A PARAMETRIC STUDY ON REPRODUCTIVE COMPETENCE IN AUTO-CONSTRUCTIVE ARTIFICIAL LIFE

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DECLARATION

I hereby declare that the material in this thesis is my own except for quotations, excerpts, equations, summaries and references, which have been duly acknowledged.

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ABSTRACT

A PARAMETRIC STUDY ON REPRODUCTIVE COMPETENCE IN AUTO-CONSTRUCTIVE ARTIFICIAL LIFE

Auto-constructive artificial life is the study of biological phenomena in silico using computer simulations of digital organisms that are capable of self-reproduction. Although a number of advanced artificial life simulators have been developed recently, very little is known about how reproductive competence may be affected by parametric changes of evolutionary settings in auto-constructive artificial life. This thesis presents a systematic investigation of how different parametric changes can affect the self-reproduction capabilities of a collectively-intelligent flying swarm of simulated organisms. To achieve this objective, an auto-constructive artificial life simulation was developed based on the Breve system. This system contains various parameters whose values can be changed to control the characters of the swarm at the Genetic, Organism and Environment levels. Observations are then made on how the collective swarm evolves and is affected by different parameter settings in terms of reproductive competence. Each level has four individual parameters and is simulated for 50 runs with 50 different seeds which were terminated at 6000 generations each. The reproductive competence was measured at the start of a particular point of evaluation where no new organism is injected by the system within 5500 generations continuously and all new offspring were autonomously produced through the swarm's reproductively capabilities itself. A total of 6000 evolutionary simulation runs were conducted. From the results, it was found that the individual parameters at the Environment level were most sensitive to parametric changes compared to parameters at the Organism and Genetic levels. Overall, the three individual parameters that had the greatest impact on the swarm's reproduction competence were Number of Feeders at the Environment level (58%), followed by Lifetime at the Organism level (42%) and Maximum Random Code Size at the Genetic level (38%).

ABSTRAK

Kehidupan buatan berasaskan penghasilan semulajadi adalah kajian berdasarkan prinsip biologi yang dilaksanakan dalam pensimulasian komputer dengan mengaplikasikan organisma yang reproduktif secara semulajadi. Sungguhpun model menarik tentang kehidupan buatan menerusi pensimulasian telah lama diperkenalkan, namun penyelidikan tentang kesan penggunaan beberapa jenis parameter terhadap kompetensi reproduktif di dalam kehidupan buatan masih lagi tidak dikaji. Permasalahan ini telah mendorong untuk mengkaji bagaimana penggunaan pelbagai jenis parameter boleh memberi impak ke atas keupayaan reproduktif semulajadi terhadap kelompok organisma yang dilaksanakaan dalam kajian ini. Untuk mencapai matlamat tersebut, kehidupan buatan reproduktif semulajadi dilaksanakan menerusi penggunaan sistem Breve. Sistem ini mengandungi beberapa parameter dengan nilai yang berasingan bertujuan untuk mengawal tingkah laku kelompok organisma pada tahap Genetik, Organisma dan Persekitaran. Tinjauan dilaksanakan ke atas evolusi kelompok organisma dan kesan daripada parameter yang telah digunakan terhadap kompetensi reproduktif. Setiap tahap mempunyai 4 parameter yang mana setiap satunya mengandungi 11 nilai yang berbeza ditentukan oleh pengguna. Nilai tersebut akan dilaksanakan sebanyak 50 kali pengujian dengan 50 nilai permulaan yang berbeza dan setiap satunya akan terhapus pada generasi ke 6000. Kompetensi reproduktif diukur pada titik permulaan generasi di mana organisma dapat menghasilkan sendiri organisma baru yang dikenali sebagai "anak" secara berterusan sepanjang 5500 generasi. Hasil kajian mendapati parameter di tahap Persekitaran menunjukkan kelompok organisma sangat sensitif dalam mencapai kompetensi berbanding daripada tahap Genetik dan Organisma. Pada keseluruhannya, tiga parameter telah menunjukkan kesan ke atas keupayaan reproduktif semulajadi terhadap kelompok organisma iaitu Kuantiti Makanan pada peringkat Persekitaran (58%), diikuti dengan Jangka Hayat pada peringkat Organisma (42%) dan Saiz Kod Rawak Maksimum pada peringkat Genetik (38%).

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A-Life	Artificial Life
CA	Cellular Automata
EXEC	Execution
GP	Genetic Programming
MCS	Maximum Code Size
MMNCS	Maximum Mutation New Code Size
MRCS	Maximum Random Code Size
PEL	Push Execution Limit

CHAPTER 1

INTRODUCTION

1.1 Overview

Artificial Life (A-Life) is an attempt to understand the essential general properties of biological organism possess such as self-reproduction, homeostasis, adaptability, mutational variation and optimization of external states by synthesizing life-like behavior in software, hardware and other human-made systems (Langton, 1984). A-Life provides a synthetic perspective where it begins with simple rules in a computer simulation to achieve complex life-like results for observation of unexpected phenomena in silico.

A-Life was first studied by the mathematician John Von Neumann in late 1940. Neumann delivered a paper entitled "The General and Logical Theory of Automata," in which the concept of a machine that follows simple rules and reacts to information in its environment was discussed and proposed that living organisms are just such machines (Johnston, 1994). Neumann also studied the concept of machine self-replication, and conceived the idea that a self-replicating machine or organism, must contain within itself a list of instructions for producing a copy of itself (Neumann, 1966). In the 1960s, a professor named John Conway devised a simple cellular automaton (CA) that was called the Game of Life. This is the first exposure of A-Life concepts to the general public which came through the "Mathematical Games" column in Scientific American magazine (Gardner, 1970).

Up to this point, there was no discipline for these concepts that was readily recognizable as being related to A-Life. It was not until the late 1970s and early 1980s that an unconventional programmer named Christopher Langton organized the first conference and defined it as "the study of artificial systems that exhibit behavior characteristic of natural living systems", at the International Conference on the Synthesis and Simulation of Living Systems at the Los Alamos National Laboratory (Langton, 1984).

Since 1980s, the study of A-Life in computer has science become very significant, generally simulating the behavior of life systems categorized into three categories that are Hard A-Life, Soft A-life and Wet A-Life, which would be described in detail in Chapter two.

1.2 Motivation

The studies of artificial self-reproducing structures have been taking place since the early half of the previous century (Perrier *et al.,* 1996). It is motivated by the needs of biologists and computer scientists to understand biological mechanisms of reproduction by identifying and studying the conditions that any self-reproducing system must satisfy, thereby providing alternative explanations for empirically observed phenomena. The self-reproducing structures are divided into two major classes, according to the model in which they are based either by using Cellular Automata (CA) or computer program.

The concept of artificial self-replicating systems was originated by John von Neumann in the 1950's in his theory of Cellular Automata (CA). Cellular automata is a state machine that consist of an array of cells that behave according to an identical set of rules of its own state and the state of the neighboring cells and whether either it is occupied or free is represented using one and zero, respectively. Self-reproducing automata are an organized collection of small rectangular of automata (cell) and linked to each of their four nearest neighbors into a copy of itself. Over the years, a number of researchers had worked toward simplifying self-reproducing structures by using CA such Codd (1960), Smith and Turney (2003), Langton (1984) and Reggia and Lohn (2000).

However in the early 1970s, Bratley and Millo (1972) and Burger *et al.,* (1980) respectively formalized a new structure of self-reproducing programs that is a computer program that when executed, would create copies their own source code. Core War is an example of a computer game developed by Dewdney which was a major advance in the use of self-replicating computer code in 1980. This computer game was written in an abstract assembly language called Redcode that attempted to copy themselves elsewhere in memory and then run the extra copies. Meanwhile, in early 1990, Tom Ray had started to study the evolution process in the real world and wanted to observe the effects of evolution on thousands of generations of organisms. Ray's major development was to design an instruction set for his self-replicators in a virtual computer program called "Tierra" system which was robust to mutations and therefore evolvable, while at the same time retaining the property of computational universality (Ray, 1990, 1994). Following from these contributions, a number of a similar system have been produced, these include "Avida" by Chris Adami and Titus Brown (Adami and Brown, 1994) and 'Computer Zoo' written by Jakob Skipper (Skipper, 1992), Koza's system (1994), Ofria and Wilke (2004), Hutton (2007) and Teuscher (2007).

However, although numerous self-reproduce manually A-Life systems have been studied, generally the new organism need to be injected into the environment system based on a hand-designed and not self-evolved genotype (Ray, 1994; Adami and Brown, 1994). As such, this new organism is not a very accurate analogy of real biology. Recently however, the Breve application succeeded to implement a more biologically-plausible framework of "auto-constructive" A-Life (Klein, 2002), where the simulated digital organisms were able to achieve self-reproduction through their own capabilities.

In this work, the Breve application is used as a simulation tool to simulate a collective swarm of flying organism in a realistic 3D environment. In the collective swarm system, an initial number of flying organisms are injected into the system. Each of flying organism is programmed to fly towards the food and eat the food for their energy and longevity. The successful organisms that are able to eat the food would re-grow their energy and can live longer in the system. As mentioned earlier, the framework of "auto-constructive" A-Life in Breve would evolve flying organisms that are capable to reproduce their own children during the simulation.

Besides developing the collective swarm system, this work presents a number of different parameter settings to determine how these settings would affect the behavior of collective swarm in terms of reproductive competence. An organism's behavior is characterized by parameters that determine the rules of interaction of the flying organism in the simulated environment. Changing any of the parameter settings may greatly alter the behavior of the collective swarm. Thus, this study includes investigating the effects of different parameter settings on the emergence of collective behavior in terms of reproductive competence.

The parameter settings are categorized into three levels, which are the Genetic, Organism and Environment levels, where each level consists of four different individual parameters and involves 11 different parameter settings for each individual parameter.

Within these 11 different settings of each individual parameter, the default value is referred based on the Spector's work (2005).

The first 11 different parameter settings at each individual parameter at the Genetic level are used to determine the limitation of instructions (genes) of the computer program (code) such as the parameters of Maximum Random Code Size: the settings are used to control the maximum length of the code size for an initial population in the simulated environment, the parameter of Push Execute Limit: the settings are applied to control the limitation of instructions to be evaluated; the parameter of Maximum Mutation New Code Size: to control the size of a new code size that are used for the addition of instruction in the mutation process, and finally; the parameter of Maximum Code Size to specify the limit of the complete list of instructions constructed in the program code. Generally, the quantity of the instructions that are being applied for the certain task would lead to the behavior of the flying organism in the simulated environment.

Meanwhile, the other 11 different settings of each individual parameter at the Organism level are used to control the features of the flying organism such as the parameters of Coloration: the settings are used to control of their color during the simulation representing speciation; the parameter of Mobility: the settings are used to control how fast an organism can fly in the simulated environment; the parameter of Lifetime: the settings are used to control the longevity of an organism being alive in the environment, and finally the parameter of Corpse: to control the longevity of a dead body of an organism before disappearing from the environment.

Finally, the 11 different parameter settings at the Environment level are used to control the changes of different environmental features such as the parameters of Population Size: this parameter is used to control the quantity of flying organisms at the start of simulation; the parameter of Neighborhood Distance: the settings are used to control the distance of each organism in a group where the sharing energy process of similar species of organisms that are co-located within the range of the Neighborhood Distance; the parameter of Number of Feeders: the settings are used to control the quantity of food in the environment; and finally the parameter of Stability of Feeders: the settings are used to control the frequency with which the feeders begin to drift to new random locations representing the difficulty of organisms tracking and obtaining their food.

Each setting would be conducted for 50 run times which were terminated at 6000 generations. The parameter change process is implemented when the first setting has been completely conducted, the second setting would be conducted through the same process until the whole 11 settings have been completely executed. Thus during the implementation of each setting, the reproductive competence is measured at the point in time where the collective swarm is capable of reproducing their own children with no new organism being randomly injected from the system for 5500 generations; continuously out of the permissible 6000 generations; this measurement process would be explained in more detail in Chapter three.

In investigating the parameter changes in the collective swarm system systematically to determine how the different parameter settings would affect the organism in achieving the reproductive competence or otherwise. Meanwhile, it also gives a big picture on the interactions of the different parameter settings in the context of the evolving population in terms of achieving the reproductive competence. Currently, there has been no study yet which systematically explores the affect of various parameter changes on the emergence of reproductive competence in collective swarms.

1.3 Research Question

In this research, the focus is on investigating how different evolutionary parameter values can affect a collectively intelligent swarm of flying organisms in terms of reproductive competence in an auto-constructive A-Life simulation.

1.4 Objectives

As mentioned in section 1.2, various parameter settings are going to investigate categorized at Genetic, Organism and Environment levels. Thus, based on the above research question, there are three main objectives to be investigated:

a) To investigate parametric changes at the Genetic level

- The individual parameters at the Genetic level of Maximum Random Code Size, Push Execute Limit, Maximum Mutation New Code Size and Maximum Code Size were investigated. Each individual parameter has 11 different settings that will be explained in Chapter four. The objective of this first set of experiments is to elucidate how changes at the Genetic level can affect the evolution self-reproducing capabilities of auto-constructive digital organisms.

b) To investigate parametric changes at the Organism level
   - The individual parameters at the Organism level of Coloration, Mobility, Lifetime and Corpse were investigated. Similar to the Genetic level, each individual parameter has 11 different settings that will be discussed in further in Chapter five. The objective of this second set of experiments is to elucidate how changes at the Organism level can affect the self-reproducing capabilities in auto-constructive digital organisms.

c) To investigate parametric changes at the Environment level
   - Finally, the other four individual parameters at the Environment level of Population Size, Neighborhood Distance, Number of Feeders and Stability of Feeders were investigated. There are again 11 different settings for each parameter that will be elaborated in Chapter six. The objective of this third and last set of experiments is to elucidate how changes at the Environment level can affect the evolution of self-reproducing capabilities in auto-constructive digital organisms.

1.5 Thesis Overview

This dissertation has seven chapters and is organized as follows:

Chapter one includes the introduction of the research work, overview, motivation, research question addressed, the objectives, thesis overview and the contributions.

Chapter two consists of the literature review which provides the fundamentals and background of A-Life and the previous work that are relevant to this study. In this section, the previous work also includes simulation models through computer-based A-Life, those that utilize genetic programming as the artificial evolution engine, soft A-Life, collective A-Life models, intelligent agents, auto-constructive systems, the Breve auto-constructive A-Life system and finally the critical summary of the literature review.

Chapter three details the methodology and elaborates the Breve auto-constructive system as an A-Life simulator, Push3 Implementation, the implementation of stacks in the auto-constructive system, genetic programming as the evolutionary engine. Meanwhile, all evolutionary settings from each individual parameter and how the reproductive competence is measured using a worked example are also explained.

Chapter four observes the reproductive competence through an auto-constructive evolution of A-Life at the Genetic level. There are four individual parameters that will be investigated at this level, which are Maximum Random Code Size, Push Executed Limit, Maximum Mutation New Code Size and Maximum Code Size.

Chapter five investigates the reproductive competence through an auto-constructive evolution of A-Life at the Organism level. Four individual parameters will be investigated at this level which is Coloration, Mobility, Lifetime, and Corpse.

Chapter six studies the reproductive competence through an auto-constructive evolution of A-Life at the Environment level. The Population Size of organisms, Neighborhood Distance, Number of Feeders and Stability of Feeders will be investigated. A comparison across all three evolutionary levels investigated is also summarized here.

Chapter seven summarizes the conclusion of the twelve different evolutionary parameters in achieving reproductive competence. The most and least sensitive set parameters from each level is analyzed. This chapter also includes the suggestions and proposals for future research.

1.6 Contributions

The contributions from the results carried out in this research are as follows:

a) A systematic parametric investigation and data collection of self-reproduction capabilities for an evolving swarm of collectively-intelligent flying organisms in an auto-constructive A-Life simulation environment.

b) Analysis of reproductive competence achievements for individual parameters at the Genetic, Organism and Environment levels of the A-Life simulation environment.

REFERENCES

Ackley, D. & Littman, M. 1992. Interactions between Learning and Evolution. *In* Langton C., Taylor, C., Farmer, J. & Rasmussen, S. (eds) *Journal of Artificial Life II, Santa Fe Institute Studies in the Sciences of Complexity Proceeding.* Berlin: Springer, **10**(2):487-509.

Adami, C. 1998. Introduction to Life. pp. 408. New York: Springer.

Adami, C. & Brown, C. T. 1994. Evolutionary Learning in the 2D Artificial Life Systems Avida. In Brooks, R. & Maes, P. (eds.). *Proceeding of Artificial Life IV*, pp. 377-381. July,1994. Cambridge, MA, USA.

Adamatzky, A. & Komosinski, M. (eds.). 2005. Artificial Life Models in Software. pp. 189. Verlag: Springer.

Altenberg, L. 1994. The Evolution of Evolvability in Genetic Programming. *In* Kinnear, K. (ed.). *An Advances in Genetic Programming*, pp. 47-74. Cambridge: MIT Press.

Baig, A., R. & Rashid, M. 2007. Honey Bee Foraging Algorithm for Multimodal and Dynamic Optimization Problem. pp. 169. United Kingdom.

Baig, A., R. & Rashid., M. 2006. Foraging for Fitness: A Honey Bee Behavior Based Algorithm for Function Optimization, *Technical report*, pp. 169-169. *NUCES*, Pakistan.

Barandiaran, X. & Moreno, A. 2006. A-Life Models as Epistemic Artifacts. *Proceeding of the 10th International Conference on Artificial Life*, pp. 513-519. June 3-7, 2006, Cambridge: MIT Press.

Bedau, M. 1992. Philosophical Aspects of Artificial Life. *In* Varela, F. & Bourgine, P. (eds.). *Towards a Practice of Autonomous Systems*, pp. 494-503. Cambridge Bradford Books/MIT Press.

Benko, G., Flamm, C. & Stadler, P. F. 2005. Explicit Collision Simulation of Chemical Reactions in a Graph Based Artificial Chemistry. *In* Capcarrere, M. S., Freitas, A. A., Bentley, P. J., Johnson, C. G. & Timmis, J. (eds.). *European Conference on Artificial Life proceeding (ECAL05)*, October 26, 2005. Berlin. pp. 725-733.

Belew, R. K. 1991. Artificial Life: A Constructive Lower Bound for Artificial Intelligence. *Journal of the Computer Society*. **6** (1):8-15.

Bouchard, V. 2006. Self-Organisation, Emergence and Management: Some Empirical Findings. *Journal of the Systemist*. **28** (2):26-35.

Burger, J., Brill, D. & Machi, F. 1980. Self-Reproducing Programs. *Journal of Byte*. *5*:72–74.

Burks, A. W. 1970. *Essays on Cellular Automata* (1^{st} edition). Urbana: University of Illinois Press.

Bratley, P. & Millo, J. 1972. Computer Recreations: Self-Reproducing Programs. *Journal of Software Practice and Experience*. **2**:397–400.

Bruce, W., S. 1996. Automatic generation of object-oriented programs using genetic Programming. *In* Koza, J., R., Goldberg, D., E., Fogel, D., B. & Riolo R., L. (eds.). *Proceeding of the First Annual Conference in Genetic Programming*. July, 1996. Cambridge. pp. 267–272. 28-31.

Carrillo, D. P. 2006. Intelligent Agent to Improve adaptability in Web Based Learning Environment. PhD's Thesis. Department of Electronic, Computer Science and Automatic Control. University of Girona.

Codd, E. F. 1968. Cellular Automata. pp. 64-73. New York: Academic Press.

Collins, R. J. & Jefferson, D. R. 1992. AntFarm: Towards Simulated Evolution.*In* Langton C. G., Taylor, C., Farmer, J. D. & Rasmussen, S. (eds.). *Journal of Artificial Life II, Santa Fe Institute Studies in the Sciences of Complexity Proceeding*. Wesley: Addison. **10**: 579-601.

Damer, B., Marcelo, K. & Revi, F.1998. Nerve Garden: A Public Terrarium in Cyberspace. *Proceedings of the First International Conference on Virtual Worlds,* July 1-3,1998, Paris, France. pp. 177–185.

Dewdney, A. K. 1984. Core War. *Journal of the Scientific American*. **250** (5):15-19.

Dittrich, P., Ziegler, J. & Banzhaf, W. 2001. Artificial Chemistries a Review. *Journal of Artificial Life*. Cambridge: MIT Press. **7** (3): 225-275.

Dorigo, M. & Gambardella, L. M. 1997. Ant Colony System: A Cooperative Learning Approach to the Traveling Salesman Problem. *Journal of an IEEE Transaction on Evolutionary Computation* **1**(1): 53-66.

Forst, C. V., Flamm, C., Hofacker, I. L. & Stadler, P. F. 2006. Algebraic Comparison of Metabolic Networks, Phylogenetic Inference, and Metabolic Innovation. *Journal of BMC Bioinformatics* **7**:67.

Flake, G. W. 1999. *The Computational Beauty of Nature.* pp. 524. Cambridge: MIT Press.

Flamm, C., & Stadler, P. F. 1993. Topology of Chemical Reaction Networks a Bioinformatics Group. Master's Thesis. Department of Computer Science and Interdisciplinary Center for Bioinformatics, University of Leipzig.

Gazi, V. & Passino, K. M. 2004. Stability Analysis of Social Foraging Swarms. *Journal of an IEEE Transactions on systems, man, and cybernetics.* **34**(1): 539-557.

Heppner, F. & Grenander, U. 1990. A Stochastic Nonlinear Model for Coordinated Bird Flocks. *In* Krasner, S. (ed.). *The Ubiquity of Chaos,* pp. 233-238. Washington: AAAS Publications.

Hsin, Y. C. 2006. Emergence of Vortex Swarming in Daphnia. *Technical report for Emergent State of Matter.* Spring publication.

Hillis, W. D. 1990. Co-Evolving Parasites Improve Simulated Evolution as an Optimization Procedure. *Journal of Physica.* Amsterdam: Elsevier Science. **42** (1):228-234.

Holland, J. 1990. Echo: Explorations of Evolution in a Miniature World. *In* Langton, C. G., Taylor, C., Farmer, J. D. & Rasmussen, S. (eds.). *Journal of Artificial Life II.* **13** (2):159-187. Cambridge: MIT Press.

Hutton, T. J. 2007. Evolvable Self-Reproducing Cells in a Two-Dimensional Artificial Chemistry. *Journal of Artificial Life.* **13**(1):11-30.

Jeschke, J. M. & Tollrian, R. 2007. Prey Swarming: Which Predators Become Confused and Why? *Journal of the Association for the Study of Animal Behaviour.* Elsevier ScienceDirect. **74**: 387-393.

Kauffman, S. A. 1993. *The Origins of Order:Self-Organization and Selection in Evolution.* pp. 709. Oxford University Press.

Komosinski, M. & Ulatowski, S. 1999. Framsticks: Towards a Simulation of a Nature-like World, Creatures and Evolution. *In* Floreano, D., Nicoud, J. D. Modada, F. (eds.). *Advances in Artificial Life. Lecture Notes in Artificial Intelligence 1674*: pp. 261-265. Verlag: Springer.

Koza, J. R. 1992. Genetic Programming II: Automatic Discovery of Reusable Programs, pp. 746. Cambridge: MIT Press.

Koza, J., R. 1994. Artificial Life: Spontaneous Emergence of Self-Replicating and Evolutionary Self-Improving Computer Program. *In* Langton, C. G. (ed.). *Journal of Artificial life III,* Wesley: Addison. **4** (3):225-262.

Klein, J. 2002. BREVE: A 3D Environment for the Simulation of Decentralized Systems and Artificial Life. *Proceeding of Eighth International Conference on Artificial Life.* pp. 329–334. October, 2002. Cambridge: MIT Press.

Langton, C. G. 1984. Self-Reproduction in Cellular Automata. *Journal of the Physica D.* **10**:135-144.

Millonas, M. M.1994. Swarms, Phase Transitions, and Collective Intelligence. *In* Langton, C. G. (ed.). *Artificial Life III,* pp. 417-445. Wesley: Addison.

Minati, G. 2006(a).Multiple Systems, Collective Beings and the Dynamic Usage of Models *Journal of the Systemist,* **28**(2):200-11.

Minati, G. & Pessa, E. 2002 (eds.). *Emergence in Complex Cognitive, Social and Biological Systems.* pp. 410. London: Kluwer Academic/Plenum Publishers.

Minati, G. & Pessa, E. 2006. *Collective Beings.* pp.26. Springer, New York.

Moore, M. 2004. Using an Automated Knowledge Agent for Reference and Customer Service. *Medical Library Association.* **92**(2):271-273.

Neumann, J. V. 1966. Theory of self-reproducing automata. *In* Burks, A. W. (ed.). Urbana: University of Illinois Press. **18** (4):254.

Nordin, P., Banzhaf, W. & Francone, F. D. 1999. Efficient Evolution of Machine Code for CISC Architectures Using Instruction Blocks and Homologous Crossover. *In* Spector, L. & Langdon, W. B, pp. 275–299. Cambridge: MIT Press.

Ofria, C. & Wilke, C. 2004. Avida: A Software Platform for Research in Computational Evolutionary Biology. *Journal of Artificial Life.* 10:191-229.

Oros, N. & Nehaniv, C. L. 2007. Self-Reproduction, Evolution and Sex in Cellular Automata. *Proceedings of the 2007 IEEE Symposium on Artificial Life (CI-ALife 2007),* April1-5,2007. United Kingdom. pp. 24-39.

Osborn, T. R., Charif, A., Lamas, R. & Dubossarsky, E. 1997.Genetic Logic Programming. *In* IEEE Conference Evolutionary Computation. IEEE Press: New York **2**: 728–732.

Packard, N. H. & Bedau, M. A. 2000. Artificial Life. *In Encyclopedia of Cognitive Science.* Macmillan. **1**: 209-215.

Pedrycz, W. & Reformat, M. 2001. Evolutionary Optimization of Logic-Oriented Systems. *Proceeding of Genetic and Evolutionary Computation, July 7-11, 2001,California.* pp. 1389–1396.

Perrier, J. Y., Sipper, M. & Zahnd, J. 1996. Toward a Viable, Self-Reproducing Universal Computer. *Journal of the Physica D.* Lausanne: Elsevier. **97**:335-352.

Pessa, E. 1998. Emergence, Self-Organization, and Quantum Theory. *Proceedings of the 1st Italian Conference on Systemics, Apogeo Scientifica, Milano.* July 5-6, 1998. Italy. pp. 59-79.

Pessa, E. 2002. What Is Emergence? *In* Minati, G. & Pessa, E. (eds.). *Emergence in Complex Cognitive, Social and Biological Systems.* pp. 379-82. New York: Kluwer.

Pessa, E. 2006. Physical and Biological Emergence: Are They Different? *Proceeding of the Systemics of Emergence: Research and Development.* October 6, 2006. New York. pp. 355-74.

Pesavento, U. 1995. An Implementation of Von Neumann's Self-Reproducing Machine. *Journal of Artificial Life.* **2**(4):337-354.

Ray, T. S. 1992. Synthesis life: Evolution and Optimization of digital organisms. *Proceeding of the Scientific Excellence in Supercomputing.* June 8-12,1992. Athen. pp. 489-531.

Ray, T. S. 1992. An Approach to the Synthesis of Life. *In* Langton, C. G., Taylor, C., Farmer, J. D. & Rasmussen, S. (eds.). *Journal of the Artificial Life II, Santa Fe Institute Studies in the Sciences of Complexity.* Wesley: Addison. **10**:371-408.

Ray, T. S. 1994. Evolution and Complexity. *In* Cowan, G., Pines, D. & Meltzer, D. (eds.). *Complexity: Metaphors, Models, and Reality. SFI Studies in the Sciences of Complexity,* pp. 161–176. Wesley: Addison.

Reggia, J., A. & Lohn, J. D., 2000. Automatic Discovery of Self-Replicating Structures in Cellular Automata. *IEEE Transactions on Evolutionary Computation* **1**(3):165–178. Resnick, M. 1997. *Turtles, Termites, and Traffic Jams: Explorations in Massively Parallel Microworlds.* (4th edition). Cambridge: MIT Press.

Reynolds, C. W. 1987. Flocks, Herds, and Schools: A Distributed Behavioral Model. *In* Computer Graphics. **21**(4):25–34.

Russell, S. & Norvig, P. 2004. *Artificial Intelligence: A Modern Approach.* (2nd edition). Prentice-Hall.

Sichman, J. S. & Demazeau, Y. 2001. On Social Reasoning in Multi-Agent Systems. *Journal of the Revista Ibero-Americana de Intelligence Artificial*, (AEPIA). **13**: 68-84.

Sims, K. 1994. Evolving Virtual Creatures. *In* Computer Graphics, Annual Conference Series .*SIGGRAPH'94 Conference Proceedings.* July, 1994. pp. 15-22. ACM Press.

Sipper, M. 1994. Non-Uniform Cellular Automata: Evolution in Rule Space and Formation of Complex Structures. *In* Brooks R. A. & Maes P. (eds.). *Artificial life IV.* pp. 394–399. Cambridge: MIT Press.

Skipper, J. 1992.The complete zoo evolution in a box. *In* Varela, Francisco J. & Bourgine, Paul (eds). *Toward a Practice of Autonomous Systems.* pp.355-364. Cambridge: MIT Press.

Smith, A. & Turney, P. 2003. Self-Replicating Machines in Continuous Space with Virtual Physics. *Journal of Artificial Life.* **9**:21-40.

Spector, L., Klein, J., Perry, C. & Feinstein, M. 2005. Emergence of Collective Behavior in Evolving Populations of Flying Agents. *Journal of the Genetic Programming and Evolvable Machines.* **6** (1):111-125.

Spector, L., & Robinson, A. 2002. Multi-type, Self-adaptive Genetic Programming as an Agent Creation Tool. *In* Barry A., W. (ed.). *Proceedings of the Workshop on Evolutionary Computation for Multi-Agent Systems, (ECOMAS-2002).* July 8, 2002. New york. International Society for Genetic and Evolutionary Computation, pp. 73-80.

Spector, L. 2002. Adaptive Populations of Endogenously Diversifying Pushpop Organisms are Reliably Diverse. *In* Standish, R. K., Bedau, M. A. & Abbass H. A. (eds.). *Proceedings of Artificial Life VIII, the 8th International Conference on the Simulation and Synthesis of Living Systems,* December, 2002. Cambridge. pp. 142-145.

Spector, L. & Robinson, A. 2002. Genetic Programming and Autoconstructive Evolution with the Push Programming Language. *Journal of the Genetic Programming and Evolvable Machines.* **3**(1):7-40.

Spector, L., Perry, C., Klein, J. & Keijzer, M. 2004. *Push 3.0 Programming Language Description.* Cognitive Science, Hampshire College. Technical Report HC-CSTR-2004-02. 04 September.

Spector, L., Klein, J, & Keijzer, M. 2005. The Push3 Execution Stack and the Evolution of Control. *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO-2005),* June 25-29, 2005. Washington, USA. pp. 1689-1696.

Spector, L., Klein, J., Perry, C. & Feinstein, M. 2005. Emergence of Collective Behavior in Evolving Populations of Flying Agents. *In* Genetic Programming and Evolvable Machines. **6**(1):111-125.

Sugawara, K., Sano, M., Yoshihara, I., Abe, K. & Watanabe, T. 1999. Foraging Behavior of Multi-robot System and Emergence of Swarm Intelligence. *Journal of IEEE International Conference on Systems, Man, and Cybernetics (SMC '99).* **3**:257-262.

Teller, A. 1996. Evolving Programmers: The Co-Evolution of Intelligent Re-Combination Operators. *In* Angeline P. J. & Kinnear, K. E. (eds.), *Advances in Genetic Programming 2.* pp. 45–68. MIT Press: Cambridge.

Terzopoulos, D., Tu, X. & Grzeszczuk, R. 1994. Artificial Fishes with Autonomous Locomotion, Perception, Behavior and Learning in a Simulated Physical World. *In* Brooks, R. A. & Maes, P. (eds.). *Journal of Artificial Life IV.* Cambridge: MIT Press. **1**(4):327–351.

Teuscher, C. 2007. From Membranes to Systems: Self-Configuration and Self-Replication in Membrane Systems. *Journal of BioSystems,* **87**(2-3):101–110.

Tomlinson, B. & Blumberg, B. 2002. Social Synthetic Characters. *In* Bill Hibbard (ed.), *Journal of Computer Graphic.* **26**:2.

Tunstel, E. & Jamshidi, M. 1996. On Genetic Programming of Fuzzy Rule-Based Systems for Intelligent Control. Journal of the Soft Computing and International Intelligent Automation. **2**(3):273–284.

Yaeger, L. 1994. Computational Genetics, Physiology, Metabolism, Neural Systems, Learning, Vision and Behavior or Poly-World: Life *In* Langton, C. G. (ed.). *Journal of Artificial Life III, Santa Fe Institute Studies in the Sciences of Complexity.* Wesley: Addison. **17**:263-298.

Walsh, P. 1998. Evolving Pure Functional Programs.*Proceeding of Third Annual Conference, July 22-25, 1998. California.* pp. 399–402.

Wan, A. D. M. 2002. Experimental Swarm Design. *Innovative Concepts for Agents-Based Systems.* pp. 92-105. Berlin:Springer.

Webster, M. & Malcolm, G. 2007(a). Reproducer Classification Using the Theory of Affordances. *Proceedings of the 2007 IEEE Symposiumon Artificial Life (CIALife 2007),* April 1-5, 2007, Honolulu. pp. 115–122.

Webster, M. & Malcolm, G. 2007(b). Reproducer Classification Using the Theory of Affordances: Models and Examples. *International Journal of Information Technology and Intelligent Computing,* **2**:2.

Wright, S. 1978. Evolution and the Genetics of Populations, Variability within and Among Natural Populations. *Journal of the Biometrics.* **35**(1):359.

Yang, L. & Wang, F. Y. 2005.Driving into Intelligent Spaces with Pervasive Communications. *IEEE Intelligent Systems.* ***19*** (5), 12-15.

Yu, G., T. 1999. An Analysis of the Impact of Functional Programming Techniques on Genetic Programming. PhD Thesis, University College, London.