lines are completed (here due to the hazard; which in Ventrella's version is a very rare event), they are removed and the 'matter' above falls towards the bottom composed of uncompleted lines. Another examples are colloidal aggregation coupled to sedimentation, characterised by González (2006), or precipitation-based patterns (Müller and Venzl 1983). A deposit progressively forms but due to the absence of turn-over (no catalysis), this system, as well as the gravity Tetris, nevertheless remains close to the equilibrium and does not "look like" the active muds of living ecosystems.

In our simulations, artificial life appears to be more active (i.e. in the sense of vitality and biodiversity) and robust (i.e. their survival is increased) when both sedimentation and random motion act on a strong catalytic system. While classical cellular automata (e.g. here a classical Game of Life) usually generate homogenous and isotropic milieu, the addition of energy and symmetry breaking is necessary and sufficient to cause the formation of local heterogeneities and anisotropic environments. Such heterogeneities could play the role of ecological microcosms.

The presence of thermal agitation maintains a self-organising system farther from equilibrium than a pure, weak or strong, catalytic system. Thermal agitation indeed constitutes one of the elementary features of all natural suspensions of particles, including many living systems. In addition to local catalysis (i.e. the reactions) and thermal agitation (that allow reactions between particles at a less local level), the presence of a directional weak field such as gravity may counter-balance the disorder generated by diffusion. It also prevents the ecosystem from chaotic dynamics that would not be favourable to the emergence of behaviours appearing as in life-like systems. Through sedimentation, a density gradient forms that separates the milieu into two states (Fig. 7C), the one at the bottom, very dense and chaotic and in which life is short, and the other diluted and in which creatures can live for longer times (Fig. 9). We find that "*survival of the fittest*" is not always synonymous with "*survival of the most populous*" (see Adami 1995): stratification of the milieu also counts in the survival of species. As in Adami's *Avida* in which chance mutation is transferred from the environment into the genome, environmental stratification (spatial organisation in general) is also transferred into the genome (or the behaviour) of the population.

Vertical heterogeneity is important in numerous ecosystems although it is rarely taken into account in the understanding of their self-organisation. Its role is essential in sea or lake mud formation in the context of benthic system ecology or in humus dynamics in forest ecology where life is very stratified, or even in the micro-ecology of rain puddles containing bacterium bio-films.

Sedimentation-driven stratification could also be implied in the formation of microcosms where very simple molecules started to assemble and organise into larger catalytic or informative structures (e.g. heavy molecule aggregates) during the early stages of life. This breaks with the classical vision of homogeneous soups of reacting elements.

Like in many other Alife studies, more general questions rise: is it possible to learn about the nature of the living from artificial life ? What makes synthetic systems more active and life-looking? And finally, can it help to imagine what life could be elsewhere in the Universe (Adami 1995, 1998)?

We think that living systems can be analysed in an objective manner or seen through a subjective way. Emergence, biodiversity, life-like behaviours...; such aspects can be comprehended using the one or the other. This question is related to the one of emergence itself for which the objective or subjective nature is still a subject of debate (Ronald et al. 1999; Pattee 2015). It also concerns the likeness of artificial systems with the living (Rennard 2004). This likeness can be evaluated by measurable quantities like the diversity of components and their organisation within space or time. But finding signs of biochemical molecules or any chemical activity in an atmosphere or in the ground of a planet is clearly not sufficient to prove the presence of life nor even to associate such molecules and reactions to bio-signatures. Life likeness is indeed also something less measurable, something subjective, something that could be called "biological beauty", a criterion that even a child could feel. To appear living, systems may not be too simple and in the same time not too close to disorder nor too diverse. In our artificial system, although one part of the environment is boiling of emerging creatures with transient shapes, the system is maintained sufficiently ordered and rich enough to let us think it as living.

It is obvious—at the least natural—among beings (humans as well as animals) to assign living features to things, living or not. Nowadays, this is frequently used by roboticists and game designers, to make robots and virtual creatures more realistic. This is also used in the fields of computational biology and medicine to show more photo-realistic simulations. Subjective identification of living features in any kind of things, were they living or not, is not indeed new. For example, although occurring very close to the thermodynamic equilibrium, Leduc's chemical gardens (Leduc 1911; Barge et al. 2015) as well as the synthetic creatures of D'Arcy Thompson (Wentworth 1942) look similar to some forms of life, in particular they steer the observer to believe in a certain richness of the life-mimicking forms that compose them. Thompson D'Arcy does not hesitate to compare the "Mr Worthington's beautiful experiments on splashes" to the living when he writes

“The naturalist may be reminded also of the beautifully symmetrical notching of the calyces of many hydroid zoophytes, which little cups had begun their existence as liquid or semi-liquid films before they became stiff and rigid”. Leduc did the same when comparing his chemical gardens to microcosms whose order and structures were generated by micro-organisms or fungi. A short research on the internet of “Leduc’s chemical garden” keywords shows how they still fascinate and are still thought as a plausible pathway from inorganic to life, even if they are effectively very far from even single lifeforms. Dawkins in his *biomorphs* (Rennard 2002) or Bec (for whom *Art* is the *living*) (Bec 2008) created a huge zoology of forms that resemble insects, shrimps, trees and kangaroos, or that appear as more complex and functional creatures that do not exist on Earth. Splashes, downflows or limited growth aggregates of chemicals are not alive but they present sometimes some aspects of the living. On the same way, the recent comparison of silica deposits observed on Mars by the rover Spirit with those observed in the geyser discharge channels at El Tatio in Chile is mainly qualitative (Ruff and Farmer 2016).

Although it is something subjective, the question of ‘beauty’ of synthetic lifeforms is also often associated with their complexity. Using a set of objective measures gives an quantitative evaluation of the distance between synthetic and living systems. Measuring entropies and the densities in a system, following the time-dependent number of its elements, their mobility and their survival, gives clues of the presence of life in it, and then helps to establish its living nature.

From now, none of the objective manners to detect whether a system possesses a biological metabolism (analysing the light spectrum of earth’s reflected light on the moon still does not allow to say if life is present or not!; nor the presence of simple organic molecules in molecular clouds in the universe ensures the presence or even the possible emergence of life), or is living, are sufficient. Subjective evaluation of the living must be combined to objective measurements to ensure the living nature of a system, and reciprocally. Numerical experiments on Alife naturally combine both, first because imagining new forms of life requires to have qualitative mental images of their possible design and to respect at the same time the limits of physics and chemistry, second because their analysis must reveal lifeforms that convince as well by their aspects and behaviours as by measurable criteria. Finally, in answer to the opinion that researches on the *origins of life* constitute “an unfalsifiable conjecture” (Whitfield 2009), we believe that studying Alife systems may help to converge to several convincing stories (Bedau 1999; Varenne et al. 2015).

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