Modeling Emergence of Complexity: the Application of Complex System and Origin of Life Theory to Interactive Art on the Internet

Christa SOMMERER & Laurent MIGNONNEAU

ATR Media Integration and Communications Research Lab
2-2 Hikaridai, Seika-cho, Soraku-gun
61902 Kyoto, Japan
christa@mic.atr.co.jp, laurent@mic.atr.co.jp

Abstract

The origin of this paper lies in the fundamental question of how complexity arose in the development of life and how one could construct an artistic interactive system that can model and simulate this emergence of complexity. Based on the idea that interaction and communication between entities of a system are the driving forces for the emergence of higher and more complex structures than its mere parts, we propose to apply principles of Complex System Theory to the creation of an interactive, computer generated and audience participatory artwork on the Internet and to test whether complexity within the system can emerge.

1. Introduction

The Internet seems to be especially capable of dealing with interactions and transformations of data and information. Users on the Internet can be considered entities or particles who transport information, such as written texts or images. As these data of information or entities are carried from location to location they could, in principle, change their status and value. We could imagine a system that can increase its internal complexity as more and more users interact with its information. Just as a genetic string or "meme" (Blackmoore & Dawkins, 1999), these strings of information would change and mutate as they are transmitted by the users; they eventually could create an interconnected system that features, similar to the models presented by Stewart Kauffman (1995), a phase transition toward more complex structures. Based on these considerations, we propose a first prototype system for modeling a complex system for the Internet, introduce its construction principles and translation mechanisms, and analyze how the data of information have changed over time.

2. Conceptual Objective

The aim of this research is to construct an Internet based interactive artwork that applies and tests principles of Complex System Theory and Origin of Life theories to the creation of a computer generated and audience participatory networked system on the Internet. Complex Systems Theory is a field of research that allows simpler subsystems to increase in complexity by using phase transitions. These phase transitions take place when a network of particles is given and these particles can switch one another on or off to catalyze or inhibit their production. The proposal of this paper is to test the principle of phase transition for an interconnected web of people who can transmit visual and written information over the Internet. As the information is transported from location to location it will be transformed, creating an interconnected open-ended system that features phase transitions toward more complex structures. Before investigating how to actually build the system, a short summary is given of the theories that ground this research proposal.

3. Origin of Life Theories

The search for "laws of form" to explain the patterns of order and complexity seen in nature has intrigued researchers and philosophers since the Age of Enlightenment. These searchers have included famous scholars such as William Bateson (1894), Richard Owen (1861), Hans Driesch (1914), D'Arcy Wentworth Thompson (1942), and Conrad Waddington (1966). Their quest could generally be subsumed under the term Rational Morphology, a counterpart to the functionalistic approach of the Natural Theology promoted by Charles Darwin (1859, 1959) and Neo-Darwinist Richard Dawkins (1986). Whereas Natural Theology considers form mainly a function of natural selection and adaptation, Rational Morphologists emphasize the creative principle of emergence that accounts for the order of structures found in nature. The quest for the "laws of form" is closely linked to the question of the Emergence of Life. The discussion on how life emerged has a long tradition and basically involves two opposing views: the Artistotelian and the Platonic. These two views of the natural world have dominated science over the past two millennia (Lewin, 1993). Baltscheffsky (1997) notes that "Fundamental to a deeper understanding of complex biological functions are ideas about how life originated and evolved. They include questions about how the first compounds, essential to life, appeared on Earth; how the first replicating molecules came into being; how RNA and DNA were formed; how prokaryotes and the earliest eukaryotes emerged; how different species, with traits like susceptibility, sentience, perception, cognition, and self-consciousness, and with various patterns of behaviors, evolved; and how with these developments, the environment and the ecological systems changed. "

Speculations of how life on earth might have originated have a long history, perhaps as long as the history of humanity. The widely accepted hypothesis that life originated from chemical processes largely derives from the work of Russian biochemist Alexander I. Oparin (1924, translated to English, 1938). In the 1930s, Alexander I. Oparin and J.B.S. Haldane (1932) suggested that life on earth could have emerged by natural means in an early atmosphere filled with different gases such as methane, ammonia, hydrogen and water vapor. Oparin and Haldane called this early atmosphere the Primordial Soup. In their Primordial Soup Theory, life would have originated in the sea as a reaction of these chemical gases triggered by the energy of lightning, ultraviolet radiation, volcanic heat and natural radioactivity.

In the early 1950s, Stanley Miller (1953) of the University of Chicago's Chemistry Department simulated such a primordial atmosphere and was able to synthesize significant amounts of amino acids, main components of all life forms, from methane, ammonia, water vapor and hydrogen. This experiment gave credence to the belief that the chemical building blocks of life could be created by natural physical processes in the primordial environment. Modern proponents of the Primordial Soup Theory now think that the first living things were random replicators that assembled themselves from components floating around in the primordial soup (Miller, 1953). Based on experiments by Sol Spiegelman (1967), who was able to create self-replicating RNA strings in an environment filled with a primitive "seed" virus and a constant supply of replicase enzymes, Manfred Eigen (1992) went a step further by omitting the initial "seed" virus. Eigen succeeded in showing that self-replicating RNA strands can assemble themselves from only replicase enzymes. In Eigen's theory of the origin of life, RNA molecules can evolve self-replicating patterns and finally develop a primitive genetic code. As the molecules specify and take on different functions, complex and cooperative interactions take place: Eigen calls these the "hypercycles" (Eigen, 1992). Mutation and competition among these hypercycles finally create prototypes of modern cells and the earlier chemical evolution is finally replaced by biological evolution. A similar theory on the origin of life was also presented by Walter Gilbert (1986).

Even though the "RNA world" model seems very convincing, the question of where RNA came from in the first place remains open. L. Orgel (1987), C. Böhler (1995), and P. Nielsen (1991) found that a peptide nucleic acid, called PNA, could be a pre-form of RNA because it can act to transcribe its detailed genetic information directly to RNA; consequently, PNA could have initiated the RNA world. Another scientist, Hendrik Tiedemann suggests that the nucleotide bases and sugars needed in RNA could have been built from hydrogen cyanide and formaldehyde, both available in the early atmosphere of the Earth.

Completely opposite to the "RNA world" theories on the origin of life is the Dual-Origin Theory of A.G. Cairns-Smith (1982). According to Cairns-Smith, the starting point in early crystallization of life was not "high-tech" carbon but "low-tech" silicon, a component of clay. In his theory clay has the capacity to grow and re-assemble itself by exchanging its ion components through mutation and mechanical imperfections. More recent proponents of the mineral and early molecular based theories on the molecular evolution of metabolism subscribe to the "iron-sulphur world" theory of Wächtershäuser (1997), the "thioester world" theory of deDuve (1991), and the "inorganic pyrophosphate world" or "PPi world' theory of Baltscheffsky (1991). Wächtershäuser (1994) proposes a model where early evolution of life as a process begins with chemical necessity and winds up in genetic exchange.

Somewhat related to the question of how life occurred in the first place, whether the first stages of life were metabolic or genetic, is the question of how to draw the line between life and non-life. While generally it is agreed that the RNA world (Gilbert, Eigen, Böhler, Nielsen, Orgel) is a first stage of life, Wächtershäuser (1997) and others believe that rather primitive entities on mineral surfaces can also be called alive; however he calls them "two-dimensional life. " On the other hand, Maynard Smith and Szathmáry (1995) stress that a living organism needs to possess at minimum a reproduction mechanism, and Gánti (1979) proposes that a minimum requirement for a living organism is that it possesses three essential subsystems: a genetic system, a functioning unit synthesizing the components, and a membrane part.

Another big question in understanding life's origin is to determine the origin of the translation apparatus and the genetic code (Crick, 1968, Crick et al. 1976, Woese, 1967). Clas Blomberg (1994) claims that the only way to get a stable translation mechanism is a feedback between the code and the proteins that were synthesized by the mechanisms they controlled. Furthermore, Maynard Smith and Szathmáry (1995) suggest that the relations between amino acids and nucleic acid sequences were established before the translation apparatus, serving as an improved catalyst in the RNA world.

It would exceed the scope of this report to describe all the other theories on the origin of life in detail; however some of them should be mentioned here briefly: the "Membrane First" theory of Harold Morowitz (1992) and the "Self-replicating protein" theory of Ghadiri et al. (1996). Theories that life was first introduced by meteorites that came from other planets or stars include the "Radiopanspermia" theory of Hoyle and Wickramasinghe (1979) and the "handedness of the solar system" theory and its influence on the origin of life of Carl Chyba (1997) as well as the "Chirality" theories of Yoshihisa Inoue (1992).

John Casti notes in the manuscript of his forthcoming book "Paradigms Regained" (Casti, 2000) (from which much of the above information is taken), that "when it comes to defining what it means to be alive, there are as many answers as there are biologists." While the numerous theories about the origin of life suggest that scientists today are still in the dark about the details of life's beginnings and have not been able to create it from scratch, Richard Dawkins (1986) argues that this is rather to be expected. "If the spontaneous origin of life turned out to be a probable enough event to have occurred during a few man-decades in which chemists have done their experiments, then life should have arisen many times on Earth and many times on planets within the radio range of Earth. "

4. Complex System Theory

Closely related to the question of how life on earth originated is the question of how complexity arises. Complex System Theory, as a field of research, has emerged in the past decade. It approaches the question of how life on earth could have appeared by searching for inherent structures in living systems and trying to define common patterns within these structures. Among others, researchers at the Santa Fe Institute in New Mexico, USA have been looking at emergent structures in nature and have called this approach the new science of Complex System Theory. Stuart Kauffman is one of the most prominent proponents of this new theory. According to Kauffman (1995), the pure evolutionary view of nature in the Darwinian sense fails to explain the vast structures of order found in nature. By stressing only natural selection, patterns of spontaneous order cannot be sufficiently described or predicted. In Kauffman's view, this order arises naturally as an "order for free." As a consequence, life is an expected phenomenon deeply rooted in the possibilities of the structures themselves. Kauffman argues that, considering how unlikely it is for life to have occurred by chance, there must be a simpler and more probable underlying principle. He hypothesizes that life actually is a natural property of complex chemical systems and that if the number of different kinds of molecules in a chemical soup passes a certain threshold, a self-sustaining network of reactions - an autocatalytic metabolism - will suddenly appear. It is thus the interaction between these molecules that enables the system to become more complex than its mere components taken by themselves.

4.1. Complexity through Phase Transition

Kauffman and other researchers at the Santa Fe Institute for Complex Systems Research call the transition between the areas of simple activity patterns and complex activity patterns a phase transition. Kauffman (1995) has modeled a hypothetical circuitry of molecules that can switch each other on or off to catalyze or inhibit one of their production. As a consequence of this collective and interconnected catalysis or closure, more complex molecules are catalyzed, which again function as catalyzers for even more complex molecules. Kaufmann argues that, given that a critical molecular diversity of molecules has appeared, life can occur as catalytic closure itself crystallizes. A model built by Kauffman is the Boolean network model, which basically describes the connections and relations between three elements (Kauffman, 1995). The networks described by Kauffman in the Boolean network model show stablility, homeostatis, and the ability to cope with minor modifications when mutated; they are stable as well as flexible. The poised state between stability and flexibility is commonly referred to as the "edge of chaos."

Other researchers have also analyzed this phase transition between order and chaos. Brian Goodwin (1994) describes this transition phase as a kind of biological attractor: "For complex non-linear dynamic systems with rich networks of interacting elements, there is an attractor that lies between a region of chaotic behaviour and one that is 'frozen' in the ordered regime, with little spontaneous activity. Then any such system, be it a developing organism, a brain, an insect colony, or an ecosystem will tend to settle dynamically at the edge of chaos. If it moves into the chaotic regime it will come out again of its own accord; and if it strays too far into the ordered regime it will tend to "melt" back into dynamic fluidity where there is a rich but labile order, one that is inherently unstable and open to change."

4.2. Life at the Edge of Chaos

Two of the first scientists to describe the idea of complex patterns and the ones who defined the term "life at the edge of chaos" were Christopher Langton (1992) and Norman Packard. They discovered that in a simulation of cellular automata there exists a transition region that separates the domains of chaos and order. Cellular automata were invented in the 1950s by John Von Neumann (1966). They form a complex dynamical system of squares or cells that can change their inner states from black to white according to the general rules of the system and the states of the neighboring cells. When Langton and Packard observed the behaviour of cellular automata, they found that although the cellular automata obey simple rules of interaction of the type described by Stephen Wolfram (1986), they can develop complex patterns of activity. As these complex dynamic patterns develop and roam across the entire system, global structures emerge from local activity rules, which is a typical feature of complex systems. Langton and

Packard's automata indeed show some kind of phase transition between three states. Langton and Packard hypothesize that the third stage of high communication is also the best place for adaptation and change and in fact would be the best place to provide maximum opportunities for the system to evolve dynamic strategies of survival. They furthermore suggest that this stage is an attractor for evolving systems. Subsequently, they called the transition phase of this third stage "life at the edge of chaos" (Langton, 1992).

Other researchers at the Santa Fe Institute have extended this idea of life found in this transition phase and applied it to chemistry. In 1992, Walter Fontana developed a logical calculus that can explore the emergence of catalytic closure in networks of polymers (Fontana, 1992). A related approach is seen in the models of physicist Per Bak (1991), who sees a connection between the idea of phase transition, or "life at the edge of chaos," and the physical world, in this case a sand pile onto which sand is added at a constant rate (Bak, 1991).

To summarize, we can see that the various observations and models of Kauffman, Langton, Packard, Fontana and Bak describe complex adaptive systems, systems at the "edge of chaos" where internal changes can be described by a power law distribution. These systems are at the point of maximum computational ability, maximum fitness and maximum evolvability. It is hypothesized that these models could indeed function to explain the emergence of life and complexity in nature. While Kauffman's concept of phase transition is not the only model for creating complexity (many more approaches are currently being discussed on-line, see: www.comdig.org, http://necsi.org/ or published in recent conference proceedings, see: Bar-Yam, 2000), it does however provide an advantageous starting point for creating an artistic system that tries to incorporate some of the features of complex adaptive systems.

5. VERBARIUM - Modeling Emergence of Complexity for Interactive Art on the Internet

Based on the above objective and the literature search in Origin of Life and Complex System Theories, with special focus on the concept of phase transitions, we have developed a first prototype to model a complex system for the Internet (Sommerer and Mignonneau, 1999).

Artists have been working with the potential of user interaction on the Internet over the past several years, and some of the pioneering artworks include works by Anzai (1994), Fujihata (1996), Amerika (1997), and Goldberg (1998). A good overview of this work is also provided by the on-line exhibition "Net-Condition" at the ZKM Center in Karlsruhe, Germany (ZKM, 1999). While many of the above works feature a significant amount of user interaction, their main interest does not seem to be based on the objective of modeling complexity as described in Chapter 2 of this paper.

Our system, called VERBARIUM, is an interactive web site where users can choose to write email messages that are immediately translated into visual 3-D shapes. As the on-line users write various messages to the VERBARIUM's web site, these messages are translated by our in-house Text-to-Form editor into various 3D shapes. By accumulation, these collective shapes can create more complex image structures than the initial input elements. It is anticipated that through the users increased interaction with the system increasingly complex image structures will emerge over time.

5.1. VERBARIUM System Over View

VERBARIUM is available on-line at the following web page: http://www.fondation.cartier.fr/verbarium.html.
The on-line user of VERBARIUM can create 3-D shapes in real-time by writing a text message within the interactive text input editor in the lower-left window of the web site. Within seconds the server receives this message and translates it into a 3-D shape that appears on the upper-left window of the web site. Additionally, this shape is integrated into the upper-right window of the site, where all messages transformed into shapes are stored in a collective image. An example screenshot of the VERBARIUM web site is shown in Fig. 1.

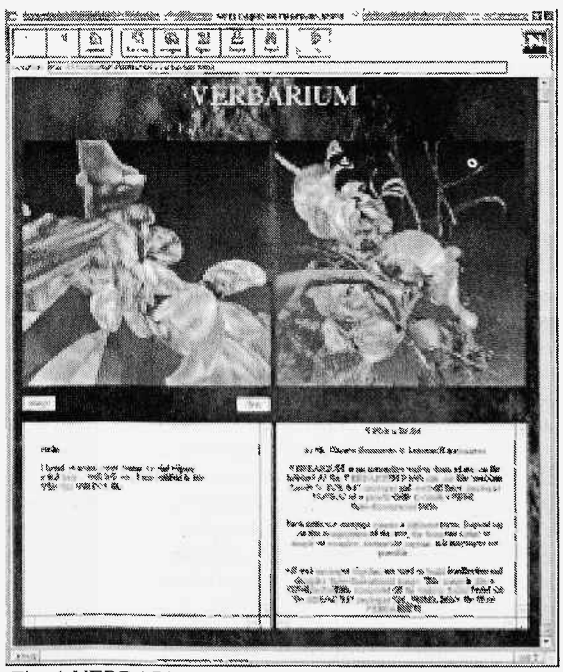

Fig. 1 VERBARIUM web page

VERBARIUM consists of the following elements:

1. a JAVA based web site (Fig.1)
2. an interactive text input editor (lower-left window in Fig.1)
3. a graphical display window to display the 3-D forms (upper-left window in Fig.1)
4. a collective display window to display the collective 3-D forms (upper-right window in Fig.1))
5. a genetic Text-to-Form editor to translate text characters into design functions

5.2. VERBARIUM´s Text-to-Form Editor

We have set up a system that uses the simplest possible component for a 3-D form that can subsequently model and assemble more complex structures. The simplest possible form we constructed is a ring composed of 8 vertices. This ring can be extruded in x, y and z axes, and during the extrusion process the rings' vertices can be modified in x, y and z axes as well. Through addition and constant modification of the ring parameters, the entire structure can grow, branch and develop. Different possible manipulations, such as scaling, translating, stretching, rotating and branching of the ring and segment parameters, creates diverse and constantly growing structures, such as those shown in Fig. 2.

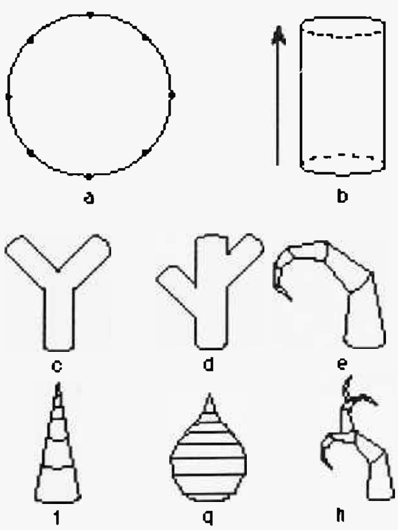

Fig. 2 Example of VERBARIUMS's growing structures

Figure 2a shows the basic ring with 8 vertices, and Fig. 2b shows the extruded ring that forms a segment. Figures 2c and 2d show branching possibilities, with branching taking place on the same place (=internodium) (2c) or on different internodiums (2d). There can be several branches attached to one internodium. Figure 2e shows an example of segment rotation, and Fig. 2h shows the combination of rotation and branching. Figures 2f and 2g are different examples of scaling. In total, there are about 50 different design functions, which are organized into the design function look-up table (Fig. 3). These functions are responsible for "sculpting" the default ring through modifications of its vertex parameters.

function1 translate ring for certain amount (a) in x
function2 translate ring for certain amount (a) in y
function3 translate ring for certain amount (a) in z
function4 rotate ring for certain amount (b) in x
function5 rotate ring for certain amount (b) in y
function6 rotate ring for certain amount (b) in z
function7 scale ring for certain amount (c) in x
function8 scale ring for certain amount (c) in y
function9 scale ring for certain amount (c) in z
function10 copy whole segment(s)
function11 compose a new texture for segment(s)
function12 copy texture of segment(s)
function13 change parameters of RED in segment(s)texture
function14 change parameters of GREEN insegment(s)texture
function15 change parameters of BLUE in segment(s)texture
function16 change patterns of segment(s)texture
function17 exchange positions of segments
function18 add segment vertices
function19 divide segment in x to create branch
function20 divide segment in y to create branch
function21 divide segment in z to create branch
function22 create new internodium(s) for branch(es)
function23 add or replace some of the above functions
function24 randomize the next parameters
function25 copy parts of the previous operation
function26 add the new parameter to previous parameter
function27 ignore the current parameter
function28 ignore the next parameter
function29 replace the previous parameter by new parameter
....
function50

Fig. 3 VERBARIUM's design function table

The translation of the actual text characters of the user´s email message into design function values is done by assigning ASCII values to each text character according to the standard ASCII table shown in Fig. 4.

33 !	34 "	35 #	36 $	37 %	38 &	39 '	
40 (	41)	42 *	43 +	44 ,	45 -	46 .	47 /
48 0	49 1	50 2	51 3	52 4	53 5	54 6	55 7
56 8	57 9	58 :	59 ;	60 <	61 =	62 >	63 ?64
@ 65 A	66 B	67 C	68 D	69 E	70 F	71 G	
72 H	73 I	74 J	75 K	76 L	77 M	78 N	79 O
80 P	81 Q	82 R	83 S	84 T	85 U	86 V	87 W
88 X	89 Y	90 Z	91 [	92 \	93]	94 ^	95 _
96 `	97 a	98 b	99 c	100 d	101 e	102 f	103 g
104 h	105 i	106 j	107 k	108 l	109 m	110 n	111 o
112 p	113 q	114 r	115 s	116 t	117 u	118 v	119 w

120 x	121 y	122 z	123 {	124 |	125 }	126 ~

Fig. 4 ASCII table

Each text character refers to an integer. We can now proceed by assigning this value to a random seed function *rseed*. In our text example from Fig. 5, *T* of *This* has the ASCII value 84, hence the assigned random seed function for *T* becomes *rseed(84)*. This random seed function now defines an infinite sequence of linearly distributed random numbers with a floating point precision of 4 bytes (float values are between 0.0 and 1.0). These random numbers for the first character of the word *This* will become the actual values for the modification parameters in the design function table. Note that the random number we use is a so-called "pseudo random," generated by an algorithm with 48-bit precision, meaning that if the same *rseed* is called once more, the same sequence of linearly distributed random numbers will be called. Which of the design functions in the design function table are actually updated is determined by the following characters of the text, i.e., *his*; we then assign their ASCII values (104 for *h*, 105 for *i*, 115 for *s* ...), which again provide us with random seed functions *rseed(104)*, *rseed(105)*, *rseed(115)*. These random seed functions are then used to update and modify the corresponding design functions in the design function look-up table, between design function1 and function50. For example, by multiplying the first random number of *rseed(104)* by 10, we get the integer that assigns the amount of functions that will be updated. Which of the 50 functions are precisely updated is decided by the following random numbers of *rseed(104)* (as there are 50 different functions available, the following floats are multiplied by 50 to create integers). Figure 5 shows in detail how the entire assignment of random numbers to design functions operates. As mentioned above, the actual float values for the update parameters come from the random seed function of the first character of the word, *rseed(84)*.

Example word: *This*

T => *rseed(84)* => {0.36784, 0.553688, 0.100701,...}
(actual values for the update parameters)

h => *rseed(104)* => {0.52244, 0.67612, 0.90101,...}
0.52244 * 10 => get integer 5 => 5 different functions are called within design function table

0.67612 * 50 => get integer 33 => function 33 within design function table will be updated by value 0.36784 from 1. value of *rseed(84)*

0.90101 * 50 => get integer 45 => function 45 within design function table will be updated by value 0.553688 from 2. value *rseed(84)*
.... until 5. value

Fig. 5 Example of assignment between random functions and design functions

As explained earlier, the basic "module" is a ring that can grow and assemble into segments that can then grow and branch to create more complex structures as the incoming text messages modify and "sculpt" the basic module by the design functions available in the design function table in Fig. 3.

5.3. VERBARIUM's Complexity Potential

Depending on the complexity of the incoming text messages, the 3-D forms become increasingly shaped, modulated and varied. As there is usually great variation among the texts, the forms themselves also vary greatly in appearance. As a result, each individual text message creates a very specific three-dimensional structure that can at times look like an organic tree or at other times look more like an abstract form. All forms together build a collective image displayed in the upper-right window of the web site: it is proposed that a complex image structure could emerge that represents a new type of structure that is not solely an accumulation of its parts but instead represents the amount and type of interactions of the users with the system. Another example of forms created by a different text message is shown in Fig. 6, this time the text was written in French.

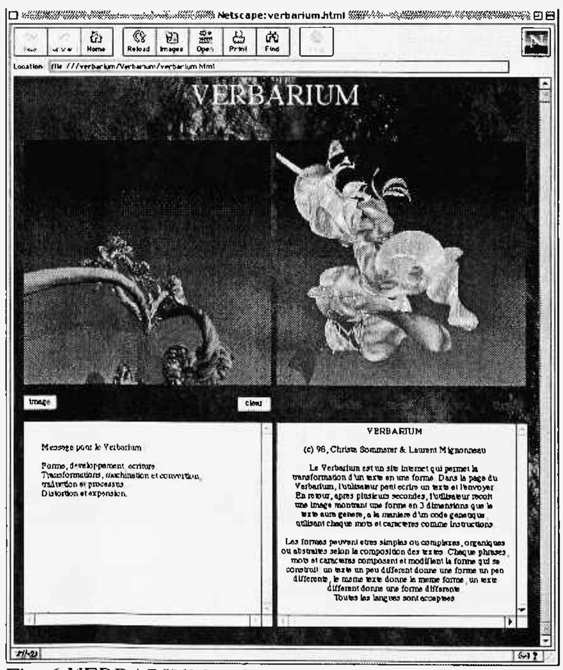

Fig. 6 VERBARIUM web page - example

6. Conclusions and Outlook

We have introduced an interactive system for the Internet that enables on-line users to create 3-D shapes by sending text messages to the VERBARIUM web site. Using our text-to-form editor, this system translates the text parameters into design parameters for the creation and modulation of 3-D shapes. These shapes can become increasingly complex as the users interact with the system. A collective image hosts and integrates all of the incoming messages that have been transformed into 3-D images, and as users increasingly interact with the system it is anticipated that an increasingly complex structure will emerge. As it will no longer be possible to deconstruct the collective image into its initial parts, some of the features of complex systems are thought to have emerged. However, it remains to be tested whether one can call this system a truly complex and emerging system. Future versions of the system should address the current shortcomings such as the limited amount of design functions as well as the somewhat nontransparent translation process. Furthermore, we plan to expand the capacity of the system to simultaneously display all messages in the browser's window; this should make it possible for users to retrieve all messages ever sent. Finally, another crucial aspect will be the ability of the forms to start to interact with each other more actively; this could be done by using the genetic exchange of information (text characters) between forms, creating off-spring forms through standard genetic cross-over, and mutation operations as we have used them in the past (Sommerer and Mignonneau, 1997).

References

Amerika, M. 1997. *Gammatron*, http://www.grammatron.com/

Anzai, T. and Nakamura, R. 1994. *RENGA*, http://www.renga.com/

Baas, N., Olesen, M. W. and Rasmussen, S. 1999. Generation of Higher Order Emergent Structures. *Physica D*. North Holland Publishing Company.

Bak, P. and Chen, K. 1991. Self-Organized Criticality. *Scientific American*. January 1991, pp. 46-54.

Baltschefsky, H. 1997. Major "Anastrophes" in the Origin and Early Evolution of Biological Energy Conversion. *J. Theoretical Biology*, 187, pp.495-501.

Bar-Yam, Y (ed.), 2000. Unifying Themes in Complex Systems: Proceedings of the First Necsi International Conference on Complex Systems, New York: Perseus Books.

Bateson, W. 1894. *Materials for the Study of Variation*. Cambridge: University Press.

Blackmoore, S. and Dawkins, R. 1999. *The Meme Machine*. New York: Oxford University Press

Blomberg, C., Liljenström, H. Lindahl, B.I.B. and Århem, P. eds. 1994. Mind and matter: essays from biology, physics and philosophy. *J. Theoretical Biology*, 171, pp.1-122.

Böhler, C., Nielsen, P.E. and Orgel, L.E. 1995. *Nature* Vol.376. pp. 578-581.

Cairns-Smith, A.G. 1982. *Genetic Takeover*. Cambridge: Cambridge University Press.

Cairns-Smith, A.G. 1986. *Clay Minerals and the Origin of Life*. Cambridge: Cambridge University Press

Casti J. 2000. *Paradigms Regained*. New York: William Morrow & Co. forthcoming.

Chyba, C. 1997. A Left-Handed Solar System? *Nature*, Vol.389, pp. 234-235.

Clancey, W. J. 1979b. Transfer of Rule-Based Expertise through a Tutorial Dialogue. Ph.D. diss., Dept. of Computer Science, Stanford Univ.

Crick, F.H.C. 1968. The origin of the genetic code. *J. Molecular Biology*, Vol. 38, pp. 367-379.

Crick, F.H.C., Brenner, S., Klug, A. and Pieczenik, G. 1976. A speculation of the origin of protein synthesis. *Origins Life*, Vol. 7, pp.389-397.

Darwin, C. 1959 [1859]. *The Origin of Species*. Reprinted. London: Penguin.

Dawkins, R. 1986. *The Blind Watchmaker: why the Evidence of Evolution Reveals a Universe without Design*. London: Longman.

De Duve, C. 1991. The Beginnings of Life on Earth. *American Scientist*, Vol. 83, pp. 428-437.

Driesch H. 1914. *The History and Theory of Vitalism*. London: Macmillan.

Eigen, M. and Winler-Oswatitch, R. 1992. *Steps Towards Life: A Perspective on Evolution*. New York: Oxford University Press.

Fontana, W. 1992. Algorithmic Chemistry. *In:* C.G. Langton, J.D. Farmer, S. Rasmussen and C. Taylor (eds.) *Artificial Life II: Santa Fe Institute Studies in the Sciences of Complexity*. Vol. 10. Reading, MA: Addison-Wesely, pp. 159-209.

Fujihata M. 1996. *Light on the Net Project*, http://www.flab.mag.keio.ac.jp/light/

Gánti, T. 1979. *A Theory of Biochemical Supersystems and its Application to Problems of Natural and Artificial Biogenesis.* Baltimore, MD: University Park Press.

Gilbert, W. 1986. The RNA World. *Nature,* Vol. 319, p. 618.

Goldberg, K. 1998. *Memento Mori: an Interface to the Earth,* http://memento.ieor.berkeley.edu/

Goodwin, B. 1994. *How the Leopard Changed its Spots.* London: Orion Books (Phoenix), p. 169.

Haldane, J.B.S. 1932. *The Forces of Evolution.* London: Longmans Green.

Hoyle, F. and Wickramasinghe, N.C. 1979. *Diseases from Space.* New York: Harper and Row.

Inoue, J. 1992. Asymmetric Photochemical Reactions in Solution. *Chemical Reviews,* Vol.92, pp.741-770.

Kauffman, S. 1995. *At Home in the Universe. The Search for Laws of Complexity.* New York: Oxford University Press, pp. 23 - 112.

Langton, C. 1992. Life at the edge of chaos. *In* : C.G. Langton, J.D. Farmer, S. Rasmussen and C. Taylor (eds.) *Artificial Life II: Santa Fe Institute Studies in the Sciences of Complexity* . Vol. 10. Reading, MA: Addison-Wesely, pp. 41-91.

Lee, D.H., Granja, J.R.; Martinez, J.A., Severin, K., Ghadiri, M. R. A Self-Replicating Peptide. 1996. *Nature* , Vol. 382, pp. 525-528.

Lewin, R. 1993. *Complexity: Life at the Edge of Chaos.* London: Macmillan Publishing, pp. 178.

Maynard Smith, J. and Szathmár, E. 1995. *The Major Transitions in Evolution.* Oxford: W.E. Freeman.

Miller, S.L. 1953. Production of amino acids under possible primitive earth conditions. *Science.* 117: 528.

Morowitz, H. 1992. *Beginnings of Cellular Life.* New Haven, CT: Yale University Press

Nielsen P. E., Egholm, M., Berg, R.H. and Buchardt, O. 1991. *Science.* Vol. 254, pp. 1497-1500.

Orgel, L.E. 1987. The Origin of Self-Replicating Molecules. In*: Self-Organizing Stystems: The Emergence of Order.* (F.E. Yates, ed.), New York: Plenum Press, pp. 65-74.

Oparin, A. I. 1924 [translated to English 1938, new edition 1957]. *The Origin of Life on Earth.* New York: Academic Press.

Owen, R. 1980 [1861]. *Paleontology or a Systematic Summary of Extinct Animals and Their Geological Relation.* London: Ayer Co. Publisher

Ruse, M. 1997. The Origin of Life: Philosophical Perspectives. In: *J. Theoretical Biology,* 187, pp.473-482.

Sommerer, C. and Mignonneau, L. 1997. Interacting with Artificial Life: A-Volve, In *Complexity Journal.* New York: Wiley, Vol. 2, No. 6, pp. 13-21.

Sommerer, C. and Mignonneau, L. 1999. VERBARIUM and LIFE SPACIES: Creating a Visual Language by Transcoding Text into Form on the Internet, In: *1999 IEEE Symposium on Visual Languages,* Tokyo, Japan, pp. 90-95.

Spiegelman, S. 1967. An in Vitro Analysis of a Replicating Molecule. *American Scientist,* Vol. 55, pp: 3-68.

Thompson, D'A. W. 1942. *On Growth and Form.* Cambridge: University Press.

Von Neumann, J. 1966. *Theory of Self-Reproducing Automata.:*Completed and edited by A.W. Burks, Champaign-Urbana: University of Illinois Press.

Waddington, C. H. 1966. *Principles of Development and Differentiation.* New York: Macmillan.

Wächterhäuser, G. 1997. The Origin of Life and its Methodological Challenge. In: *J. Theoretical Biology,* 187, pp.483-494.

Whitehead, A. N. 1971 [1920]. *The Concept of Nature.* Reprinted. Cambridge: Cambridge University Press.

Woese, C.R. 1967. *The Genetic Code - The Molecular Basis for Genetic Expression.* New York: Harper and Row.

Wolfram, S. 1986. *Theory and Applications of Cellular Automata.* Singapore: World Scientific Press

ZKM Center Karlsruhe, Germany, 2000. *Net-Condition,* http://on1.zkm.de/netCondition.root/netcondition