A Stress-based Speciation Model in LifeDrop

Marc Métivier*, Claude Lattaud*, Jean-Claude Heudin**
* Laboratoire d'Intelligence Artificielle de Paris 5
UFR de Mathématiques et d'Informatique, Centre Universitaire des Saints Pères
45, rue des Saints Pères 75006 Paris - France
{metivier, lattaud}@math-info.univ-paris5.fr
** International Institute of Multimedia, Pôle Universitaire Léonard de Vinci
92916 La Défense Cedex — France
Jean-Claude.Heudin@devinci.fr

Abstract

This paper presents a stress-based speciation model implemented within LifeDrop, a virtual world with bio-inspired agents. In this model, individuals are distributed among species separated by a "barrier" mechanism preventing the reproduction between individuals of different species. An analysis of species dynamics in relation to stress is presented. Results show diversity maintenance and a reactive capacity during crisis situations favoring the emergence of new species.

Introduction

Over the last decades, several studies of artificial ecosystems have been published in the field of Artificial Life. Typically, such a system includes a population of bio-inspired autonomous agents which compete to survive in a simulated environment. Each agent is described using a genotype which, associated to a speciation mechanism, provides an evolutionary process permitting the emergence of more adapted agents in the environment. Among them, LifeDrop is a virtual ecosystem consisting of creatures evolving in a virtual drop of water. One of the objectives is to provide a model for studying the complexity of species dynamics in the framework of a larger project addressing the "evolution of complexity" in various classes of dynamical systems (Heudin 1998).

An original feature of LifeDrop relies in its model and implementation of the species concept. In most previous artificial ecosystem experiments, individuals are generally spread over different groups that are considered as species, but the underlying models usually do not provide a well defined speciation mechanism. Rather, a separation between agents using a phenotypic observation is often used. Several works in molecular biology have proposed an explanation of speciation related to stress (Matic, Rayssiguier, & Radman 1995; Taddey, Matic, & Radman 1996). Based on these studies, this paper present a stress-based speciation model and its implementation within LifeDrop.

Related works

Several Artificial Life ecosystems have been designed during the last fifteen years. Among them, Tierra (Ray 1991) and Avida (Adami & Brown 1994) are based on populations of self-reproducing strings with a Turing-complete genetic basis subjected to Poisson-random mutations. PolyWorld (Yaeger 1994) and Gaïa(Gracias *et al.* 1996) are two-dimensional ecology simulators studying evolution of competing agents controlled with neural networks. Darwin Pond (Ventrella 1998) and Gene Pool[1] are two-dimensional virtual worlds where physics-based organisms, respectively called "swimbots" and "swimmers", evolve over time. Framsticks (Komosinski 2000) is a three-dimensional life simulation project where both the physical structure of creatures and their control systems are evolved.

All these systems implement populations of autonomous entities, sometimes spread over different species, but none of them proposes a well defined speciation model. In Framsticks, individuals are spread over species defined as sets of individuals having similar genotypes. The speciation is not managed by any mechanism, but is favored by lowering the fitness of new agents having similar genotype to existing ones. PolyWorld and Gaïa propose simulations where new species emerge. However, they use a qualitative determination based on observed behaviors. In Gaïa, a competition between two species in which individuals can mate only with individuals from the same species has been studied but no speciation mechanism has been proposed.

Fundamental principles of evolution dynamics have been explored in systems built by Conrad (1987) and Packard (1989). Wagner and Altenberg (1995) reports a study about the "evolvability" in evolutionary processes. Population dynamics as result of interactions between individuals have been studied, among others, in Taylor *et al.* (1989). Bedau has presented a comparison and a classification of evolvable capacities obtained in artificial ecosystems and from Biosphere examples (Bedau *et al.* 1998; Bedau, Snyder, & Packard 1998).

[1] http://www.ventrella.com

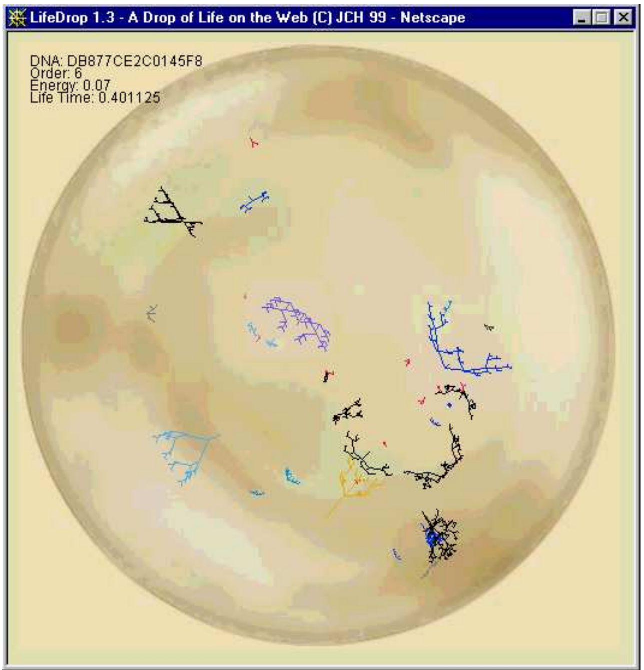

Figure 1: A screenshot of the first version of LifeDrop showing a small set of creatures moving in the 3D environment.

LifeDrop Overview

The environment

LifeDrop[2] is a java-based virtual ecosystem inhabited by bio-inspired creatures. The environment consist of a "virtual water drop" with boundaries acting as "walls" for creatures. It integrates a physical engine managing forces using the "steering behaviors" model for autonomous characters (Reynolds 1999).

The environment includes several parameters such as water fluidity, acidity, etc. The *pH* parameter ranges from 0.0 (no creature can live) to 1.0 (no impact). It simulates the chemical impact of the number of living creature in a closed environment.

The creatures

Each creature is an autonomous agent that can be described by a layered hierarchical model (Heudin 1998) inspired from the subsumption architecture (Brooks 1991). In this model, a given level relies on the existence of its sub-levels and all levels are intrinsically parallel. During a cycle, each layer receives information from the environment and selects an action to be executed. The current model implements five layers:

Genotype: the "digital DNA" of the creature. Metabolism: manages the essential cycles like lifetime, development and growth, mating, etc.

Dynamics: manages the creature's "incarnation" simulating the impact of the "physical conditions" such as water fluidity, *pH*, etc.

Reactive behaviors: manages basic reactive behaviors, such as obstacle avoidance, fleeing, etc.

Cognitive behaviors: manages behaviors such as the selection of a mating partner.

Creature genotype

Each creature is characterized by a genotype that determines most of its morphological and behavioral parameters. It is composed of 4 "chromosomes", each of them containing 8 "genes". Figure 2 gives the mapping of these encoded parameters.

In addition to these parameters, each creature gets an additional set of parameters after its development process. These include, among others, the "alive", "hungry", "fecund" and "stressed" states. As we will see later, the "stressed" state has a direct impact on the creature's behaviors and also on the speciation mechanism.

Creature morphology and behaviors

The morphology of LifeDrop's creatures was inspired by the works done by Richard Dawkins with the *Blind Watchmaker* (Dawkins 1986; 1989). Within LifeDrop, these 2D shapes called "Biomorphs", have been extended to autonomous agents characterized by 3D shapes and showing a variety of behaviors.

Each agent has its own elementary perception system. It perceives all other creatures close enough in a "perception sphere" which main parameters are encoded in the fourth chromosome. Depending on these sensory information and its internal state, an agent selects an action in the set of possible behaviors at each simulation cycle. Examples of possible behaviors are the following: looking for mate, looking for food, fleeing a danger, moving randomly, flocking, etc.

All agents interact in the same virtual drop of water resulting in a complex (eco-)system. There is no explicit fitness function or any global selection procedure. The success of some phenotypes emerges from the interactions between agents in the environment. Some agents show a good adaptation while some others die quite rapidly (killed by others for example). Thus, any individual born inherits genes that have succeeded in building a series of successful phenotypes. In this sense, we can state that LifeDrop implements the principle of natural selection.

[2]LifeDrop can be experimented on-line on the following web site at http://www.virtual-worlds.net/lifedrop.

Chromosome #0 — Meta genes	
Gene #0:	Number of chromosomes in the genotype.
Gene #1:	Matching level with another genotype.
Gene #2:	Mutation level.
Gene #3:	Internal clock: lifetime in cycles.
Gene #4:	Internal clock: cycle time.
Gene #5:	Maximum energy level.
Gene #6:	Maximum number of children per reproduction.
Gene #7:	Unused.

Chromosome #1 — Structural genes	
Gene #0:	Recursion order for development.
Gene #1:	Segmented or not (Dawkins 1988).
Gene #2:	Number of segments if segmented (Dawkins 1988).
Gene #3:	Delta parameter for segmentation (Dawkins 1988).
Gene #4:	Gradient parameter for segmentation (Dawkins 1988).
Gene #5:	Jaws force level.
Gene #6:	Color.
Gene #7:	Unused.

Chromosome #2 — Morphological genes	
Gene #0:	dx #3 parameter (Dawkins 1988).
Gene #1:	dx #4 parameter (Dawkins 1988).
Gene #2:	dx #5 parameter (Dawkins 1988).
Gene #3:	dy #2 parameter (Dawkins 1988).
Gene #4:	dy #3 parameter (Dawkins 1988).
Gene #5:	dy #4 parameter (Dawkins 1988).
Gene #6:	dy #5 parameter (Dawkins 1988).
Gene #7:	dy #6 parameter (Dawkins 1988).

Chromosome #3 — Behavioral genes	
Gene #0:	Number of creatures which can be perceived.
Gene #1:	Maximum radius for perception.
Gene #2:	Recognition rate.
Gene #3:	Mating behavior weight.
Gene #4:	Eating behavior weight.
Gene #5:	Fleeing behavior weight.
Gene #6:	Flocking behavior weight.
Gene #7:	Render behavior weight.

Figure 2: The encoded parameters in the genotype.

The Stress-based Speciation Model

Biological inspiration

The most widely accepted definition of a species is the one proposed by Ernst Mayr (1982). He defines a species as a set of individuals that "can mate and be fecund between them, and only between them". Such a definition implicitly involves a "species barrier" principle, which prevents reproduction between two individuals from different species.

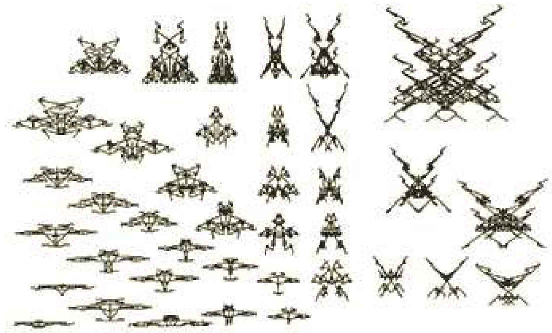

Figure 3: Examples of biomorphs' shapes (after Dawkins).

Recently, Matic and his colleagues have proposed an explanation of the species formation at molecular scale for bacteria (Matic, Rayssiguier, & Radman 1995). This study shows that the species barrier is maintained by genes controlling a mismatch repairing system (MRS) of DNA. In addition to its repairing property, this system warrants that two genotypes with too high differences cannot recombine between them. Thus, when the MRS is active, only individuals having similar genotypes are fecund between them and will be able to mate successfully. However, if the MRS genes are inactivated, the species barrier becomes weak and individuals do not need anymore to have much genetic proximity to be fecund between them. Moreover, in such a case, the observed mutational rate becomes very high.

A key feature of this study is that inhibition occurs for individuals stressed by their environment. When individuals are stressed by difficult environmental conditions, they can reproduce with individuals that, in a non-stressed situation, would be considered from another species. Adding the fact that the mutational rate is then higher, stressed species go through diversification. When the stress decreases, the species barrier is restored.

Model implementation

Each LifeDrop agent is characterized by a parameter named *matching level* which is encoded in its first chromosome (cf. figure 2). This parameter represents the minimum "genetic proximity" value this individual must have with another to be able to reproduce. It simulates the structural compatibility between two different genotypes. As a consequence, the definition of a species is: *Two individuals are considered of the same species if their genotypic proximity is greater than each of their respective matching level values.*

The genotypic proximity P_{g1g2} is given by the expres-

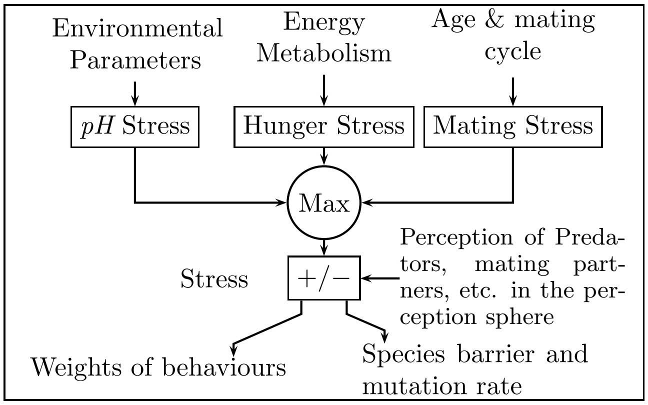

Figure 4: Stress computation of a creature during a cycle.

sion:

$$P_{g1g2} = k\left(1 - \frac{D_{g1g2}}{D_{\max}}\right) \tag{1}$$

where D_{g1g2} is the distance between genotype $g1$ and genotype $g2$, $D_{\max}$ the maximum possible distance between two genotypes, and k an implementation constant with a value of 100.

We have used the Euclidean distance for computing D_{g1g2}, each genotype being considered as a vector. Such a choice has been made in order to consider all genes from a neutral point of view. This means that the phenotypic impacts of genes are not taken into account. This constitutes a major difference with previous artificial life studies. Note that other distance expressions could be used in other experiments but they will not be addressed in this paper.

The stress plays an important role for each creature. It is implemented as a floating point value ranged from 0.0 (not stressed) to 1.0 (extremely stressed). The computation of this value, called S_i, takes further steps as shown in figure 4. It involves many parameters related to the environment, the energy metabolism, the reproduction metabolism, and the perception system.

Besides its impact on the behavior selection, it also acts on the species barrier. During important stress situations, the *matching level* M_i of an agent is lowered and its *mutational rate* Π_i is increased. These reproduction parameters are functions of the stress and two base values, M_{gi} and Π_{gi}, given by the first chromosome:

$$M_i = M_{gi} - \alpha S_i \tag{2}$$
$$\Pi_i = \Pi_{gi} + (\beta^{-1} S_i)^2 \tag{3}$$

where α and β are implementation dependant constants with a value of 20 and 2 respectively.

Experimental results

General observation

We have conducted three different types of experiments with varying initial conditions and parameters. The first type includes runs with a set of randomized genotypes and the observer does not act in any sort during the simulation. The second type includes also simulations with randomized initial genotypes but the user sets the *pH* value to 0.5 at a particular instant and during a certain time. This means that the environment suddenly becomes unfavorable for survival. These “crisis periods” allow one to study the impact of a difficult environment on species dynamics. In the third set of simulations, all initial creatures have the same genotype (randomly chosen) and the user can force crisis periods.

All experiments show a fast population decrease during the first 20,000 simulation cycles. In some rare cases, this decrease leads to a population extinction. However, in most cases the decrease is followed by an important increase. When some creatures are still living after 20,000 cycles, then no population extinction has ever been observed.

The number of species vary a lot during an experiment. This means that species frequently appear or disappear over the time. It is important not to simply relate this it with births or deaths. As a matter of fact, the species definition is based on the species barrier which itself depends on the stress of creatures. Thus, the species delimitation between individuals is in constant evolution.

Experiments without crisis

In these experiments, the species number decreases during a first phase and then stays relatively constant. The average stress of the creatures varies a lot during the first steps of simulation and then tends to stabilize itself as for the population. In all experiments of this type, the stable state corresponds to low number of species, usually ranged between 5 and 10. In any cases, the species number stay strictly greater than one, which means that different species co-evolve permanently in the environment. Figure 5 shows the time series for a typical experiment with an initial set of 100 creatures.

Experiments with crisis

All experiments of the second type show the same dynamics as in the first type with the exception of crisis periods. During these periods, the *pH* is forced to 0.5. This has the effect to reduce by half the lifetime of the creatures and to force their stress rate up to 0.5, which rarely appears in normal simulations.

As a result, the number of species decreases when the crisis begins. This is a consequence of two facts. First, a high number of individuals die, which may cause the disappearance of a number of species. Then the species barriers become low due to the high value of stress. Thus, surviving agents are distributed among few species. Despite the lowness of the barriers, the number of species increases slowly during the crisis. The stress rates having quite no variation, this means that newborn creatures

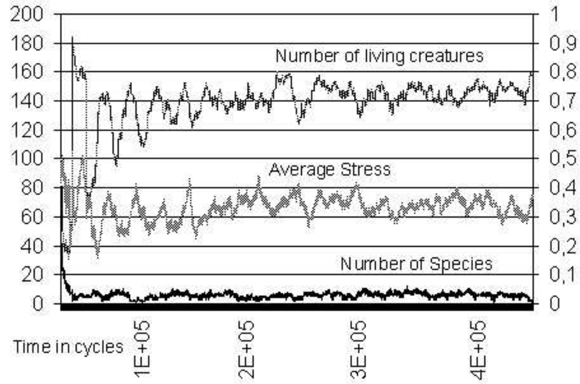

Figure 5: Time series of population, number of species (both on the left axis) and average stress (right axis).

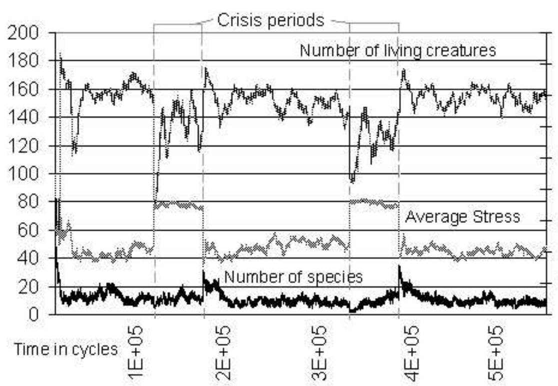

Figure 6: Time series of population, number of species (both on the left axis) and average stress (right axis).

present a high variability, enough to be considered as belonging to different species than the already present one. It is well showed at the end of the crisis. When the pH returns to a "normal" value, the species number strongly increases, showing that the diversity between individuals issued from the crisis is very high. Figure 6 shows results for a typical experiment of this kind with 100 initial randomized genotypes.

The third type of experiments shows this behaviors still better (cf. figure 7). When a simulation begins with a set of creatures having the same genotype, the number of species increases slowly even before a crisis period is forced by the user. The stress is rather high during a long period at the beginning of the simulation, around 0.4, which may be understood as the initial creatures were not well adapted to their environment. As a reaction, population goes through diversification and new species appear. This is followed by a decrease of the average stress. Later, after a crisis period, the diversity has become even more important and the system stabilizes, as seen in first type simulation. Note that the beginning of these experiments is rather different than

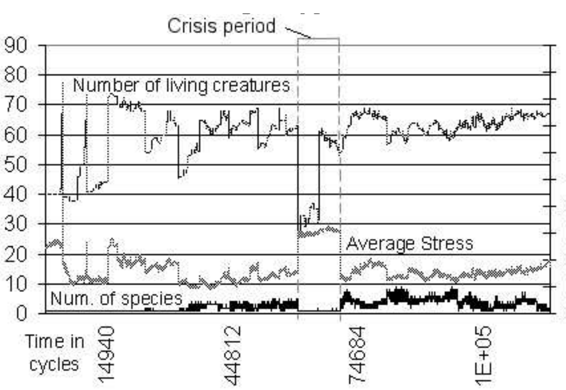

Figure 7: Time series of population, number of species (both on the left axis) and average stress (right axis).

previous ones. As a matter of fact, all creatures having the same genotype, population extinction is more frequent. The "success" of an experiment is thus highly dependent on the chosen genotype.

Discussion

Results showed that in "normal" situations the population, the species number and the mean stress tend to stabilize over the time. The evolution leads to a population composed of individuals well adapted to their environment spread over a few number of species. When environmental difficulties appear, results show a decrease of species and barriers become lower. This leads to new recombination between individuals and favors new species formation. At the end of a crisis, the barriers are restored and a high number of species emerge. The behavior of the system is thus to favor emergence of new species in response to the population lack of adaptation. As pointed out by Matic *et al.* (1995), this might be a possible explanation (at molecular scale) for the species dynamics observed in fossil record. These patterns, named "punctuated equilibria", reveal most species in stasis followed by abrupt appearance of newly derived species (Eldredge & Gould 1972). Of course, this hypothesis must be confirmed by further studies showing that this model could be also applied to the evolution of multicellular organisms.

In our experiments, the final species number has been always greater than one (with exception of some complete population extinctions). This property appears to be significant in comparison to previous artificial ecosystem studies. In Gaïa, Gracias (Gracias *et al.* 1996) observed that cohabitation between two species never occurs, even when beginning with two highly adapted species. The explanation of this phenomenon is that, in a system where individuals have to find a mating partner, the probability of achieving reproduction is highly dependant on the number of individuals of the same species. When two species cohabit, an implicit competition takes place, favoring the most numerous species. All Gaïa simulations ended with only one species. In contrast, LifeDrop allows cohabitation between different species. After a first chaotic phase, the number of species tends to stabilize around a global value proper to each simulation. Even after an increase at the end of a crisis period, the number of species decreases returning to a value near to the one observed before the crisis.

The stress is generally considered as a disagreement for an individual. It is an indicator of some difficulties to live in an environment and it impacts on behaviors. In our model, the stress has another property. It helps evolution, acting as a kind of dynamic fitness function for exploring the genotype space, favoring diversity by decreasing the species barrier between individuals and increasing the mutation rate during reproduction.

Conclusion

This paper has presented a genetically-based species definition involving a barrier mechanism and a stress-based speciation model. Results show a clear convergence with those obtained by biological experiments with bacteria (Taddey, Matic, Radman 1996), thus validating this approach. Future works include the study of species dynamics as complexity classes (Wolfram 1984) and their corresponding attractor structures. This will be then compared to observed species dynamics (phyletic gradualism, punctuated equilibria, etc) in nature.

References

Adami, C., and Brown, C. 1994. Evolutionary learning in the 2D artificial life system “Avida”. In Brooks, R. A., and Maes, P., eds., *Artificial Life IV, Proceedings of the Fourth International Workshop on the Synthesis and Simulation of Living Systems*, 377. MIT Press.

Bedau, M. A.; Snyder, E.; Brown, T.; and Packard, N. H. 1998. A comparison of evolutionary activity in artificial evolving systems and in the biosphere. Technical Report WP 98-03-024, Santa Fe Institute.

Bedau, M. A.; Snyder, E.; and Packard, N. 1998. A classification of long-term evolutionary dynamics. In Adami, C.; Belew, R.; Kitano, H.; and Taylor, C., eds., *proceedings of the Artificial Life VI Conference*, 228–237. MIT Press.

Brooks, R. 1991. How to build complete creatures rather than isolated cognitive simulators. In VanLehn, K., ed., *Architectures for Intelligence*. Hillsdale: Lawrence Erlbaum Assosiates. 225–239.

Conrad, M. 1987. Computer test beds for evolutionary theory. Oral presentation at Artificial Life I Conference.

Dawkins, R. 1986. *The Blind Watchmaker*. Penguin Books.

Dawkins, R. 1989. The evolution of evolvability. In *Artificial Life* (1989), 201.

Eldredge, N., and Gould, S. 1972. Punctuated equilibria: an alternative to phyletic gradualism. In Schopf, T., ed., *Models in Paleobiology*. San Francisco: Freeman, Cooper.

Gracias, N.; Pereira, H.; Lima, J.; and Rosa, A. 1996. An artificial life environment for ecological systems simulation. In Langton, C., and Shimohara, K., eds., *Artificial Life V*, 124–133. MIT Press.

Heudin, J. 1998. Virtual worlds. In Heudin, J., ed., *Virtual Worlds: Synthetic Universes, Digital Life and Complexity*. Perseus Books. 1–28.

Komosinski, M. 2000. The world of Framsticks: Simulation, evolution, interaction. In Heudin, J.-C., ed., *Proceedings of the Second International Conference on Virtual Worlds*, volume 1834 of *Lecture Notes in Computer Science*, 214–224. Springer-Verlag.

Langton, C. G. 1989. *Artificial Life*, volume 6 of *Santa Fe Institute Studies in the Sciences of Complexity*. Addison-Wesley.

Matic; Rayssiguier, C.; and Radman, M. 1995. Interspecies gene exchange in bacteria: the role of sos and mismatch repair systems in evolution of species. *Cell* 80:507.

Mayr, E. 1982. *The Growth of Biological Thought : Diversity, Evolution and Inheritance*. Harvard University Press.

Packard, N. 1989. Intrinsic adaptation in a simple model evolution. In *Artificial Life* (1989), 141.

Ray, T. 1991. An approach to the synthesis of life. In Langton, C. G.; Taylor, C.; Farmer, J. D.; and Rasmussen, S., eds., *Artificial Life II*. New York: Addison-Wesley. 371.

Reynolds, C. 1999. Steering behaviors for autonomous characters. Presented at the 1999 Game Developer Conference.

Taddey; Matic; and Radman. 1996. Du nouveau sur l'origine des espèces. *La Recherche* 291:52–59.

Taylor, C.; Jefferson, D.; Turner, S.; and Goldman, S. 1989. RAM : Artificial life for the exploration of complex biological systems. In *Artificial Life* (1989), 275.

Ventrella, J. 1998. Designing emergence in animated artificial life worlds. In Heudin, J., ed., *Proceedings of the First International Conference on Virtual Worlds*, volume 1434 of *Lecture Notes in Computer Science*, 143. Springer-Verlag.

Wagner, G., and Altenberg, L. 1995. Complex adaptations and the evolution of evolvability. *Evolution* 50:967–976.

Yaeger, L. 1994. Computational genetics, physiology, metabolism, neural systems, learning, vision, and behavior or PolyWorld: Life in a new context. In Langton, C. G., ed., *Artificial Life III*, 263. Reading, Mass.: Addison-Wesley.